TALLINNA TEHNIKAÜLIKOOL
INSENERITEADUSKOND
Elektroenergeetika ja mehhatroonika instituut

HARJAVABADE ALALISVOOLUMOOTORITE LAAGRIRIKETE ANALÜÜS

BEARING FAULT ANALYSIS OF BRUSHLESS DC MOTORS

MAGISTRITÖÖ

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(Tiitellehe pöördel)

AUTORIDEKLARATSIOON

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/ nimi ja allkiri /

LÕPUTÖÖ LÜHIKOKKUVÕTE

Autor: Karolina Kudelina *Lõputöö liik:* Magistritöö

Töö pealkiri: Harjavabade alalisvoolumootorite laagririkete analüüs

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Töö konsultant (konsultandid): -

Sisu kirjeldus:

Käesolev magistritöö tutvustab harjadeta alalisvoolumootorite peamisi rikkeid ja nende diagnostikavõimalusi. Eriti on antud töö uurimisaineks harjavabade alalisvoolumootorite laagririkked. Selliste mootorite populaarsuse kasvu tõttu on nende masinate hooldus ja diagnostika muutunud üha olulisemaks just viimasel kümnendil. Antud elektrimasinate ootamatud rikked on ebasoovitavad ja võimalusel tuleb neid vältida.

Elektrimasina üheks põhielemendiks on laager ning harjavabade alalisvoolumootorite rakenduste kasvuga võib sellise olulise elemendi ootamatu tõrge põhjustada ebasoovitavaid tagajärgi. Antud uuring tutvustab katseid, kus tüüpilisi laagrivigu rakendatakse korras laagritele, et uurida tõrgete mõju elektrimasinale. Peamised rikked harjadeta alalisvoolumootorites on töös välja toodud. Laboratoorsed katsed nii korras kui ka rikkis laagritega on selgitatud ja esitatud. Rikete seire ja diagnostika võimalused on välja toodud.

Märksõnad: alalisvoolumootorid, harjavabad masinad, kuullaagrid, rikete diagnostika, vibratsioonid, kiire Fourier’ teisendus.

ABSTRACT

Author: Karolina Kudelina *Type of the work:* Master Thesis

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Supervisor(s) of the thesis: Senior Researcher Toomas Vaimann, Early Stage Researcher Bilal Asad

Consultant(s): -

Abstract:

This Master thesis presents the main faults of brushless DC motors and their diagnostic possibilities. The main topic of this work is the brushless DC motors' bearing faults. Due to the popularity gain of such machines in the past decade, the maintenance and diagnostic of such machines is getting more important. As the motors are used in various applications, they are often critical parts of devices. Due to this, the unexpected failures of such machines are undesired and are to be avoided.

One of the main components of the electric machine is the bearing and with the growing popularity of brushless DC motors, unplanned failure of an important component such as a bearing can lead to significant economic consequences. This research presents the case study, where these faults are implemented to healthy bearings, in order to further test the impact on machine performance. Laboratory experiments of the setup with healthy as well as faulty bearings are explained and presented. The main faults of the brushless DC machines are listed. Possibilities of fault monitoring and diagnostics have been pointed out.

Keywords: DC motors, brushless machines, ball bearings, fault diagnosis, vibrations, fast Fourier transforms.

LÕPUTÖÖ ÜLESANNE

Lõputöö teema:	**Harjavabade alalisvoolumootorite laagririkete analüüs**
Lõputöö teema inglise keeles:	**Bearing Fault Analysis Of Brushless DC Motors**
Üliõpilane:	**Karolina Kudelina, 183142 AAAM**
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Üliõpilane (allkiri)	Juhendaja (allkiri)	Õppekava juht (allkiri)

1. Teema põhjendus

Antud uurimisteema on oluline ja väga aktuaalne, sest tänapäeval kasutatakse harjavabu alalisvoolumootoreid nii Eestis kui ka välismaal väga paljudes rakendustes. Need on olulisel kohal nii kodumajapidamises kui ka tööstuses. Oluliseks on nende töökindluse tagamine tööstuses, sest seda tüüpi mootorid on kasutuses viimasel ajal väga palju ka elektrisõidukites: elektri- ja hübriidsõidukites, isesõitvates autodes, elektrilistes jalg- ja tõukeratastes. Kuna keskkonnasõbralike sõidukite populaarsus kasvab iga päevaga, siis on oodata nõudluse kasvu ka antud mootori tüübiga sõidukitele. Kasvav rakenduste arv muudab mootori seisundi jälgimist väga oluliseks, eesmärgiga vältida rikete negatiivseid tagajärge.

2. Töö eesmärk

Töö eesmärgiks on uurida harjavabade alalisvoolumasinate laagririkkeid. Tutvuda vastava erialakirjandusega. Leida võimalused laagririkete tekitamiseks laboris. Katsetuste teel selgitada rikete tuvastamise võimalused.

3. Lahendamisele kuuluvate küsimuste loetelu:

1) Mis on harjavabad alalisvoolumootorid?

2) Millised tõrked võivad tekkida harjadeta alalisvoolumootorites?

3) Mis on võimalikud laagririkete allikad ja kuidas võib selliseid rikkeid tuvastada?

4) Millised on erinevate tõrgete vibratsioonispektrid ja mis on nende erinevus?

4. Lähteandmed

Erialakirjandus, olemasoleva katsemasina andmed, laagrite andmelehed, katseseadmete andmelehed, andurite andmelehed.

5. Uurimismeetodid

Uurimismetoodika põhineb nii mõõtmistel/katsetel, kui ka kirjanduse analüüsil. Andmete analüüsiks kasutada sobivat tarkvara.

6. Graafiline osa

Graafiline osa on osaliselt põhitöös, kuid osa läheb ka lisadesse.

7. Töö struktuur

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5.1. Eksperimentaalne katsestend

5.2. Katsete tulemused

8. Kasutatud kirjanduse allikad

1) P. Yedamale, “Brushless DC (BLDC) Motor Fundamentals,” 2003.

2) Y. Da, X. Shi, and M. Krishnamurthy, “Health Monitoring, Fault Diagnosis and Failure Prognosis Techniques for Brushless Permanent Magnet Machines,” 2011 IEEE Veh. Power Propuls. Conf. VPPC, 2011.

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4) Y. Chen, S. Liang, W. Li, H. Liang, and C. Wang, “Faults and Diagnosis Methods of Permanent Magnet Synchronous Motors : A Review,” 2019.

5) Tom Bishop, “Dealing with Shaft and Bearing Currents.”

9. Lõputöö konsultandid

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10. Töö etapid ja ajakava

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SISUKORD

EESSÕNA

Antud lõputöö teema esitati elektroenergeetika ja mehhatroonika instituudi elektrimasinate uurimisrühma poolt. Kõik katsed ja simulatsioonid olid läbi viidud elektrimasinate teaduslaboris.

Suured tänud minu juhendajale Toomas Vaimannile abi ning toetuse eest antud magistritöö kirjutamisel. Soovin tänada ka minu kaasjuhendajat Bilal Asadi, kes aitas katsete jooksul saadud andmeid töödelda ja analüüsida. Soovin avaldada suurt ja siirast tänu Ants Kallastele ja Anton Rassõlkinile, et toetasid nõuega ning aitasid säilitada motivatsiooni antud lõputöö kirjutamisel.

SISSEJUHATUS

Antud uurimistöö tutvustab harjadeta alalisvoolumootorite peamisi rikkeid ja nende diagnostikavõimalusi. Põhjalikult on uuritud levinumaid laagririkked. Need rikked tekitati füüsiliselt tervetele laagritele, et uurida tõrgete mõju elektrimasina talitlusele.

Selliste mootorite populaarsuse kasvu tõttu viimasel kümnendil on antud masinate hooldus ja diagnostika üha olulisemaks muutunud. Tänu ökonoomsele energiatarbimisele ja vähesele hooldusvajadusele, on nimetatud mootorid pälvinud laialdast tähelepanu erinevates tööstuslikes ja kodumaistes rakendustes: tööstusautomaatikas, taastuvenergeetikas, lennunduses, majapidamises, ja paljudes teistes valdkondades. Eriline tähelepanu on pööratud harjavabadele mootoritele transpordivaldkonnas, kuna harjavabad alalisvoolumootorid annavad oma panuse keskkonnasõbralike ja uuenduslike elektrisõidukite arengusse, nagu hübriid- ja elektriautod, isesõitvad autod, elektrilised jalg- ja tõukerattad.

Kuna masinaid kasutatakse nii laialt erinevates rakendustes, on selliste masinate ootamatud rikked ebasoovitavad ja neid tuleb vältida. Antud lõputöö eesmärgiks on uurida harjavabade alalisvoolumasinate laagririkkeid. Selleks on vaja leida võimalused laagririkete tekitamiseks laboris ja katsetuste teel selgitada rikete tuvastamise võimalused.

Esimeses peatükis on põhjalikult vaadeldud antud tüüpi mootoreid, nende eelised ja puudused. Lähemalt on kirjeldatud mootorite konstruktsiooni ja tööpõhimõtet. Lisaks on loetletud ka erinevad valdkonnad ja rakendused, kus kasutatakse harjadeta alalisvoolumootoreid.

Teises peatükis on loetletud põhilised tõrked, mis võivad tekkida harjavabades alalisvoolumootorites. Kuna elektrimasinad töötavad erinevates tingimustes, siis pikaajalisel talitlusel tekivad mootoris paratamatult mõningad rikked. Põhimõtteliselt võib harjadeta alalisvoolumootorites esinevad tõrked jagada kolme põhirühma: elektrilised, magnetilised ja mehaanilised tõrked. Selles peatükis on vaadeldud iga rühma kõige levinumaid rikkeid ja nende vältimise võimalusi.

Kolmandas peatükis on vaadeldud harjadeta alalisvoolumootorite laagririkkeid. Harjavabade alalisvoolumootorite rakenduste kasvuga võib sellise olulise komponendi nagu laager ootamatu tõrge põhjustada olulisi majanduslikke ja ohtlikke tagajärgi. Seega laagrite töökindluse ja usaldusväärsuse tagamine on äärmiselt oluline. Antud peatükis on vaadeldud võimalikud laagririkked, nende tekkimise põhjused ning soovitused, kuidas saab neid rikkeid vältida.

Viimastel aastakümnetel on elektrimasinate diagnostika saanud põhjendatud tähtsuse. Tänapäeval on rikkediagnostikaks palju meetodeid. Peaaegu kõik signaalitöötluse meetodid põhinevad Fourier' real. Neljandas peatükis on loetletud erinevad tehnikad, mida kasutatakse rikete tuvastamiseks, nagu kiire Fourier' teisendus, lühiajaline Fourier' teisendus ja lainikteisendus. Samuti on räägitud lühidalt edasiarenenud diagnostikatehnikatest, mis on praegu maailmas kasutusel.

Viies peatükk on kõige mahukam ja olulisem osa antud töös. Antud peatükis on kirjeldatud katsestend: kasutatud mõõtevahendid, mootor, laagritele tekitatud rikked. Kuna kasutatud katsemootor on ette nähtud kasutamiseks elektrilises tõukeratastes, siis on valitud seitse tüüpilist laagririket, mis võivad ilmneda elektrilises tõukerattas. Iga vigane laager annab teatud vibratsioonisignaali, mida saab võrrelda füüsiliselt terve laagri vibratsioonisignaaliga ja tuvastada rikke olemasoleku. Antud töö raames kirjeldatakse ja võrreldakse laagrite vibratsioonispektreid.

Esmajoones oleks antud lõputöö kasulik eelkõige ettevõtetele, mis tegelevad harjavabade alalisvoolumootoritega. Eriti oleks tehtud uuring kasulik firmadele, mis tegelevad elektriliste tõukerataste tootmise ja müügiga või rendivad elektrilisi tõukerattaid.

1. HARJAVABADE ALALISVOOLUMOOTORITE ALUSED

Struktuuri järgi võib alalisvoolumootoreid liigitada järgmiselt:

- harjadega alalisvoolumootorid (ingl. *BDC – brushed DC motors*),
- harjavabad alalisvoolumootorid (ingl. *BLDC – brushless DC motors*).

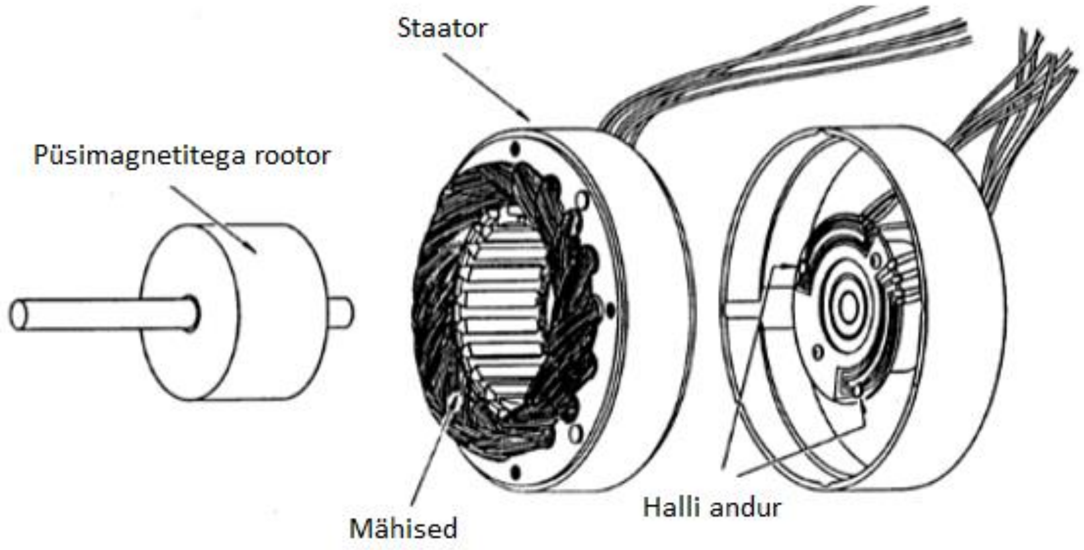
Lihtsaim mootoritüüp on harjadega alalisvoolumootor. Kõik harjadega alalisvoolumootorid koosnevad samadest põhikomponentidest: staatorist, rootorist, harjadest ja kommutaatorist. Harjadega alalisvoolumootoril on lihtne disain ja tööpõhimõte. Selliste mootorite madal hind muudab need sobivaks paljudes rakendustes. Enamasti seisnevad harjadega alalisvoolumootorite puudused harjade kasutamises. Harjad põhjustavad müra ja lühendavad mootori eluiga. Samuti vajavad harjad regulaarset väljavahetamist.

Harjade poolt põhjustatud probleemide ületamiseks töötati välja harjadeta alalisvoolumootorid. Sellistes elektrimasinates ei kasutata harju voolu ülekandmiseks ja muundamiseks [1]. Sellist tüüpi mootorid on elektrooniliselt kommuteeritud ja harjade puudumise tõttu ei tekita need sädelust. Selline omadus võimaldab neid kasutada ka rakendustes, kus sädemed on ohtlikud (näiteks gaasikeskkonnas). Lisaks sellele, harjade eemaldamine harjadeta alalisvoolumootorites vähendab mehaanilist hõõrdumist ja elektrilise erosiooniga seotud probleeme. Püsimagnetite kasutamine koos jõuelektroonikaga võimaldab harjadeta alalisvoolumootoritel toota rohkem energiat kui harjadega mootoritel. Lisaks sellele, on harjavabad alalisvoolumootorid väiksemad ja kergemad kui sama väljundvõimsusega harjadega mootorid, muutes need väärtuslikuks rakendustes, kus kriitilised tegurid on suurus ja kaal. Üldiselt on harjadeta alalisvoolumootoritel järgmised eelised harjadega alalisvoolumootorite ees [2]:

- Suurendatud efektiivsus,
- Suuremad kiirusvahemikud,
- Vähendatud müra,
- Paremad kiirus-pöördemomendi suhted,
- Väiksemad suurus ja kaal,
- Suurendatud töökindlus,
- Pikem kasutusiga.

1.1 Harjavabade alalisvoolumootorite konstruktsioon ja tööpõhimõte

Harjadeta alalisvoolumootorite konstruktsioon sarnaneb püsimagnetitega sünkroonmootoriga. Rootori ja staatori magnetväljad pöörlevad samal sagedusel. Sõltuvalt faaside konfiguratsioonist, on staatoril vastav mähiste arv. Harjavabad alalisvoolumootorid võivad olla ühefaasilised, kahefaasilised või kolmefaasilised. Neist on kolmefaasilised mootorid kõige populaarsemad ja laialdasemalt kasutatavad. Antud lõputöö keskendub kolmefaasilistele mootoritele, nagu on näidatud joonisel 1.1.



Joonis 1.1 Kolmefaasiline harjavaba alalisvoolumootor [3]

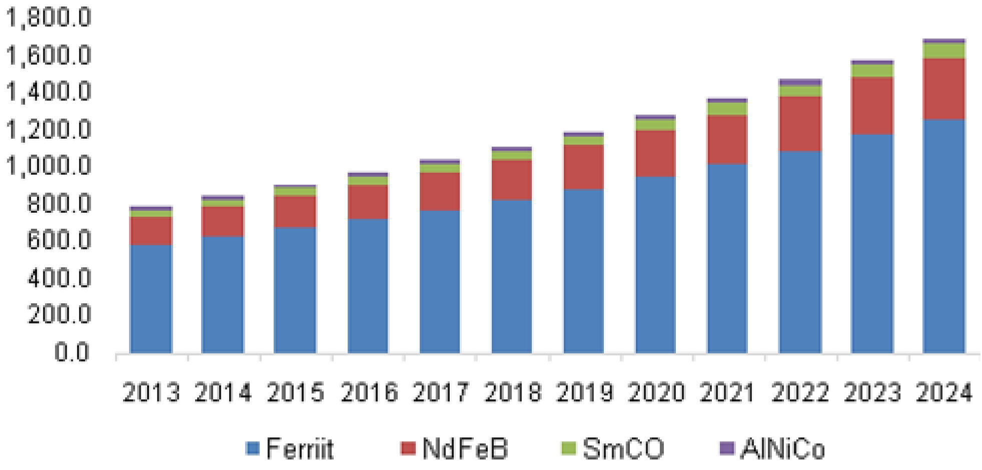
1.1.1 Rootor

Harjavaba alalisvoolumootori rootor koosneb võllist ja püsimagnetitega rummust. Rootorid võivad sisaldada kaks kuni kaheksa pooluspaari, kus põhja- ja lõunapoolused on vaheldumisi.

Püsimagnetitega elektrimasinate kasutamine on tänapäeval kasvav trend, kuna sellised elektrimasinad on tõhusamad ja usaldusväärsemad [4]. Seetõttu on viimastel aastatel kasvanud ka püsimagnetitööstus ja nõudlus selliste materjalide järele. Lähtudes rootori nõutavast magnetvälja tihedusest, valitakse rootori valmistamiseks õige magnetiline materjal. Viimasel ajal on neli peamist magnetilist materjali, mida kasutatakse erinevates rakendustes:

- Ferriit,
- AlNiCo (alumiiniumi, nikli ja koobalti sulam),
- SmCo (samariumi ja koobalti sulam),
- NdFeB (neodüümi, raua ja boori sulam).

Materjalide kasutamine viimastel aastatel ja nende prognoositud nõudlus on toodud joonisel 1.2.



Joonis 1.2. Globaalse püsimagnetituru maht materjali järgi (2013 – 2024) [5]

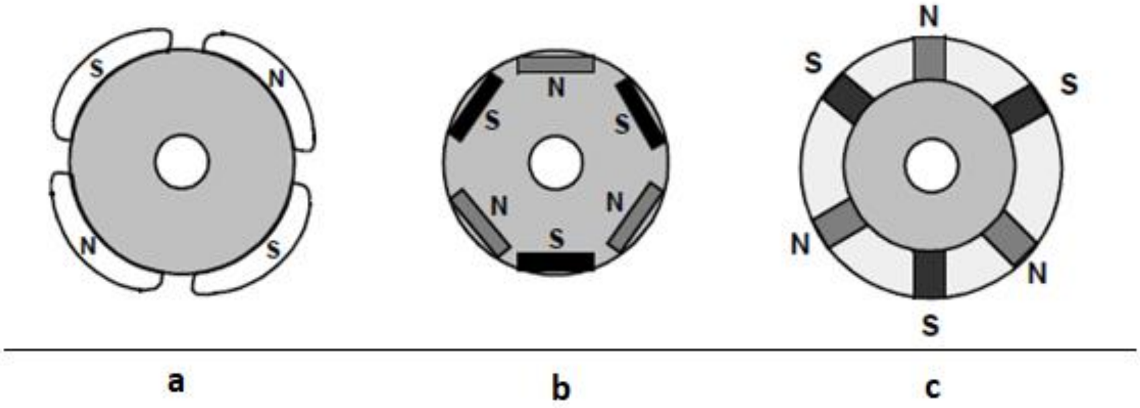
Tänapäeval domineerivad globaalses püsimagnetitööstuses ferriitmagnetid. Ferriitmaterjalide peamiseks eeliseks on nende maksumus. Seda tüüpi püsimagnetid on üks odavamaid magnetitüüpeja nende valmistamise kulud on madalamad. Samuti on ferriidil väga kõrge elektriline takistus. Nendel magnetitel on väga hea korrosioonikindlus ja pikk kasutusiga. Ferriitmaterjalide peamine puudus on madal jääkinduktsioon, mis on põhjuseks miks antud magnetmaterjali ei kasutata suure võimsustihedusega rakendustes.

AlNiCo magnetid on madala koertsitiivsusega, mis võib põhjustada materjali demagnetiseerumist. Samuti on selle materjali maksimaalne energiatihedus umbes 1/5 SmCo materjalidest, kuid samas on materjalil suurepärased kõrgendatud temperatuuritaluvuse omadused ja korrosioonikindlus [6].

Püsimagnetitega elektrimasinad, mida kasutatakse autode elektrimootorites, sisaldavad tavaliselt haruldastel muldmetallidel põhinevaid püsimagneteid (NdFeB ja SmCo), mis võimaldavad saavutada suurt jõudlust laias temperatuurivahemikus [7]. Lisaks sellele, SmCo magnetitel on parem vastupidavus termilise demagnetiseerumise suhtes, kõrge koertsitiivsus ja kõrge korrosioonikindlus [6]. Teisest küljest on SmCo magnetid rabedad ja suhteliselt kõrge hinnaga. NdFeB magnetid on vähem rabedad, kuid nendel on halvad soojusomadused ja vastupidavus korrosioonile.

Kummatigi on haruldaste muldmetallide sulamid tänapäeval tööstuses eelistatumad, eriti kasutatakse neid sellistes rakendustes nagu elektrimasinad [8]. NdFeB sulameid kasutatakse juhtudel, kus on vaja saada suurem võimsustihedus ning SmCo sulameid kasutatakse laiade temperatuurivahemike korral [9].

Harjavabade alalisvoolumootorite korral on kasutusel erineva konfiguratsiooniga rootorimagneti ristlõiked. Peamised võimalused on näidatud joonisel 1.3.



Joonis 1.3. Magnetite ristlõiked rootoril [10]:

a) pinnale paigaldatavad magnetid, b) rootori sisse paigaldatud tangentsiaalmagnetid, c) rootori sisse paigaldatud radiaalsed magnetid.

Püsimagnetitega masinate korral on magneti paigutuseks rootoril peamiselt kaks erinevat varianti [11]:

- Magnetid paigutatakse rootori pinnale nagu näidatud joonisel 1.3 a,
- Magnetid paigutatakse rootori piludesse nagu näidatud joonisel 1.3 b, c.

Mootori korral, kus magneteid paigutatakse rootori pinnale (joonis 1.3 a), muutub mootori konstruktsioon muude paigutustega võrreldes lihtsamaks. Samas võivad pinnale paigutatud magnetid vähendada elektrimasina töökindlust.

Samuti on võimalused magnetite rootori sisemusse paigutamise jaoks (joonised 1.3 b, c). Sõltuvalt põhjusest võib kasutada erinevaid paigutusviise. Sel juhul muutub rootori konstruktsioon keerulisemaks. Eeliseks sisemise paigutuse korral on koorimise või purunemise võimaluse välistamine tsentrifugaaljõudude või rikete korral [12].

1.1.2 Staator

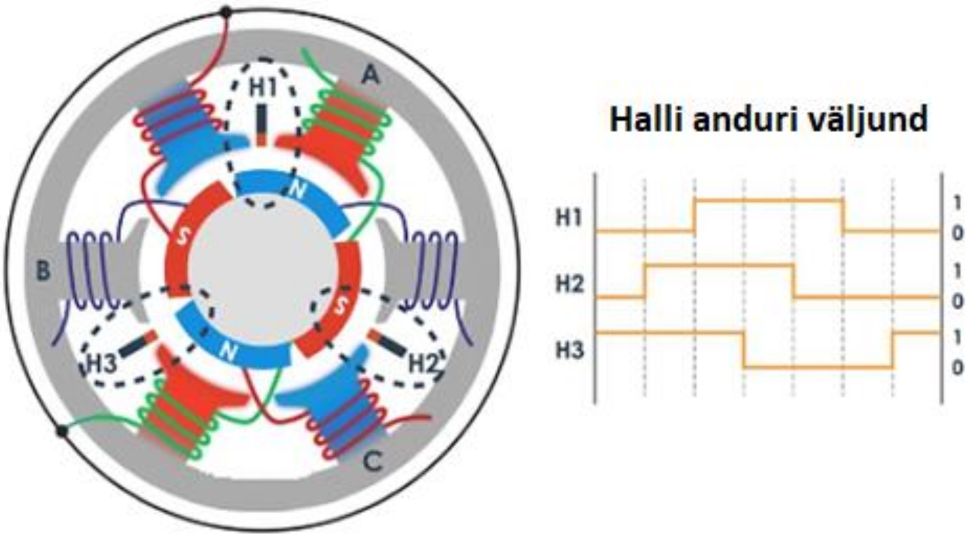
Harjavaba alalisvoolumootori staator sarnaneb asünkroonmootori staatoriga. Peamine erinevus seisneb mähiste jaotuses. Kolmefaasilise harjavaba alalisvoolumootori staator on näidatud joonisel 1.4.

Joonis 1.4. Harjavaba alalisvoolumootori staator

Harjavaba alalisvoolumootori staator koosneb järjestatud teraslaminaatidest, milles mähised on paigutatud piludesse. Pilu on lõigatud piki laminaadi sisemist serva. Üldiselt kasutatakse mootorites kolme täht-ühendusega mähist. Samuti on võimalused kolmnurk-ühenduseks. Neid kahte ühendust võrreldes kasutatakse täht-ühendust suurema väljundmomendi saamiseks ning kolmnurk-ühendust suurema pöörlemiskiiruse saamiseks [13].

1.1.3 Rootori tuvastussensorid

Erinevalt harjatud alalisvoolumootoritest on harjadeta mootorite töö elektrooniliselt reguleeritud. Rootori pideva pöörlemise saavutamiseks tuleb staatori mähiseid järjestikku pingestada. Selleks et õigele mähisele pinget anda, on oluline teada rootori asendit. Rootori asendi tuvastamiseks kasutatakse staatorisse sisse ehitatud Halli andureid, nagu on näidatud joonisel 1.5.



Joonis 1.5. Harjadeta alalisvoolumootorites kasutatav Halli andur [14]

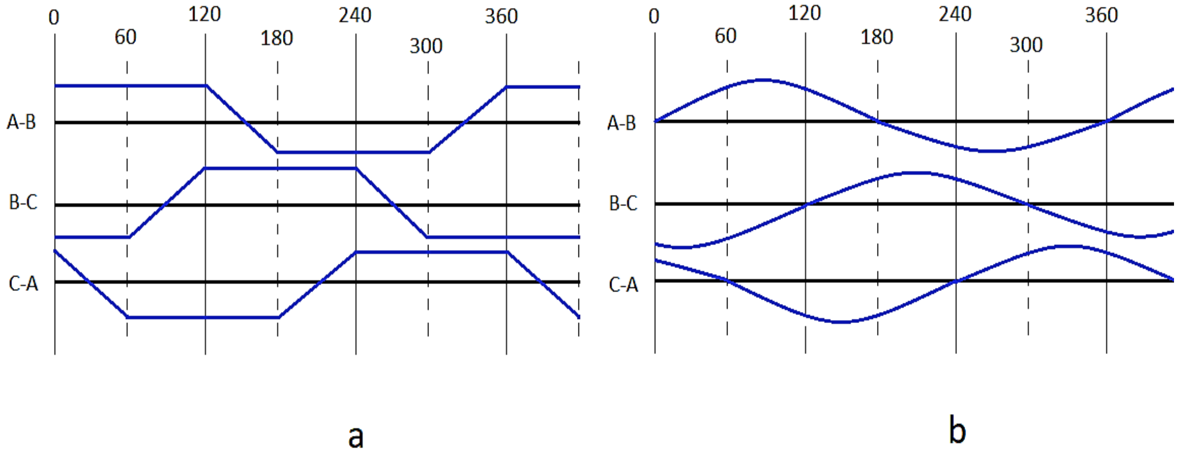
Enamikul harjadeta alalisvoolumootoritel on kolm Halli andurit, mis on sisse ehitatud staatorisse mootori mitte-ajami otsa. Halli andurite kinnitamine staatorile on keeruline protsess, kuna Halli anduri mis tahes vale paigutus rootori magnetite suhtes põhjustab rootori asendi määramisel tõrke.

Halli andurite paigaldamise lihtsustamiseks on mõningatel mootoritel lisaks rootori peamagnetidele juba rootorisse sisse ehitatud Halli anduri magnetid.

Halli andurid tuvastavad põhja- või lõunapoolust, kui magnetpool läheb andurist mööda, ning määravad rootori asukoha. Selle info põhjal otsustab kontroller, millist staatori mähist pingestada. Anduri mõõdetud signaali saab kasutada ka püsimagnetite rikete tuvastamiseks, näiteks pragude tekkimise või demagnetiseerimise korral.

1.2 Harjavabade alalisvoolumootorite tööpõhimõte

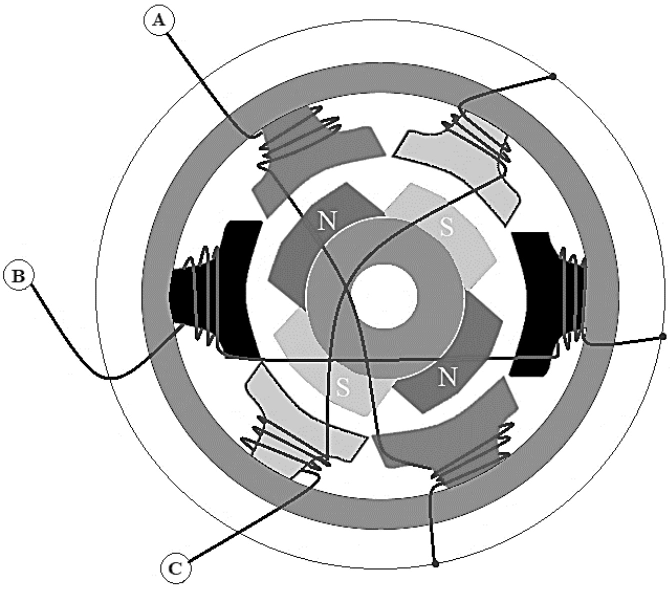
Teine kriteerium, mille järgi saab mootorite klassifitseerida, on nende vastu-elektromotoorjõu (ingl. *EMF – Electromotive Force*) järgi, ja nimelt nende juhtimise meetodi järgi. Erinevalt püsimagnetitega sünkroonmootoritest, harjavabad alalisvoolumootorid võivad kasutada kas trapetsikujulist või sinusoidset kommutatsiooni. Vastavalt juhtimise nimele, trapetsikujuline juhtimine annab trapetsikujuliset vastu-elektromotoorjõudu ja sinusoidne juhtimine annab sinusiodset vastu-elektromotoorjõudu, nagu on näidatud joonisel 1.6 (a, b).



Joonis 1.6. Vastu-elektromotoorjõu tüübid:

a) trapetsikujuline elektromotoorjõud, b) sinusoidne elektromotoorjõud.

Lisaks vastu-elektromotoorjõule, võivad faasivoolud olla kas trapetsi- või siinusekujulised, vastavalt mootori tüübile. Sinusoidne mootor muudab pöördemomendi sujuvamaks kui trapetsimootori korral. Ent sellega kaasnevad ka lisakulud, kuna sinusoidse elektromotoorjõuga mootoritel on staatoril mähiste jagunemise tõttu täiendavad ühendused, mis suurendavad kasutatava vase hulka. [10]



Joonis 1.7. Harjavaba alalisvoolumootori tööpõhimõte

Rakendades mähisele alalisvoolu, annab see energiat ja muutub elektromagnetiks. Harjadeta alalisvoolumootori tööpõhimõte põhineb püsimagneti ja elektromagneti vahelisel vastasmõjul. Jooniselt 1.7 selgub, et kui mähis A on pingestatud, rootori ja staatori vastaspoolused tõmbuvad. Kui rootor läheneb mähisele A, siis mähis B pingestub. Kui aga rootor läheneb mähisele B, siis mähis C pingestub. Pärast seda pingestub mähis A vastupidise polaarsusega. Selline protsess kordub ja rootor jätkab pöörlemist.

1.3 Harjavabade alalisvoolumootorite rakendused

Madalama energiatarbimise ja vähese hooldusvajaduse tõttu, on harjavabad alalisvoolumootorid pälvinud laialdast tähelepanu erinevates tööstuslikes ja kodustes rakendustes: lennunduses, majapidamises, taastuvenergeetikas, tööstusautomaatikas, jne. Eriline tähelepanu on pööratud harjavaba mootoritele autotööstuses ja transpordivaldkonnas.

Keskkonna- ja majandusväljavaated annavad tõuke tõhusate ja säästlike sõidukite väljatöötamiseks linnatranspordi jaoks [15]. Harjavabad alalisvoolumootorid annavad oma panuse keskkonnasõbralike ja uuenduslike elektrisõidukite arendamisse, nagu hübriid- ja elektriautod, isesõitvad autod, elektrilised jalg- ja tõukerattad.

Elektriautode tööstus on viimase kümnendi jooksul kiiresti kasvanud. Nende peamiseks eeliseks on panus, mille nad saavad anda linnaõhu kvaliteedi parandamisel. Tänapäeval on kasutusel nelja tüüpi mootoreid [16]:

- Asünkroonmootor (ingl. *induction motor*),
- Reluktants-samm-mootor (ingl. *switched reluctance motor*),
- Harjadega alalisvoolumootor,
- Harjavaba alalisvoolumootor.

Autodes kasutatavate elektrisüsteemide disainis toimub kiire areng, mille eesmärgiks on parandada kütusesäästlikkust, ohutust ja mugavust [17]. Seadmete energiatõhususe kasvava nõudluse tõttu kasutatakse suure jõudlusega püsimagnetmootoreid üha enam, asendates asünkroonmootoreid [18]. Harjavabad alalisvoolumootorid on äärmiselt sobivad elektrisõidukite jaoks laia kiiruse ning võimsuse vahemike tõttu. Samuti kasutatakse harjadeta alalisvoolumootoreid rummusiseste mootoritena. Sellise konfiguratsiooniga mootorid ühendavad endas ratta ja ratasse sisse ehitatud veoelektrimootori, ülekandemehhanismi ja mõnikord ka pidurisüsteemi. Selline konstruktsioon viib suurendatud efektiivsuse saavutamiseni ja sõiduki massi ning suurure vähendamiseni.

Veel üks märgatav trend transporditööstuses on elektrilised tõukerattad. Elektrilise tõukeratta peamised nõuded on suur võimsustihedus ja käivitusmoment, laiad kiirusvahemikud, töökindlus, vähendatud müra ja vähene hooldusvajadus [19]. Harjavabad alalisvoolumootorid vastavad antud nõuetele paremini kui muud tüüpi mootorid.

Elektrilise õhusõiduki või elektrilise gaasiturbiinmootori (ingl. *EGTE – electric gas turbine engine*) loomine on üks peamisi arengusuundi lennunduses. Elektriliste õhusõidukite disaini alused kõrge töökindlus ja kompaktne ning suure võimsustihedusega konstruktsioon. Üheks tehnoloogiliseks probleemiks, mis takistab elektritehnoloogiate kasutuselevõttu lennunduses, on üsna suured elektriseadmete gabariidid. Nii harjavabad alalisvoolumootorid kui ka reluktants-samm-mootorid on eelistatumad mootoritüübid, mis vastavad lennunduse ja kosmose rakenduste nõuetele. Üldiselt eelistatakse harjadeta alalisvoolumootoreid reluktantsmootorite asemel nende kompaktsuse ja suurema võimsustiheduse tõttu. [20], [21]

Samal ajal kui elektrilised õhusõidukid on alles arengujärgus, on üks teine lennunduse trend juba pälvinud erilist tähelepanu – droonid. Selleks, et õhus hõljuda, tuleb droonide konstruktsioonis kasutada kerget ja võimsat mootorit. Ka siin sobivad ülesande täitmiseks suurepäraselt harjavabad alalisvoolumootorid. Need mootorid võimaldavad pinget ja voolu kergemini reguleerida ja seega ka kiirust juhtida, mis on oluline drooni ühest kohast teise viimisel. [22], [23]

Lisaks logistikale ja transpordile on harjadeta alalisvoolumootorid leidnud laialdast kasutamist ka paljudes tööstuslikes rakendustes. Kuna konstruktsioonis puuduvad harjad, siis ei tekita sellised mootorid sädelust. Selle omaduse tõttu sobivad harjavabad alalisvoolumootorid väga hästi nafta- või gaasitööstusesse, kus sädemed on eriti ohtlikud. Selles tööstuses mootorite kasutamise ühe näitena võiks välja tuua õlitootmisel kasutatavad elektrilised sukeldatavad tsentrifugaalpumbad. Peamised nõuded mootoritele selles valdkonnas on järgmised:

- Mootori talitlus rootori minimaalse vibratsiooniga,
- Mootori minimaalsed gabariidid (kuna kaevu läbimõõt on piiratud),
- Mootori vastupidavus kõrgetele välistemperatuuridele.

Võrreldes teiste mootoritüüpidega, tehnoloogilisest küljest, lihtsustab harjadeta alalisvoolumootorite kasutamine sellises rakenduses pumba tööprotsessi ja võimaldab tõhusamat talitlust rasketes töötingimustes. [24], [25]

Kodumajapidamistes on alalisvoolumootoritest saanud populaarne lahendus veepumpade rakenduste valdkonnas. Näiteks, nagu on kirjeldatud artiklis [26], saab harjadeta alalisvoolumootorit kasutada kolbpumba süsteemis. Selliseid hüdrosüsteeme kasutatakse laialdaselt põllumajanduses.

Veel üheks rakenduseks, kus harjadeta alalisvoolumootoreid edukalt kasutatakse, on ventilaatorid. Võrreldes teist tüüpi elektrimasinatega, on püsimagnetitega alalisvoolumootorid ventilaatori ajami jaoks eelistatavamad. Seda eelkõige laia kiirusvahemiku ja lihtsa kiiruse juhitavuse, kõrge efektiivsuse ja pika kasutusea tõttu. Harjadega alalisvoolumootoritega ventilaatoreid võib kasutada vaid suhteliselt piiratud aja jooksul. Reluktants- ja asünkroonmootoreid ei eelistata kõrgema mürataseme tõttu [27]. Samuti, asünkroonmootori olemuse tõttu, tekivad probleemid seoses pulseeriva pöördemomendiga. Harjadeta alalisvoolumootori kasutamine sellistes rakendustes on põhjendatud ka energiasäästi silmas pidades. Energiat saab kokku hoida vähemalt 50% võrreldes asünkroonmootoril põhineva ventilaatoriga [28].

Lisaks kasutatakse tänapäeval harjadeta alalisvoolumootoreid ka autodes ventilaatorite osana mootori jahutamiseks. Mootori jahutusventilaator on sõidukite elektrisüsteemi üks olulisemaid osasid, kus on nõutud kõrge efektiivsus ja madal vibratsiooni- ning müratase.

Viimastel kümnenditel suurenenud süsinikuheide ja kahenev fossiilkütuste osakaal maailmas julgustavad kasutusele võtma keskkonnasäästlikumaid tehnoloogiaid, näiteks päikesepaneele või tuuleturbiine. Ka selles valdkonnas leiavad harjadeta alalisvoolumootorid kasutust. On kasutusel süsteemid, kus päikesepaneelidest toodetud energia abil kasutatakse alalisvoolumootoreid veepumba juhtimiseks.

2. HARJAVABADE ALALISVOOLUMOOTORITE PÕHILISED TÕRKED

Harjavabadel alalisvoolumootoritel võivad töötamise käigus tekkida erinevad rikked. Elektrimasinate rikkeid võivad põhjustada erinevad tegurid. Üldiselt võib harjadeta alalisvoolumootorites esinevad tõrked jagada kolme põhirühma [29]:

- Elektrilised tõrked (mähiste rikked),
- Magnetilised tõrked (püsimagnetite demagneetumine),
- Mehaanilised tõrked (ekstsentrilisus ja laagririkked).

Kuna elektrimasinad võivad töötada erinevates tingimustes, on pikaaegse talitluse korral tekkivad rikked paratamatud. Samal ajal on nende tõrgete vahel vastastikune seos.

2.1 Elektrilised tõrked

Seda tüüpi rikkeid põhjustab tavaliselt mähise isolatsioonirike, mis juhtub sageli piirkondades, kus laupmähised sisenevad staatori piludesse. Põhjused, mis võivad tekitada elektrilisi rikkeid, on järgmised [30]:

- Kõrgendatud temperatuur,
- Siirdeliigpinged,
- Saastumine,
- Tootmisdefektid,
- Lühised.

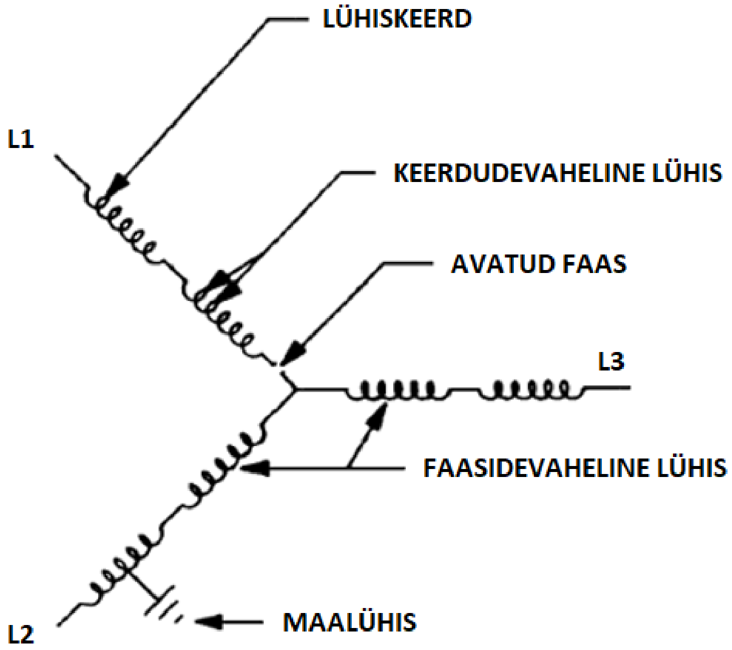
Termiline ülekoormus on kõige levinum põhjus staatori mähise isolatsiooni kvaliteedi vähenemiseks. Termiline stress võib süveneda kauakestva ülekoormuse, kõrgema temperatuuri või tasakaalustamata toitepinge tõttu [31]. Ülevoolud põhjustavad mootori ülekuumenemist ja isolatsiooni kahjustamist. Samuti võivad mootori sagedased käivitused ja seiskumised tõsta mähiste temperatuuri ja lühendada mootori eluiga.

Teiseks, elektrodünaamilised jõud võivad põhjustada mootori mähiste tõrkeid. Peamiselt põhjustavad seda atmosfääri liigpinged, muutuva sagedusega ajamid, kaitselülitite avamine või sulgemine.

Niiskus võib tekitada mootorile palju probleeme, põhjustades mootori erinevate osade korrosiooni. Eelkõige söövitab niiskus isolatsiooni ja viib lühiseni mähiste vahel, söövitab laagreid, mootori võlli ja rootorit. Selle käigus väheneb pöörlemise sujuvus, langeb efektiivsus ja lõpuks jõuab mootor täielikku rikkeolukorda.

Mustus, näiteks tolm või muu praht, võivad blokeerida õhuvoogu mootori jahutusventilaatoritesse ja põhjustada ülekuumenemist. Lisaks võivad mootori sees olevad tolmuosakesed ja muud väikesed esemed tekitada mehaanilist takistust, mis aeglustab mootorit. Samuti võivad mustuseosakesed abrasiivselt kahjustada isolatsiooni.

Elektriliste rikete võimalikuks põhjuseks on ka lühised. Nagu on näidatud joonisel 2.1, võib praktikas ette tulla viis kõige tavalisemat mähise riket.



Joonis 2.1 Võimalikud lühiste tüübid [32]

Elektrilised tõrked masinates algavad tavaliselt keerduvahelisest lühisest ja võib kasvada kuni faasidevahelise või maalühiseni kui ennetavat hooldust ei tehta. Need lühisetüübid võivad esineda ka erinevates kombinatsioonides. See võib mootorit kahjustada niivõrd, et edasine töö ei ole võimalik.

2.2 Magnetilised tõrked

Harjadeta alalisvoolumootorites kõige sagedamini esinevaks püsimagneti tõrkeks on selle demagneetumine [30]. Demagneetumine tähendab magneetumise osalist või täielikku kadu. Tingimused, mis võivad tekitada püsimasinate demagneetumist elektrimasinas, on enamasti järgmised [33]:

- Masina ülekoormamine,
- Kõrge töötemperatuur,
- Tootmisdefektid,
- Lühised.

Ülekuumenemine ja ülekoormamine on püsimagneti demagneetumise põhiliseks põhjuseks. Elektrimasina töötamine kõrgel temperatuuril ja kohase jahutussüsteemi puudumine võib suurendada püsimagnetite demagnetiseerumise riski. Teine tegur, mis võib magneti omadusi mõjutada, on lühised. Magneti jaoks on kõige ohtlikum faasidevaheline lühis. Lisaks demagneetumisele võib korrosioon vähendada magnetilise materjali omadusi. Kuigi püsimagnetitel on head magnetilised omadused ja neid kasutatakse laialdaselt erinevates tööstusharudes, on nende stabiilsus agressiivsete ja keeruliste keskkonnatingimuste suhtes piiratud. Püsimagnetite korrosioonikindluse tõstmiseks on kaks võimalust [34]:

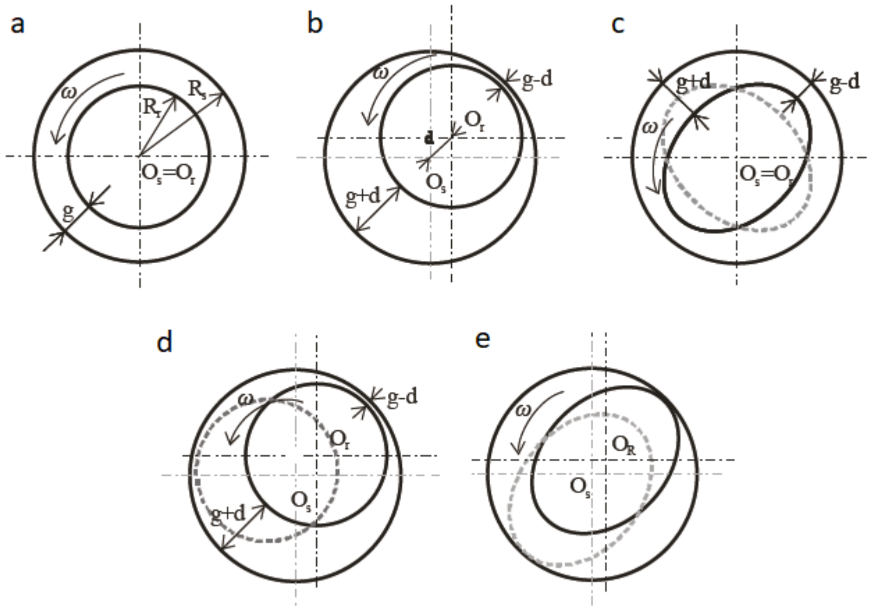
- Magneti mikrostruktuuri modifitseerimine erinevate lisaelementide abil,
- Metall- või mittemetallkihtidega pinnakatete kasutamine.

2.3 Mehaanilised tõrked

Peaaegu 50% kõigist harjadeta alalisvoolumootorite riketest on seotud mehaaniliste riketega [32]. Sellised vead viitavad enamikus masinates tavaliselt ekstsentrilisusele ja laagririketele.

Üks mehaanilisi rikkeid, mis ilmneb harjadeta alalisvoolumootorites, on ekstsentrilisus. Ekstsentrilisuse rikked põhjustavad rootori ja staatori vahelist ebaühtlast õhupilu. Selle põhjuseks on peamiselt vale paigaldamine, poltide puudumine, võlli kõverdus või rootori tasakaalustamatus

[35]. Ekstsentrilisust on kolme peamist tüüpi: staatiline ekstsentrilisus, dünaamiline ekstsentrilisus ja elliptiline ekstsentrilisus. Võimalikud ekstsentrilisuse tüübid on toodud joonisel 2.2



Joonis 2.2. Elektrimasinate ekstsentrilisuse tüübid [11]:

a) korras mootor, b) staatiline, c) elliptiline, d) ja e) dünaamiline.

Rootori ja staatori vaheline mittehomogeenne õhupilu põhjustab elektrimasinates ekstsentrilisuse tõrkeid. Õhupilu üle 10% peetakse rikkeks [36]. See tekitab uitvoolusid staatori mähistes, mis omakorda soojendab mootoreid ja põhjustab lisakadusid.

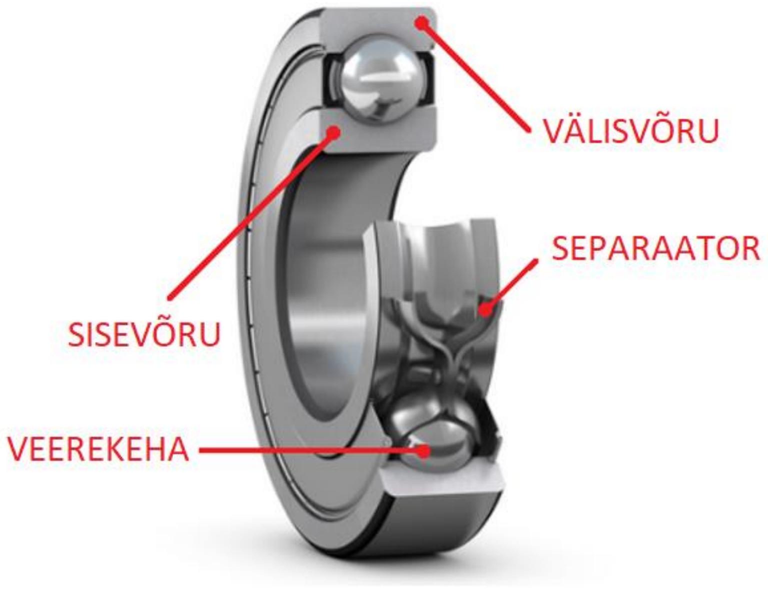
Ekstsentrilisuse rikked võivad põhjustada täiendavat müra ja vibratsiooni. Kui ekstsentrilisus muutub tõsiseks, võib see põhjustada hõõrdumist staatori ja rootori vahel ning kahjustab staatori või rootori südamikku, mõjutades mootori normaalset talitlust [35].

Teine mehaaniline tõrge, mis võib esineda harjadeta alalisvoolumootorites, on seotud laagririketega. Sellise tõrke tüübi tekkimiseks võib olla palju põhjuseid. Peamised neist on seotud laagrite halva määrimise või ülekoormamisega. Laagririket saab tuvastada suurenenud müra ja vibratsiooni kaudu [30]. Laagririketega seotud probleeme käsitletakse üksikasjalikult järgmises peatükis.

3. LAAGRID HARJAVABADES ALALISVOOLUMOOTORITES

Laagrid on elektrimasina põhielemendid. Sel põhjusel on olnud laagrid paljude uuringute objektiks viimaste aastakümnete jooksul. Laagrite tootmine toimub vastavalt laagrite kvaliteedinõuetele. Need on üks täpseimaid tooteid, mida toodetakse masinaehituses. Põhimõtteliselt, nagu on näidatud joonisel 3.1, koosneb enimkasutatud kuullaager järgmistest komponentidest:

- Sise- ja välisvõru,
- Veerekehad,
- Separaator, mis eraldab veerevaid elemente.



Joonis 3.1. Laagri konstruktsioon [37]

Laagritüübi valimisel tuleb lähtuda sellistest parameetritest nagu koormuse suund ja olemus, laagri võru püürlemiskiirus ja töökeskkond. Laagri rike pole alati enneaegne. Laagreid asendatakse enamasti seoses laagrimaterjali tavapärase väsimusprotsessiga (laagri loomuliku kulumisega). Normaaltingimustes võib õigesti valitud ja õigesti kasutatav laager töötada kauem kui masin. Üldiselt võib laagrite tüübid jagada järgmistesse rühmadesse:

- Veerelaagrid,
    - kuullaagrid
    - rull-laagrid
- Liuglaagrid,
- Magnetlaagrid.

Kuullaagrid on kõige laialdasemalt kasutatavad laagritüübid, mis on leidnud kasutust ka harjadeta alalisvoolumootorites. Optimaalsetes töötingimustes saab laagreid kasutada paljude aastate jooksul. Kuna töötingimused on harva ideaalsed, siis realiseeritakse laagrite potentsiaalne ressurss harva lõpuni. Üldiselt sõltub laagri kasutusiga tootmistehnoloogia tasemest, ladustamistingimustest, laagri õigest valimisest ja kasutamisest. Suur tähtsus on ka õigel paigaldamisel, kvaliteetsel määrimisel ja tihendamisel.

Laagrid on tavaliselt komponendid, mis on teiste suuremate mootorikomponentidega võrreldes väiksemad, samal ajal mõjub neile suur hulk erinevaid jõudusid, muutes need kahjustuste ja kulumise suhtes eriti tundlikuks.

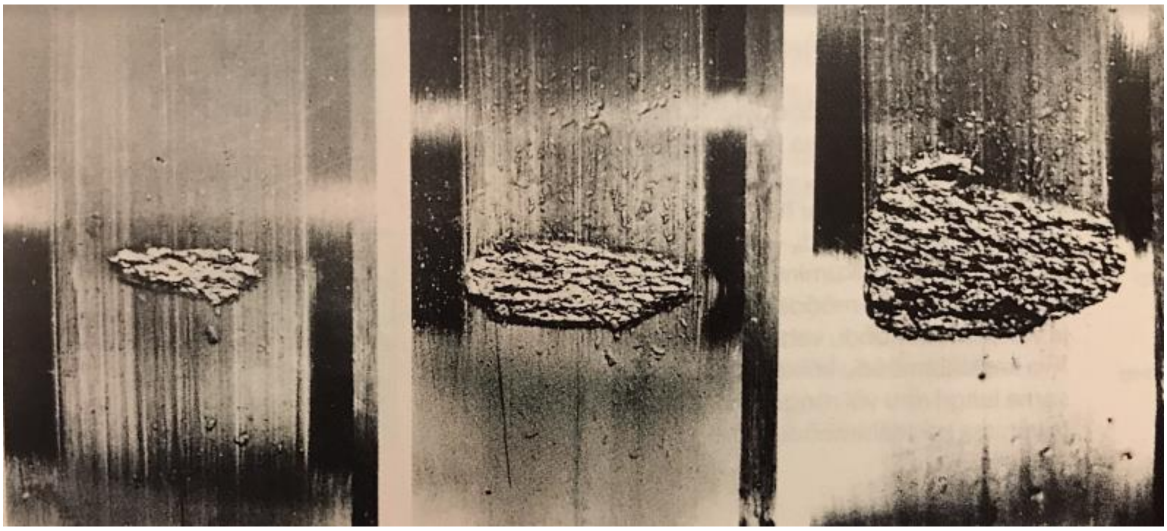
Laagririkete põhjusteks võivad olla erinevad keskkonna- või tootmistegurid [36]:

- Materjali väsimus,
- Halb määrimine,
- Vale paigaldamine,
- Saastumine,
- Uitvoolud.

Laagrite talitluse jälgimisel, müra ja vibratsiooni mõõtmisel ning perioodiliselt määrdeaine kvaliteedi analüüsimisel saab laagrite kahjustuste riski märkimisväärselt vähendada.

3.1 Materjali väsimus

Materjali väsimus on progresseeruv ja lokaalselt struktuuriline kahjustus, mis tekib materjali korduval mehaanilisel pingestamisel. Materjali väsimust põhjustavad tavaliselt tsüklilised või muutuvad koormused. Tsükliline ja kauakestev koormus põhjustab materjali pinnale pragusid. Kui väsimuspragunemine laieneb järk-järgult suuremale pinnale, muutub laager lõpuks edasiseks tööks sobimatuks. Laagri vastupidavuseks loetakse selle pöörete arvu, mille laager teeb enne, kui esimesed väsimuse rikkemärgid muutuvad märgatavateks laagri pindadel ja veerekehadel. Materjali väsimuse järkjärgulised etapid laagripinnal on näidatud joonisel 3.2.



Joonis 3.2. Materjali väsimuse järkjärgulised etapid laagripinnal [38]

Aeg, millal esimesed esimesed materjali väsimuse märgid ilmnevad, sõltub laagri pöörlemiskiirusest ja koormuse suurusest. Rikke arenemise esimesel etapil tekivad mikrolõhed. Seda tüüpi kahjustuste edasisel arenemisel hakkab laagripind kooruma ja pragunema. Väsimuse kogunemisega laagrimaterjalisse muutub laagri pind karedaks ja laager hakkab müra tekitama ning kuumenema. Pidev ülekoormus, halvasti töödeldud ja saastunud pinnad põhjustavad paratamatult väsimusnähtusi. Seda saab vältida või märkimisväärselt aeglustada, kui laager on puhas (mitte saastunud) ja hästi määritud.

3.2 Halb määrimine

Laagri üks olulisemaid töötingimusi on selle korrektne määrimine. Määrdeaine moodustab tööpindade vahel vajaliku elastohüdrodünaamilise õlikihi, mis samal ajal pehmendab veeremiskehade mõju võrude ja separaatori suhtes. Määrimine tagab laagri vastupidavuse. Määre vähendab hõõrdumist ja kaitseb laagrit korrosiooni ja kulumise eest. Samuti hoiab määrdeaine ära tahkete ja vedelate saasteainete sisenemist laagrisse.

Vale määrimine võib seisneda kas väheses või liigses määrimises, mis viib paratamatult laagri enneaegse hõõrdumiseni ja lühendab selle kasutusiga. Vähest määrimist võib põhjustada kas madala viskoossusega määrde kasutamine või selle puudulik kogus. Liigne määrimine võib omakorda põhjustada võlli libisemist, mis omakorda põhjustab pragude tekkimist ja arengut.

Lisaks sellele, määrdeainete ebaõige valimine aitab kaasa laagri saastumisele. määrdeainete tüüpide hulka kuuluvad plastsed määrded ja erinevad õlil põhinevad määrded, õliudu määrimine, õhk-õli määrimine, and piserdumismäärimine [39]. Erinevate määrdeainete võrdlus on toodud tabelis 3.1.

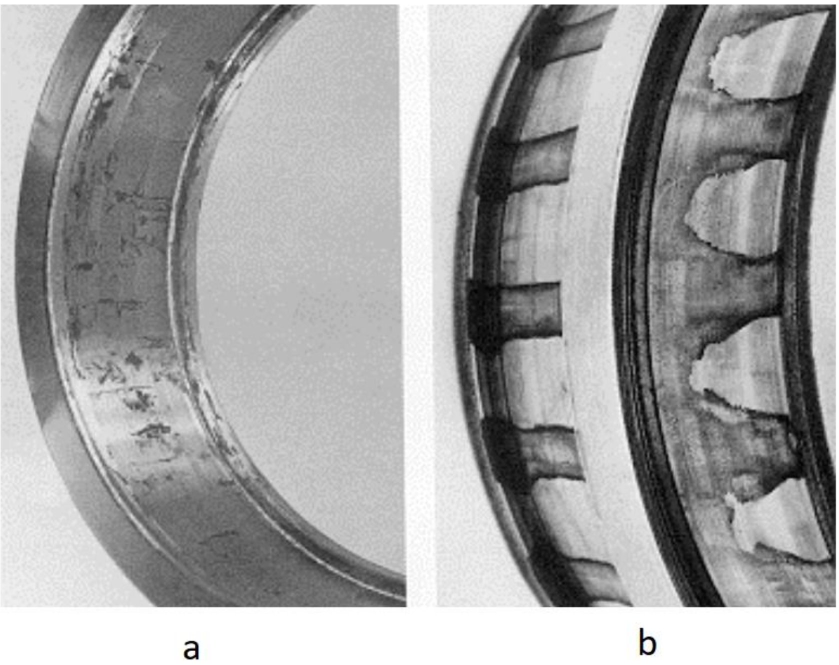
Tabel 3.1. Erinevate määrdeainete võrdlus [39]

Määrimisviisid **Kriteerium**	**Plastsed määrded**	**Õliudu määrimine**	**Õhk-õli määrimine**	**Piserdumis-määrimine**
Töökindlus	Hea	Keskmine	Hea	Suurepärane
Temperatuuri tõus	Keskmine	Keskmine	Hea	Suurepärane
Jahutav efekt	Vaene	Keskmine	Hea	Suurepärane
Kõrge pöörlemiskiirus	Vaene	Hea	Hea	Hea
Võimsuskaod	Hea	Hea	Hea	Vaene
Saastumine	Hea	Vaene	Fair	Hea

Igal määrimismeetodil on oma unikaalsed omadused. Seetõttu tuleb valida määrimismeetod, mis vastab kõige paremini määrimisnõuetele. Määrdeaine valik sõltub laagri töötingimustest, eriti temperatuurivahemikust, kiirusest ja töökeskkonnast. Peamiselt määritakse laagreid plastsete määretega. Sellise määrde tüübi peamiseks eeliseks õlide ees on see, et plastne määre töötab hõõrdekohtades pikemat aega ja vähendab seega majanduskulutusi. Õlide oluline eelis määrde ees on täiustatud soojuse hajutamine. Kuid võrreldes plastse määrdega on õlide oluliseks puuduseks kõrge hind ja nende lekke oht.

3.3 Saastumine

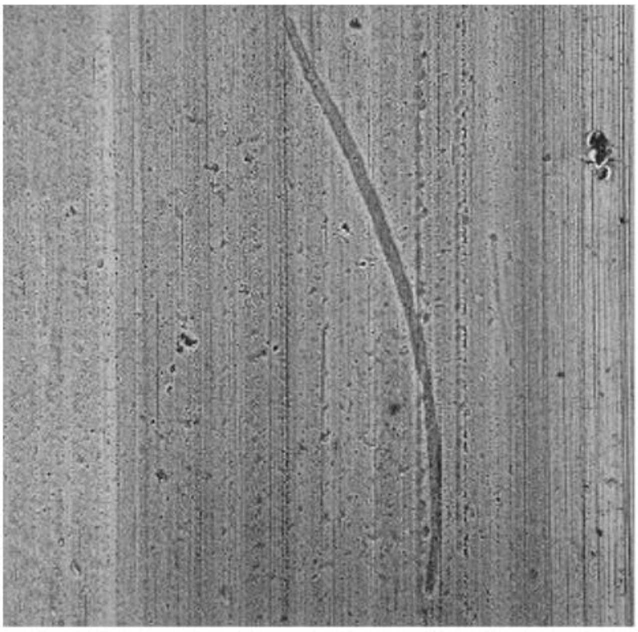
Niiske õhk, mis siseneb atmosfäärist laagrisse, lõhub määrdekihi laagri pindade kokkupuutepunktides. Samuti võib määre saastuda, kui vesi või muud keemiliselt aktiivsed ained sisenevad laagrisse. Määrdeomaduste halvenemisega tekib laagrite korrosioon. Antud tõrke vältimiseks võib kasutada korrosioonikindlaid määrdeid. Korrodeerunud laagri näide on kujutatud joonisel 3.3.



Joonis 3.3. Korrosiooni jäljed laagripinnal [40]:

a) Korrosiooni jäljed laagri välisvõrul, b) Korrosiooni jäljed laagri sisevõrul.

Saastumine juhtuda ka laagritihendite vale valiku korral. See võib omakorda põhjustada erinevate osakeste (tolmu või mustuse) sattumist laagrisse. Võõrkehad, näiteks metallilaastud, mis tungivad laagrisse, tekitavad mõlke, nagu on näidatud joonisel 3.4.



Joonis 3.4. Mõlgid, mis on põhjustatud võõrosakeste mõjuga laagrite pinnale (suurendus 50x) [40]

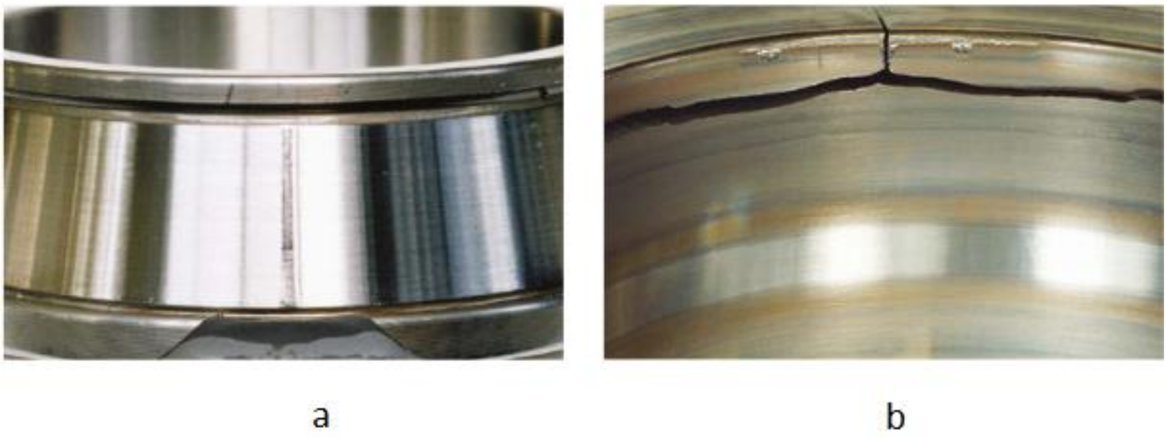
Laagri pinnal võivad tekitada mõlke ka näiteks paberiosakesed või tekstiilkiud. Mõlgid on enamasti väikesed ja jaotatud kogu laagrirajal. Selle vältimiseks tuleb valida õige tihend. Oluline hoida laagri paigutusel puhtust ja mitte kasutada saastunud määrdeaineid ning hoiduda liigse jõu kasutamisest.

3.4 Vale paigaldamine

Laagrite vead võivad ilmneda ka järgmistel põhjustel: laagri vale konstruktsioon tootmine või paigaldamine, laagriradade kõverdus, veerekehade ebavõrdsed läbimõõdud [41]. Enne paigaldamist tuleb kontrollida laagris tootmisvigade olemasolu: välimust, pöörlemist ning tehnilise dokumentatsiooni nõuete vastavust. Visuaalselt tuleb kontrollida avatud tüüpi laagrites sisselõikeid, saastumis- ja korrosioonijälgi. Suletud tüüpi laagrite korral tuleb kontrollida tihendeid võimalike kahjustuste suhtes.

Samuti tuleb enne paigaldamist kontrollida kestade ja võllide kinnituspindasid. Laagritega kokkupuutuvate võllide ja kestade pinnad tuleb põhjalikult pesta, kuivatada ja määrida määrdeaine õhukese kihiga. Veel tuleb kontrollida võlli joondust. Üldiselt on vaja kontrollida kõigi samal teljel asuvate pindade joondust.

Suure jõu rakendamine separaatorile või otse rõngale löömine laagri paigaldamisel pole lubatud. Rõngale on lubatud teha vaid kergeid lööke. Kõige sobivamad on paigaldusmeetodid, mille puhul kogu paigaldatud rõnga ümbermõõdule rakendatakse samaaegset ja ühtlast survet. Vale paigaldamise võimalikud tagajärjed on toodud joonisel 3.5.



Joonis 3.5. Laagri valest paigaldamisest tulenevad praod [42]

Joonisel 3.5 (a) on toodud pragu, mis on tekkinud koonuslaagri sisemise rõnga suurel ribil. Selline olukord juhtub siis, kui laagrile rakendatakse vale aksiaalset või liiga tugevat löökkoormust. See võib ilmneda ka siis, kui laagri paigaldamisel või demonteerimisel rakendatati ribile sobimatut jõudu.

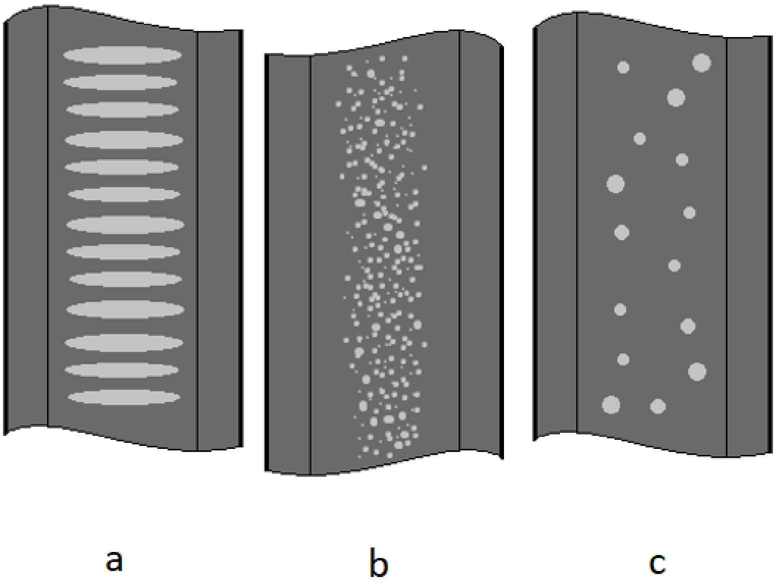
Praod, mis on näidatud joonisel 3.5 (b), tekivad tugeva löökkoormuse või liigse mehaanilise pinge korral. Sellist nähtust võib täheldada siis, kui välisvõru on võllil nõrgalt kinnitatud ja tekib libisemine. [42]

3.5 Uitvoolud

Laagreid võivad mõjutada uitvoolud. Kui elektrivool läbib laagrit ühest rõngast teise läbi veereelementide, võib laagris tekkida rike.

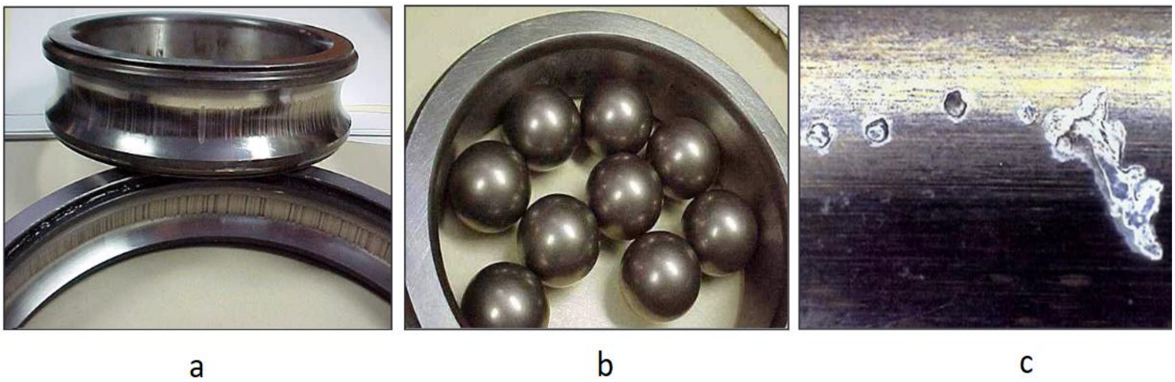
Kahjustuse suurus sõltub voolu tugevusest, koormusest, ajast, pöörlemiskiirusest, määrdeaine valikust. Sel juhul on ainus viis laagrite kaitsmiseks vältida elektrivoolu liikumist läbi laagreid. Samuti saab kasutada elektrilise isolatsiooniga laagreid. Lisaks sellele, tuleb elektrilise keevitamise ajal laagrid maandada, et vältida elektrivoolu läbimist. [40]

Selline tõrge erineb selgelt laagripinnal kõigist muudest tüüpilistest laagrikahjustustest. Antud tõrke tüüp ja välimus sõltuvad mootori töötingimustest. Joonis 3.6 näitab uitvooludega põhjustatud defekte, mida nimetatakse *"fluting"*, *"frosting"* ja *"pitting"*.



Joonis 3.6. Uitvoolude mõju laagrite pindadele [43]:
a) "*fluting*", b) "*frosting*", c) "*pitting*".

Sagedamini on laagrivoolude esimesteks sümptomiteks tekkinud müra ja vibratsioon. Samuti põhjustavad need rikked laagrimaterjali kuumenemist. Sel juhul moodustuvad erineva suurusega värvilised alad, kus materjal kuumeneb ja seejärel uuesti karastub ning mõnikord isegi sulab. Kohtades, kus metall on sulanud, võivad tekkida ka väikesed lohud. Lisaks sellele, on antud tõrke eripäraks on see, et veerekehad võivad muuta oma värvi (matistuvad). [40]



Joonis 3.7. Uitvoolude mõju laagrite pindadele praktikas [44]:
a) “fluting”, b) “frosting”, c) “pitting”.

Laagrivoolu kahjustused ilmnevad laagripindadel tavaliselt kohtades, kus on rakendatud suuremat koormust. Põhjus on see, et määrdekiht on sellistes kohtades väga õhuke. Kahjustatud pindade välimus oleneb tõrke tüübist.

Peamine laagrivooludega põhjustatud tõrge on “*fluting*”, mille välimus avaldub hulgalistes joontes, mis “lõikavad” laagri sise- ja välisvõru, nagu on näidatud joonisel 3.7 (a). Tavaliselt ilmneb “*fluting*” madalpinge ja püsiva pöörlemiskiiruse kombinatsioonis. Kui mootor aga töötab muutuva kiirusega, ilmub teine hästi tuvastatav tõrge, mida nimetatakse “*frosting*”. “*Frosting*” on näidatud joonisel 3.7 (b). Kolmandat tõrget, mida nimetatakse “*pitting*”, võib põhjustada madal pöörlemiskiirus. “*Pitting*” tekib enamasti rakendustes, kus kasutatakse alalisvoolu, näiteks raudtee veomootorites. Sel juhul tekivad laagripinnal väikesed kraatrid. Kraateri suurus, nagu on näidatud joonisel 3.7 (c), on reeglina läbimõõduga 0,1–0,5 mm ja on nähtav palja silmaga. Selliseid kraatreid võivad põhjustada kõrgepinge lahendused.

Praktikas eristatakse veel ühte uitvoolude tõrket, mida nimetatakse “*dull-finish*”. Selline rike sarnaneb väga “*pitting*”-uga, kuid palju väiksemate lohkudega, nagu näidatud joonisel 3.8. Mikrokraatrid on üsna levinud kahjustus, kui mootorit toidetakse läbi sagedusmuunduri. Kahjustatud pinnal tekivad mikrokraatrid, mis katavad veerekehasid ja laagripindasid. [44]

Joonis 3.8 “Dull-finish” ja kraatrid laagri sisevõrul [44]

Kraatri suurused on väikesed, enamasti läbimõõduga 5–8 µm, sõltumata sellest, kas kraater asub laagri siserõngal, välisrõngal või veerekehadel. Selliste kraatrite tegelikku kuju võib näha ainult mikroskoobi all, kasutades väga suurt suurendust. [44]

4. DIAGNOSTIKA VÕIMALUSED HARJAVABADES ALALISVOOLUMOOTORITES

Viimastel aastakümnetel on elektrimasinate diagnostika saanud põhjendatud tähtsuse. Tänapäeval on rikkediagnostikaks palju võimalusi. Neist suurema osa võib jagada järgmistesse kategooriatesse [45]:

- Temperatuuri mõõtmine,
- Elektromagnetvälja jälgimine,
- Raadiosageduslike häiringute seire,
- Keemiline analüüs,
- Akustilise müra mõõtmine,
- Mootori voolukuju analüüs (ingl. *MCSA – motor-current signature analysis*),
- Müra ja vibratsiooni jälgimine,
- Mudelitel, tehisintellektil ja närvivõrgul põhinevad tehnikad.

Üldiselt on kaks suurt rühma, mille alla saab liigitada elektrimasinate diagnostilised tehnikad – invasiivsed ja miiteinvasiivsed tehnikad. Invasiivsete tehnikate korral, on andurid mootorisse sisse ehitatud. Seda tüüpi diagnostilised tehnikad on tihti täpsemad, kuid võivad põhjustada keerukust ja ebatäpsusi anduri enda rikke puhul. Mitteinvasiivsete tehnikate korral, ei ole masinas sisseehitatud andureid ja otsusi tehakse kaudsete mõõtmiste teel. Kuigi mitteinvasiivsed meetodid on vähem täpsed, võrreldes invasiivsete meetoditega, on nende eeliseks see, et ei ole vaja muuta masina konstruktsiooni anduri paigaldamisel. Samuti avab globaalsete parameetrite mõõtmine suure hulga signaalianalüüsi tehnikaid, mida saab kasutada sõltuvalt masina olemusest ja selle rakendusest.

Peaaegu kõik signaalitöötluse tehnikad põhinevad Fourier' real ja selle variantidel. Fourier’ rea idee on see, et mis tahes perioodilist funktsiooni saab esitada siinuste ja koosinuste seeriana. Fourier’ rida tegeleb ainult perioodiliste signaalidega. See tähendab, et signaalid korduvad teatud aja jooksul. Fourier’ rea keerulisi valemeid saab vältida kiire Fourier’ teisenduse abil, mis muutub arvutusalgoritmi kiiremaks ja lihtsamaks.

4.1 Kiire Fourier' teisendus

Kiire Fourier' teisendus (ingl. *FFT – Fast Fourier transform*) muundab ajadomeeni sagedusdomeeniks. Võrreldes Fourier' reaga, käsitleb kiire Fourier teisendus nii perioodilisi kui ka mitteperioodilisi signaale. Andmetüübi järgi saab kiire Fourieri teisenduse jagada kahte kategooriasse:

- Pidev Fourier' teisendus (ingl. *CTFT -continuous time Fourier transform*)

$$CTFT\ X(\omega) = \int_{n=-\infty}^{\infty} x(t)e^{-j\omega t}dt \tag{1}$$

kus *x(t)* on pideva ajadomeeni funktsioon.

- Diskreetne Fourier' teisendus (ingl. *DTFT - discrete time Fourier transform*)

$$DTFT\ X(\Omega) = \sum_{n=-\infty}^{\infty} x[n]e^{\ -j\Omega n} \tag{2}$$

kus *x[n]* on diskreetne ajadomeeni funktsiooni.

Antud diagnostikaviis on väga lihtne, võrreldes paljude muude signaalitöötluse tehnikatega. Selline tehnika nõuab vähem arvutusvõimet, kuid kiirel Fourier' teisendusel on ka mitmeid puudusi ja piiranguid. Esiteks, väike diskreetimissagedus võib põhjustada signaali moonutust. Teiseks, signaali ajapiirang võib põhjustada spektrileket. Spektrileke on põhisageduse komponendi energialeke.

Kiire Fourier' teisenduse peamiseks puuduseks on aga see, et algoritm töötab ainult statsionaarsete signaalidega ja ebaõnnestub, kui signaal on mittestatsionaarne. Pealegi on selle tehnika abil keeruline käsitleda katkendlikke signaale. Sel juhul on lahenduseks lühiajaline Fourier' teisendus.

4.2 Lühiajaline Fourier' teisendus

Lühiajalise Fourier' teisenduse (ingl. *STFT – short-time Fourier transform*) algoritm põhineb originaalsignaali jagamisel lühikesteks osadeks. Akna lühenemisel võib signaali pidada statsionaarseks, mis võimaldab arvutada kiire Fourier' teisendust iga segmendi kohta eraldi. Selline tehnika tagab parema aeg-sageduse esituse. Andmete efektiivsemaks hankimiseks on võimalik tulemusi analüüsida ka 3D-graafikute (aeg-sagedus-amplituud) abil. Lühiajalise Fourier' teisenduse võrrand on järgmine:

$$X\ (m,\omega) = \sum_{n=-\infty}^{\infty} x[n]w\ [m - n]e^{-j\omega n} \tag{3}$$

kus *x[n]* on täielik signaal ja *w[m-n]* on kärpimisaken, mis liigub ja võtab osa signaalist ajaühiku kohta.

Lühiajalisel Fourier’ teisendusel on aga sarnased puudused kiirele Fourier’ teisendusele. Nende puuduste vähendamiseks on väga oluline aknafunktsiooni nutikas kasutamine signaali kärpimiseks.

4.3 Lainikteisendus

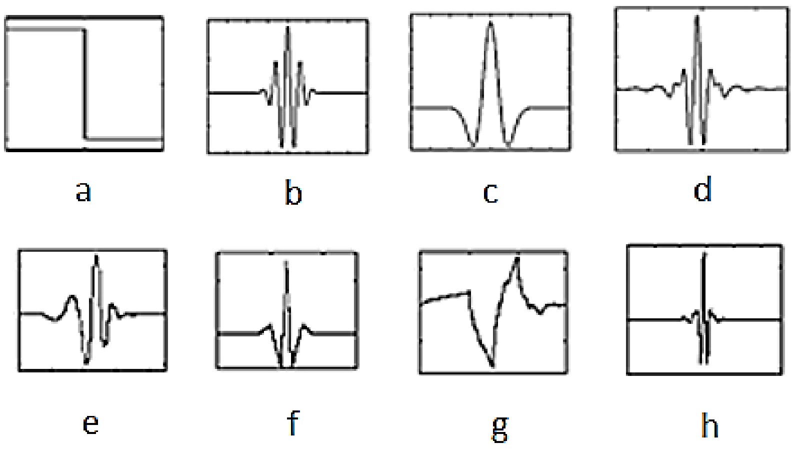
Järgmine signaalitöötluse algoritm, mis käsitleb peaaegu igat tüüpi signaale, on lainikteisendus (ingl. *Wavelet transform*). Samal ajal kui kiire Fourier’ teisenduse signaalid jagunevad lõpmatu kestusega sinusoidideks ja koosinusteks, signaalid lainekujulises teisenduses jagunevad piiratud kestusega laineteks.

Samuti, võrreldes Fourier’ teisendusega, on aeg-sageduse esitus parem. Peamiseks puuduseks on, et lainikteisendus vajab rohkem arvutusvõimsust ja mälu andmete salvestamiseks. Lainikteisenduse võrrand on järgmine:

$$W\ (a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \psi\left(\frac{t-b}{a}\right) f(t)dt \tag{4}$$

kus a on transleerimise parameeter, b on skaleerimise parameeter, $\frac{1}{\sqrt{a}}$ normaliseerimiskonstant, $\psi\left(\frac{t-b}{a}\right)$ on emalainik.

Selle tehnika algoritm põhineb ühe konkreeste emalainiku valimisel ja selle võrdlemisel mõõdetud esialgse signaaliga. Kindla sagedusega malainikut võrreldakse analüüsitava signaaliga ning transleerimise ja skaleerimise parameetrid määratakse parima korrelatsiooniga lõikudes. Pärast seda muudetakse emalainiku sagedusparameetreid ja protsessi korratakse, kuni kõik sagedused on taastatud. Kasutusel on erinevad emalainikud tüübid. Neist peamised ja kõige levinumad on näidatud joonisel 4.1.



Joonis 4.1. Levinud emalainikute tüübid [46]:

a) Haari lainik, b) Morlet' lainik, c) Rickeri lainik, d) Meyeri lainik, e) Daubechies lainik, f) Biortogonaalne lainik, g) Symlet lainik, h) Coiflet lainik.

4.4 Arenenud tehnikad

Tulenevalt asjaolust, et infotehnoloogia on väga kiiresti arenev, on mõistlik keskenduda kõrgtehnoloogiate integreerimisele elektrimasinate diagnostikasse. Tänapäeval kasutatakse palju arenenud diagnostilisi tehnikaid, nagu närvivõrgud, häguslooogika või kujutuvastus. Diagnostikas saab kasutada ka mõnda analüütiliselt arenenud tehnikat, nagu pöördprobleemi teooria, masinõpe ja parameetrite hindamist. Sellised arenenud tehnikad pakuvad tõhusamaid ja täpsemaid tulemusi. Enamik neist meetoditest sõltub süsteemi matemaatilistest mudelitest, mis muudab need keerukamaks. Ülalmainitud diagnostiliste meetodite lühikokkuvõte on toodud tabelis 4.1.

Tabel 4.1. Rikkediagnostika meetodite võrdlustabel

	Eelised	**Puudused**
Kiire Fourier'teisendus	Töö mitteperioodiliste signaalidega, Väikesed infokaod, Väiksem arvutusvõimsus.	Puudub võimalus mittestatsionaarseid signaale analüüsida, Aeg-sageduse esitus ei ole võimalik, Esitus, Spektrileke.

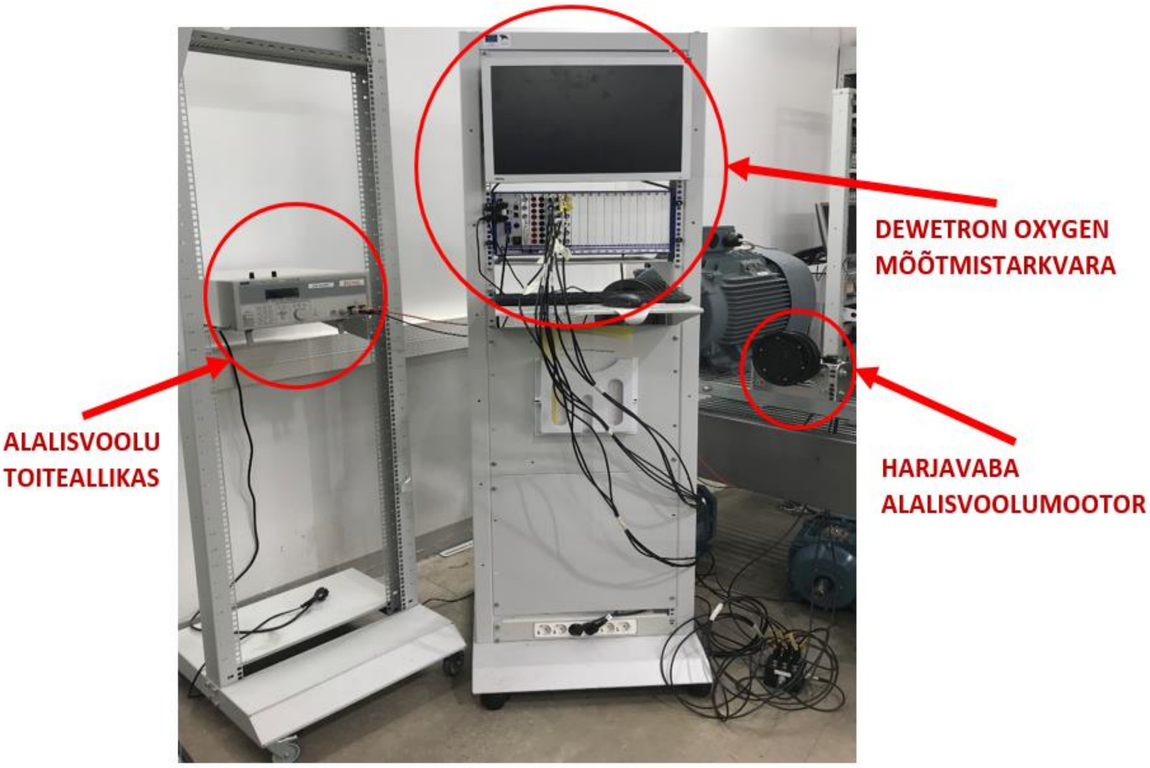
	Eelised	**Puudused**
Lühiajaline Fourier' teisendus	Töö mitteperioodiliste signaalidega, Võimalus analüüsida mittestatsionaarseid signaale, Aeg-sageduse esitus on võimalik, 3-D graafikute (aeg-sagedus-amplituud) kasutamise võimalus.	Halb aeg-sageduse esitus, Esitus, Spektrileke, Võrreldes kiire Fourier' teisendusega on vaja rohkem arvutusvõimsust.
Lainikteisendus	Väga täpne tehnika, Aeg-sagedus esitus on parem, Võimalus analüüsida mittestatsionaarseid signaale, Emalainikute mitmekesisus muudab tehnikat paindlikumaks.	Vahetulemuste salvestamiseks on vaja rohkem mälu, Võrreldes lühiajalise Fourier' teisendusega on vaja rohkem arvutusvõimsust, Suurem täpsus nõuab rohkem iteratsioone.
Arenenud tehnikad	Tõhusam analüüs, Täpsemad tulemused.	Kaasaegsed ja keerukas tehnoloogiad on nõutud, Nõuab palju arvutusvõimet.

5. TÖÖ PRAKTILINE OSA

Aeg-ajalt juhtub, et laager täidab oma funktsiooni ainult osaliselt ning kahjustub. Selline nähtus võib ilmneda mitmel põhjusel, näiteks suure koormuse, ebapiisava määrimise või ebaõige määrdeaine tõttu. Enamikul juhtudel on võimalik tuvastada kahjustuse põhjus ja võtta kasutusele asjakohaseid meetmeid, et vältida laagri korduvat kahjustamist tulevikus.

5.1 Eksperimentaalne katsestend

Eksperimentaalne katsestend on toodud joonised 5.1.

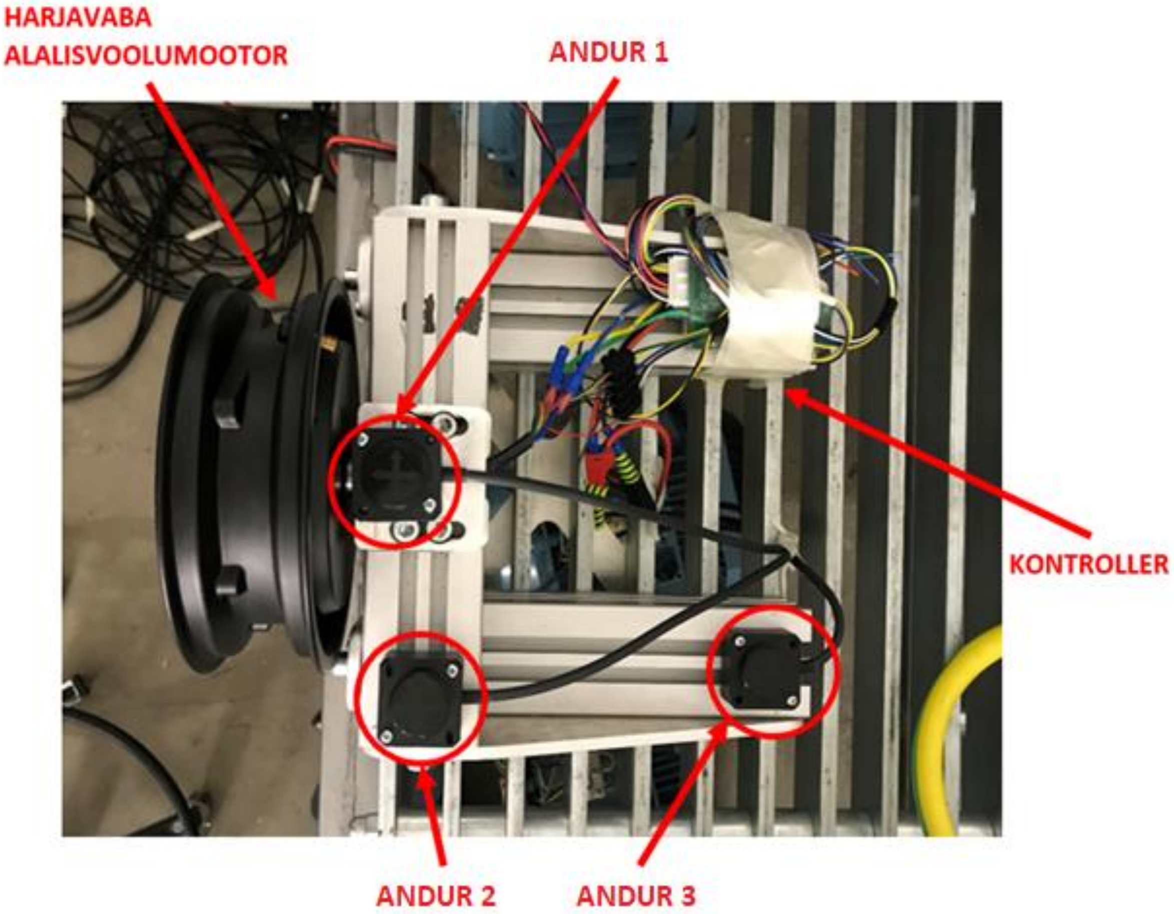


Joonis 5.1. Katsestend

Andmete hankimise tööriistana kasutati katsetes Dewetron OXYGEN mõõtmistarkvara. Antud tarkvara võimaldab andmeid hankida, mõõtmisi salvestada ja tulemusi analüüsida. On võimalus töötada on kolmes erinevates töörežiimis:

- LIVE mode: tarkvara ainult hangib ja kuvab andmeid, kuid salvestamist ei toimu.
- REC mode: tarkvara hangib andmeid ja salvestab neid andmefaili.
- PLAY mode: andmete ülevaatamine, analüüsimine ja eksportimine.

Katsestendis kasutatud mootor on näidatud joonisel 5.2.



Joonis 5.2. Kasutatud katsetes harjavaba alalisvoolumootor

Katsetes kasutati kolmefaasilist harjavaba alalisvoolumootorit, mis on mõeldud elektriliste tõukerataste rakenduseks. Testmootoril on 15 poolust ja 27 uuret. Mootori peamised elektrilised parameetrid on toodud tabelis 5.1.

Table 5.1. Katsestendis kasutatud harjadeta alalisvoolumootori tehnilised andmed

Parameeter	**Väärtus**	**Ühik**
Nimipinge	54	V
Nimipöörlemiskiirus	600±10	p/min
Nimivool	8±0,5	A
Tühijooksuvool	≤1	A
Nimivõimsus	350	W

Mõõtevahendina kasutati kolme kolmeteljelist horisontaalse kinnitusega kiirendusandurit (x, y, z-teljed). Nagu on näidatud joonisel 5.2, paigutati andurid erinevale kaugusele mootorist. Andur 1 oli paigutatud mootori võlli kohale, kus vibratsioonid on tugevamad mootori võlli läheduse tõttu. Andur 2 oli paigutatud esimese anduri kõrvale, kuid võllist eemale. Andur 3 oli asetatud mootorist kõige kaugemasse serva.

Mootoris kasutati kuullaagrid (tüüp 16003-2RS) mõõtmetega 17 x 35 x 8 mm. Kuna antud mootorit elektrilises tõukeratases valiti seitse tüüpilist laagririket, mis võivad ilmneda elektrilise tõukeratta kasutamisel. Kokku testiti kaheksat laagrit:

a) Füüsiliselt terve laager (uus laager ilma muudatusteta),

b) Laager ilma määrdeta (kuiv laager),

c) Laager kahjustatud separaatoriga,

d) Saastunud laager (määrdesse lisatud liiva),

e) Kuumenenud laager 230°C,

f) Kuumenenud laager 330°C,

g) Lõigatud laager (laagri välissaale oli ristipinnas katki lõigatud),

h) Korrodeeritud laager.

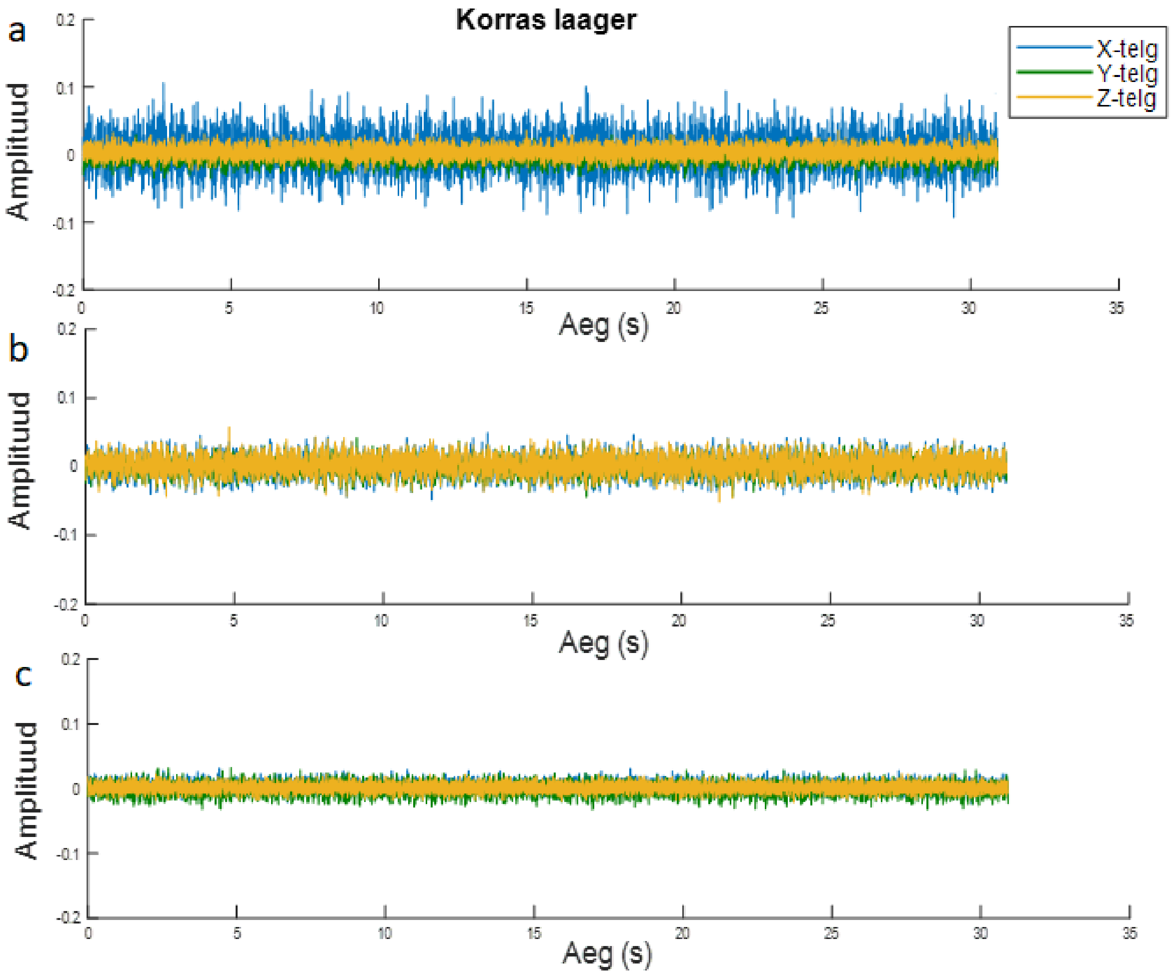
Joonis 5.3. Katsetes kasutatud laagrid:

a) korras laager, b) laager ilma määrdeta, c) laager kahjustatud separaatoriga, d) saastunud laager, e) kuumenenud laager 330°C, f) kuumenenud laager 330°C, g) lõigatud laager, h) korrodeeritud laager.

5.2 Katsete tulemused

Iga vigane laager annab mootori töötamise ajal teatud vibratsioonisignaali, mida saab võrrelda terve laagri vibratsioonisignaaliga. Kuna signaal on statsionaarne ja koormamata mootor töötas maksimaalse konstantse kiirusega, valiti andmete analüüsiks kiire Fourier’ teisendus (FFT). Täpsema andmetöötluse saamiseks oli võimalus kasutada ka lainikteisendust või mõnda arenenud tehnikat, kuid see tooks kaasa keerulisi matemaatilisi mudeleid ja muudaks protsessi keerulisemaks.

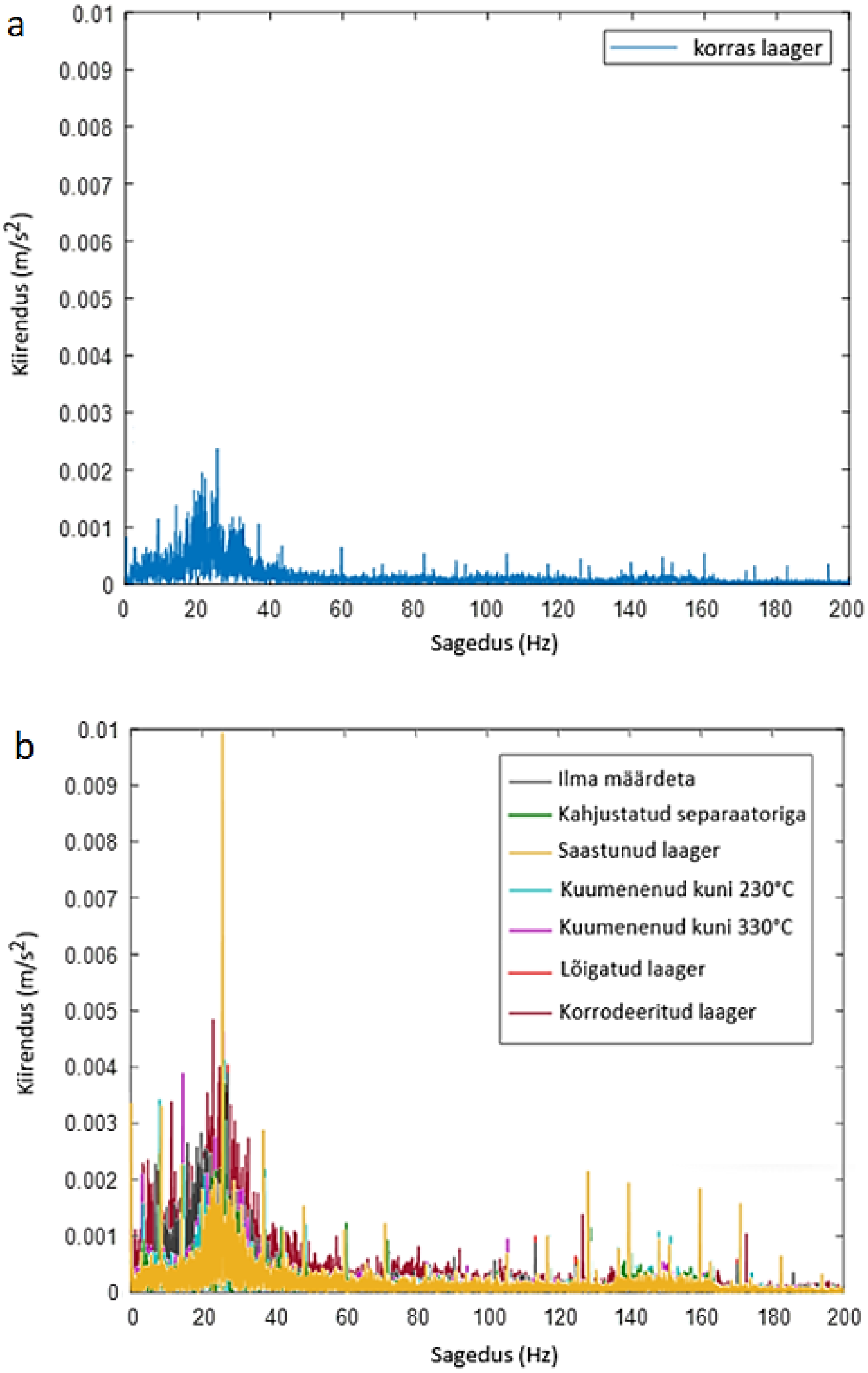
Joonis 5.4 näitab terve laagri vibratsioonisignaale, mis olid korraga salvestatud kolmelt kiirendusanduritelt kolme erineva telje suunas. Nagu on näha, kõige märgatavam vibratsioon tuleb andurist 1, mis asub võlli kohal. Võllist eemale liikudes, vibratsioon väheneb. Samuti tuleb mainida, et vibratsioonid tekivad enamasti x- ja y-teljel, samal ajal kui z-telje signaal eriti ei muutu.



Joonis 5.4. Korras laagri vibratsioonispektrid:

a) anduri 1 signaal, b) anduri 2 signaal, c) anduri 3 signaal.

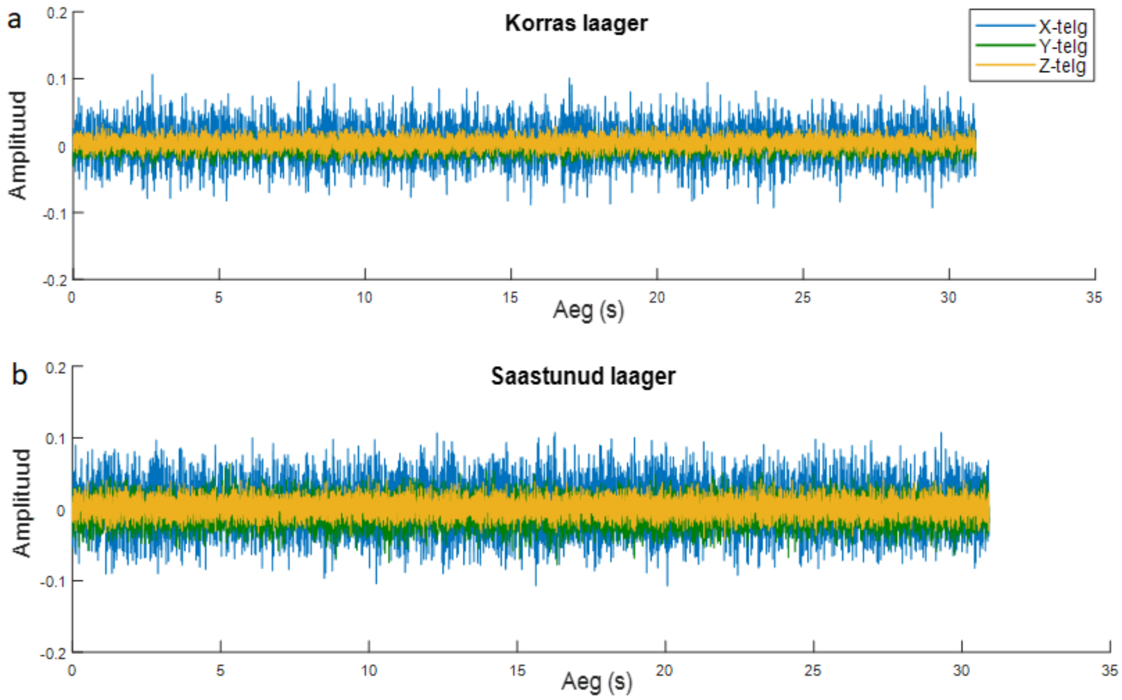
Peamine diagnostika tunnus on laagririkete spetsiifiline avaldumine vibratsioonispektris. Rikke nähud ilmnevad spektris, kui rike kasvab sellisele tasemele, et sellest vabanev energia muutub märgatavaks ja esineb spektris. Füüsiliselt terve laagri kiire Fourier' teisenduse spekter on toodud joonisel 5.5 (a). Võrreldes vigaste laagrite spektritega, mis on toodud joonisel 5.5 (b), on näha, et vigaste laagrite vibratsiooni amplituudid on palju suuremad. Erinevused amplituudides on märgatavad kõigil kolmel teljel.



Joonis 5.5. FFT spektrid:

a) korras laager, b) vigased laagrid.

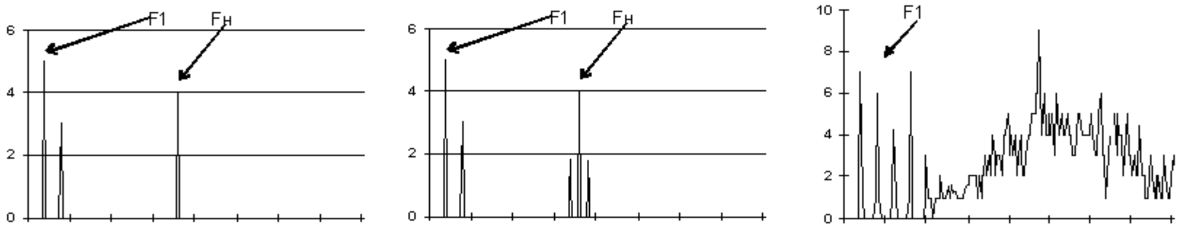
FFT spektrites on kõige märgatavamad amplituudid saastunud laagri korral (kollane joon joonisel 5.5 b). Erinevus on märgatav ka teisendamata vibratsioonispektris, mis on näidatud joonisel 5.6. Korras laagri ja saastunud laagri vibratsioonispektrite võrdlemisel on signaalide erinevus nähtav kõigil kolmel teljel.



Joonis 5.6. Vibratsioonispektrite võrdlus:

a) korras laager, b) saastunud laager.

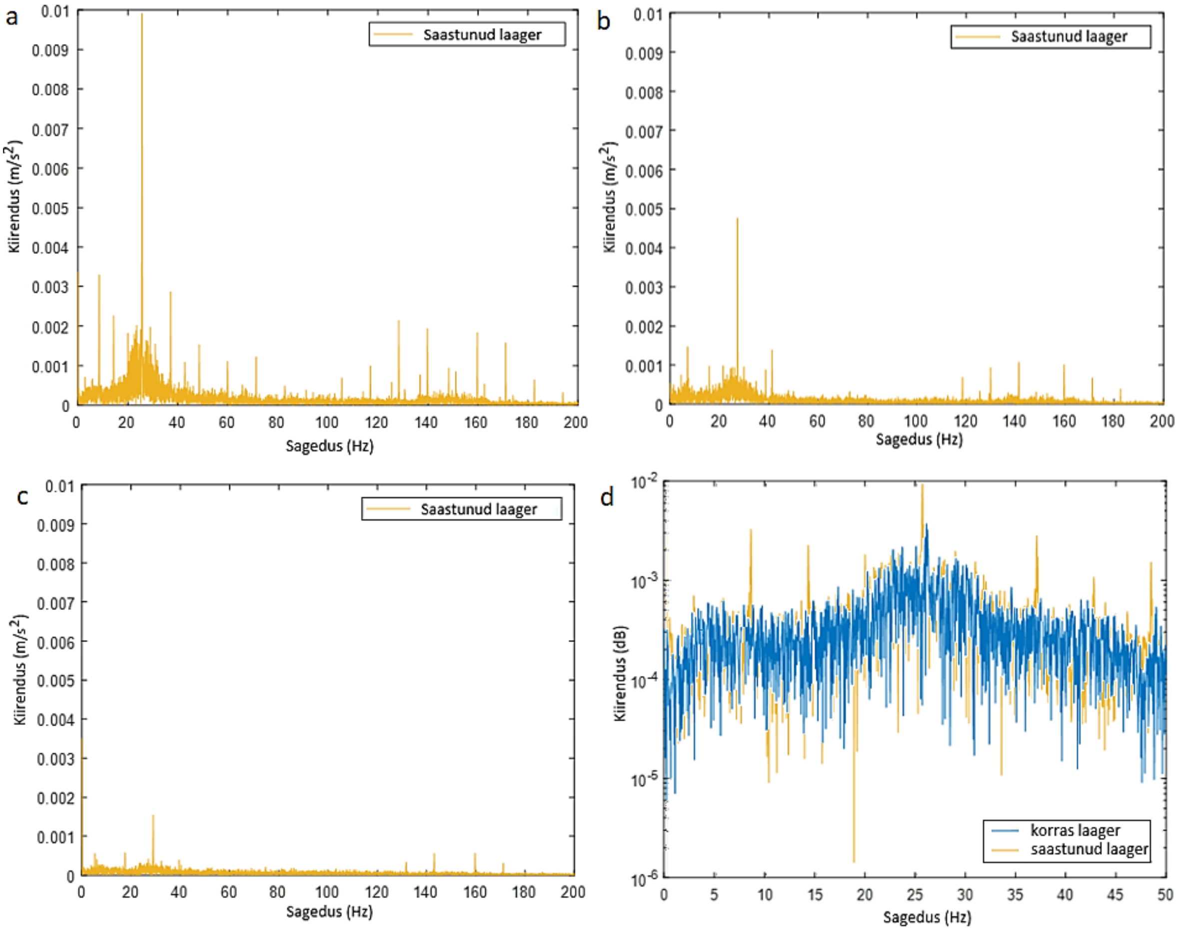
Teoreetiliselt saab eristada kolm kõige sagedamini esinevat signaalispektri tüüpi, mis vastavad erinevatele defektide arenguetappidele [47].



a b c

Joonis 5.7. Laagririkete arenguetapid [47]

Nagu on näidatud joonisel 5.7 (a), defekti tekkimise esimestel etappidel ilmneb selgelt märgatav sageduse tipp, mis oli nähtav ka saastunud laagri korral. See võimaldab täpselt defekti olemasoleku tuvastada, eriti kui sagedusspekter esitada logaritmilisel skaalal. Defekti arenemisega ilmuvad peamise sagedustipu vasakul ja paremal küljel esimene kõrvalharmooniliste paar, nagu on näidatud joonisel 5.7 (b). Antud nähtust võib täheldada ka kõigist kolmest andurist saadud signaalides saastunud laagri korral (Joonised 5.8 a, b, c). Eriti on neid piike näha logaritmilisel skaalal joonisel 5.8 (d).



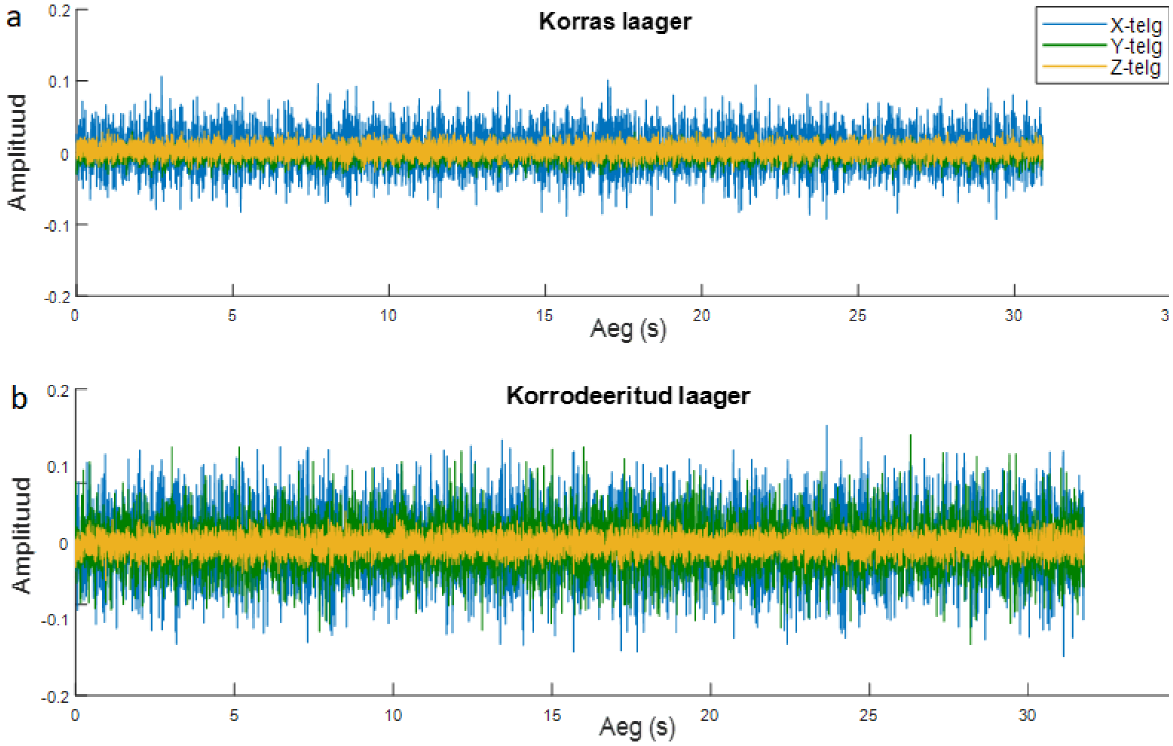
Joonis 5.8. Saastunud laagri FFT spektrid:

a) anduri 1 signaal, b) anduri 2 signaal, c) anduri 3 signaal, d) korras laagri ja saastunud laagri spektrite võrdlus.

Mida arenenum on defekt, seda rohkem külgsagedusi ilmub sageduspõhipiigi kõrval. Selle nähtuse põhjuseks on see, et vigastatud veerekeha nihkub nii palju, et külgnevad veerekehad kannavad juba põhilist koormust, et toetada võlli mehhanismi. Sellel etapil täidab laager oma funktsioone ja võib talitleda, kuid nõuab laagri väljavahetamist lähimal ajal lisanduva koormuse tõttu.

Rikke arenemise viimasel etapil on laager juba degradeerunud ja lakanud oma funktsioone täitmast. Praktiliselt iseloomustab seda etappi lisasageduste ilmumine, millel on juhuslik iseloom, nagu on näidatud joonisel 5.7 (c). Sellist nähtust antud töö raames ei täheldatud.

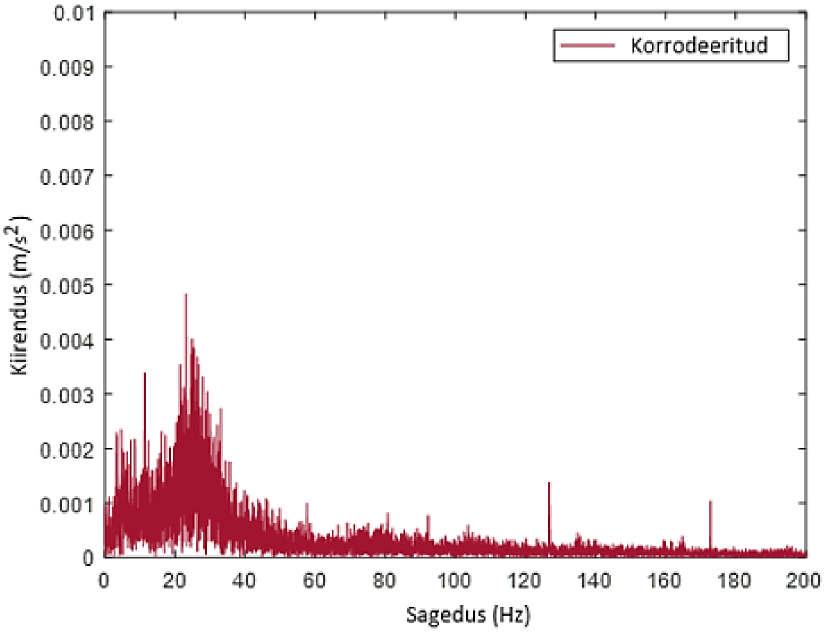
Teine spektril selgelt märgatav rike on korrosioon. Signaalide erinevus on märgatav isegi teisendamata vibratsioonispektris, mis on näidatud joonisel 5.9.



Joonis 5.9. Vibratsioonispektrid:

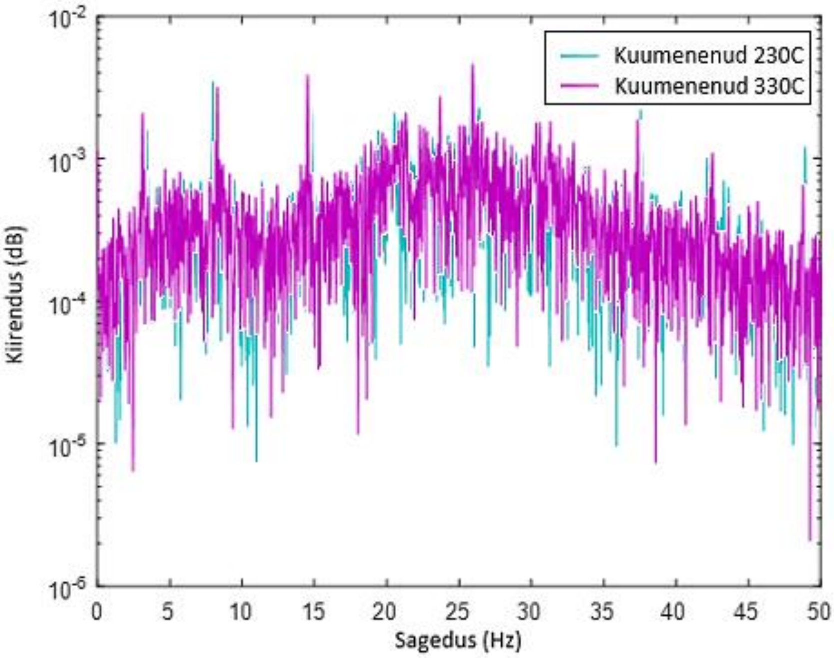
a) korras laager, b) korrodeeritud laager.

Vibratsioonispektrite võrdlemisel on signaalide erinevus nähtav kõikidel telgedel. Jooniselt 5.10 saab näha laia harmoonilist spektrit vahemikus 0-50 Hz.



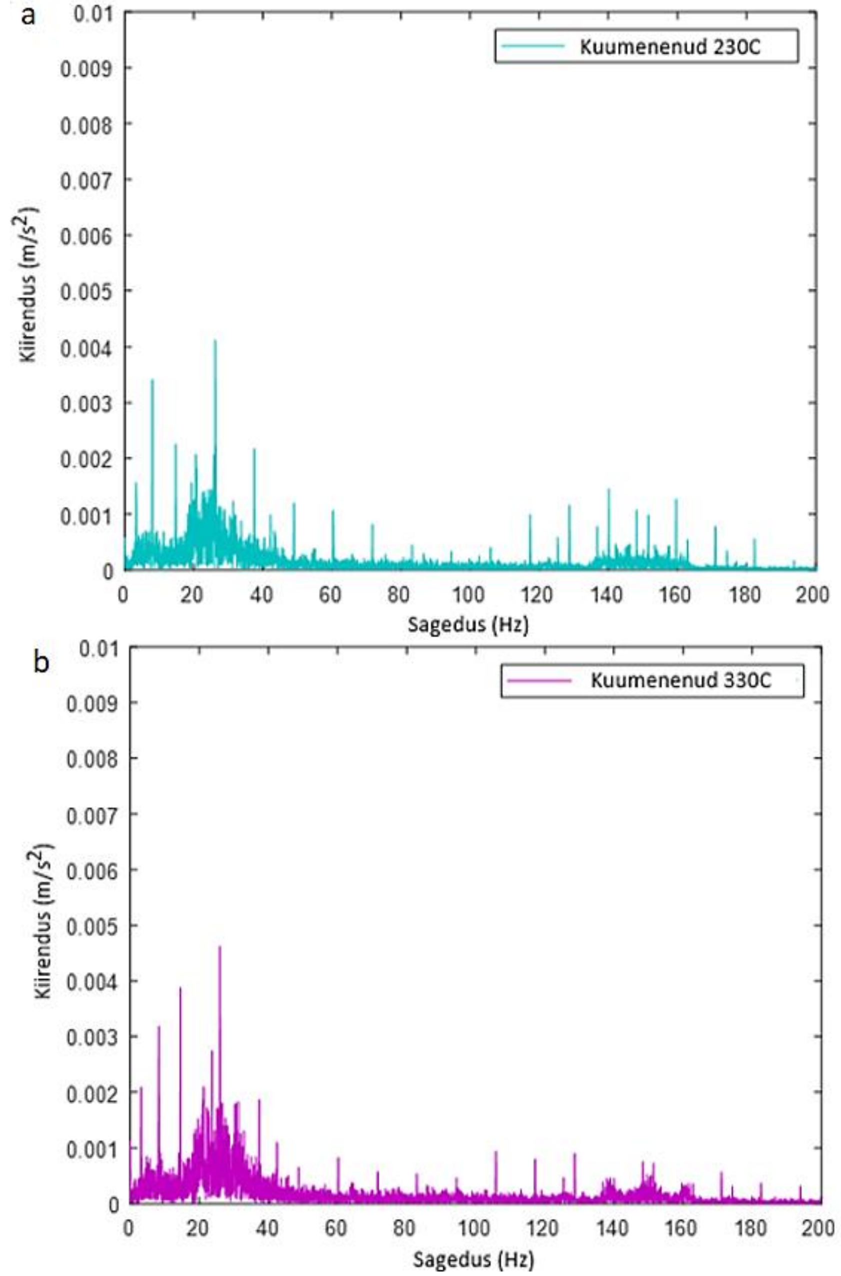
Joonis 5.10. Korrodeeritud laagri FFT spekter

Omavahel võrreldi ka erinevatel temperatuuridel kuumutatud laagreid: üks laager olid kuumutatud temperatuuril 230°C ja teine temperatuuril 330°C. Nende rikete sagedusspektrite võrdlus on toodud logaritmilisel skaalal joonisel 5.11.



Joonis 5.11. Kuumenenud laagrite FFT spektrite võrdlus logaritmilisel skaalal

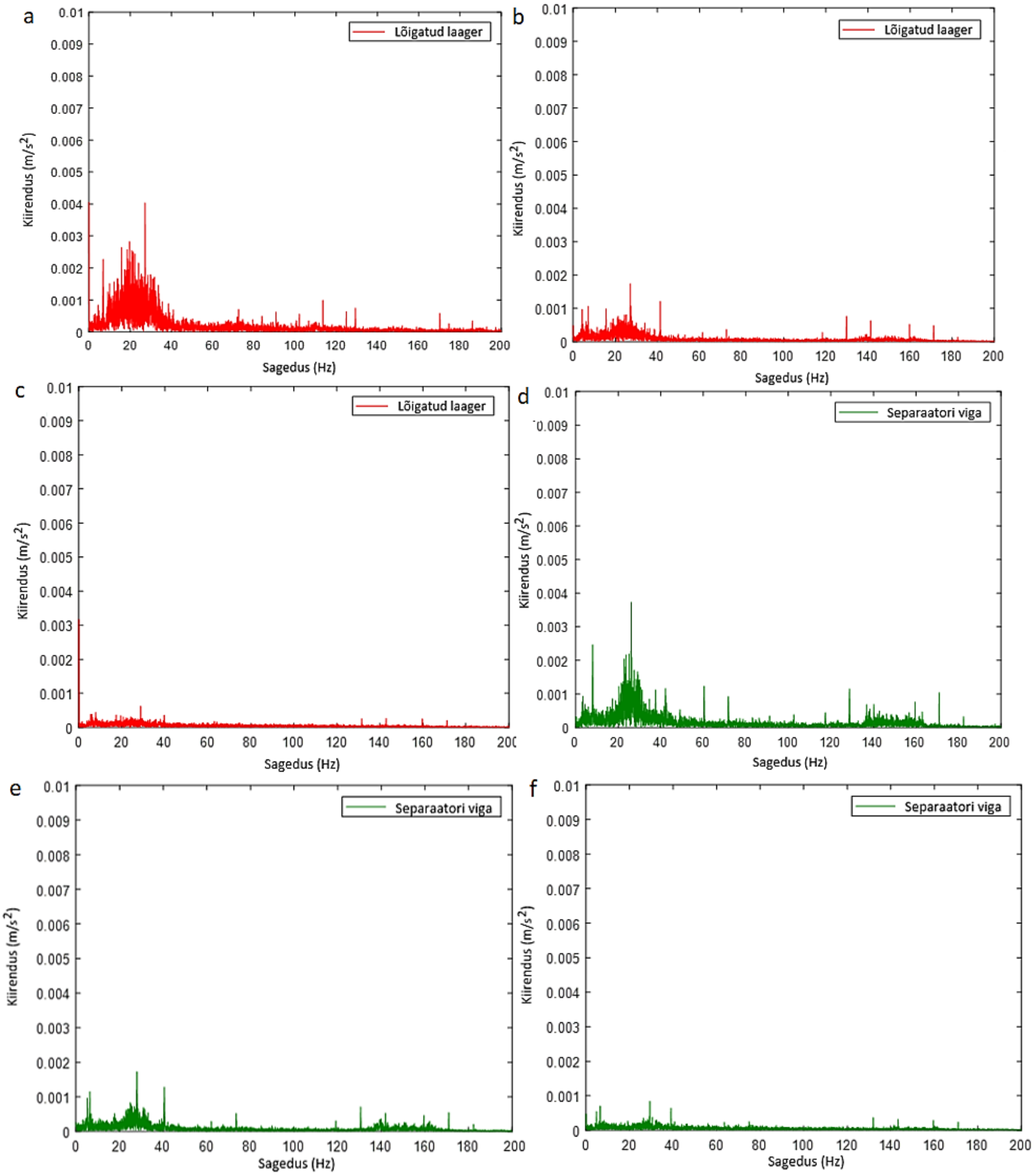
Võrreldes toodud spektreid omavahel, olulist erinevust näha ei ole. Kummatigi, nagu on näidatud joonisel 5.12, ilmnevad mõlemal juhul külgsagedused põhipiigi kõrval vasakul ja paremal küljel. Samuti on näha sageduse hüpet vahemikus 120-180 Hz. See annab märku tõsisema kahjustuste olemasolust ja laagri mehaanilisest nõrgenemisest.



Joonis 5.12. Kuumenenud laagrite FFT spektrid:

a) kuumenenud laager 230℃, b) kuumenenud laager 330℃.

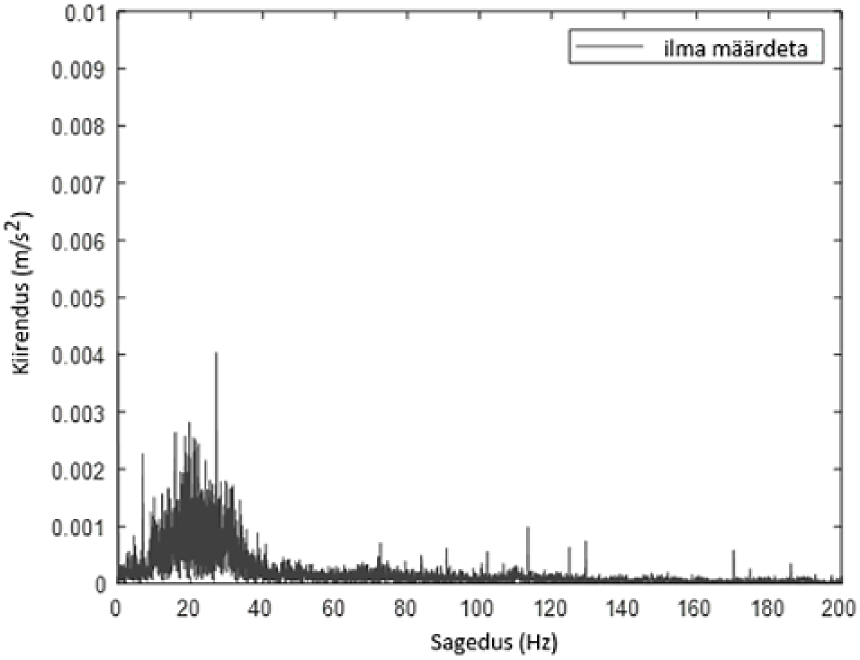
Sarnased spektrid on täheldatavad ka lõigatud laagri korral (joonised 5.13 a, b, c) ja kahjustatud separaatoriga laagri korral (joonised 5.13 d, e, f). Mõlemal juhul on sageduse amplituud kõrgem kui füüsiliselt terve laagri korral. Samuti saab vaadelda sageduse hüpet vahemikus 120-180 Hz.



Joonis 5.13. FFT spektrid:

a) lõigatud laagri signaal andurist 1, b) lõigatud laagri signaal andurist 2, c) lõigatud laagri signaal andurist 3, d) kahjustatud separaatoriga laagri signaal andurist 1, e) kahjustatud separaatoriga laagri signaal andurist 2, f) kahjustatud separaatoriga laagri signaal andurist 3.

Ilma määrdeta laagril (joonis 5.14) ilmneb lõigatud laagriga sarnane spekter.



Joonis 5.14. Ilma määrdeta laagri FFT spekter

Lisaks peatükis esitatud joonistele, on töö lisadesse pandud teised mitte põhiosas mainitud vigaste laagrite vibratsiooni- ja FFT spektrid. Üldiselt olid põhiosas kirjeldatud spektrid, mille signaalid olid võetud andurist 1. Selle põhjuseks on see, andur 1 asub otse võlli kõrval ja selle signaalid on märgatavamad ning annavad rohkem informatsiooni. Seetõttu võib selliseid spetreid põhjalikumalt uurida. Samal ajal, et saada selge pilt, andurite 2 ja 3 andmed on ka vajalikud ja neid tuleb võtta arvesse.

KOKKUVÕTE

Antud lõputöös tutvustati harjadeta alalisvoolumootorite peamisi rikkeid ja nende diagnostikavõimalusi. Eriline tähelepanu oli pööratud levinumatele laagririketele.

Antud uurimisteema on väga aktuaalne ja oluline, sest tänapäeval kasutatakse harjavabu alalisvoolumootoreid nii Eestis kui ka välismaal väga paljudes rakendustes. Need on olulisel kohal nii kodumajapidamises kui ka tööstuses. Oluliseks on nende töökindluse tagamine ka sellepärast, et seda tüüpi mootorid on kasutuses viimasel ajal väga palju elektrisõidukites: hübriid- ja elektriautodes, jalg- ja tõukeratastes. Kasvav rakenduste arv muudab mootori seisundi seire väga oluliseks, eesmärgiga vältida rikete negatiivseid tagajärgi.

Töö esimene peatükk "Harjavabade alalisvoolumootorite alused„ tutvustas harjadeta alalisvoolumootorite olemust: elektrimasina konstruktsiooni, tööpõhimõtet ja rakendusi. Teises peatükis "Harjavabade alalisvoolumootorite põhilised tõrked„ loetleti põhilisi rikkeid, mis võivad tekkida antud tüüpi mootorites. Kolmandas peatükis "Laagrid harjavabades alalisvoolumootorites„ vaadeldi võimalikke laagririkkeid, nende tekkimise põhjuseid ja esitati soovitused, kuidas neid rikkeid vältida. Neljas peatükk "Tõrgete diagnostika võimalused harjavabades alalisvoolumootorites„ tutvustas erinevaid diagnostika meetodeid, mis on maailmas laialt kasutusel. Viimases ja kõige olulisemas peatükis "Töö praktiline osa„ kirjeldati katsestendi, kasutatud mõõtevahendeid, mootorit ja mõõtmistarkvara. Samuti tutvustab peatükk antud töö raames tehtud katseid.

Töö lisades on teised mitte põhiosas mainitud vigaste laagrite vibratsiooni- ja FFT spektrid. Samuti on lisades teadusartiklid, kus lõputöö autor on osalenud põhi- või kaasautorina. Artiklid olid esitatud rahvusvahelistel teaduskonverentsidel ja publitseeritud (ETIS kategooria 3.1):

- Teadusartikkel 1: K. Kudelina, B. Asad, T. Vaimann, A. Rassõlkin, A. Kallaste, D. V. Lukichev, "Main Faults and Diagnostic Possibilities of BLDC Motors", 27th International Workshop on Electric Drives: MPEI Department of Electric Drives 90th Anniversary IWED2020 (1−6), IEEE, Moskva (Venemaa), 2020.
- Teadusartikkel 2: A. Rassõlkin, T. Vaimann, K. Kudelina, G. L. Demidova, D. V. Lukichev, S. Y. Perepelkina, "Modern Mechatronics and Robotics Education Program: Border Cooperation

between Estonia and Russia", IEEE Global Engineering Education Conference (EDUCON) (1272−1277), IEEE, Porto (Portugal), 2020.

- Teadusartikkel 3: K. Kudelina, B. Asad, T. Vaimann, A. Rassõlkin, A. Kallaste, A. "Effect of Bearing Faults on Vibration Spectrum of BLDC Motors", Open International Conference "Electrical, Electronic and Information Science" (eStream 2020), IEEE, Vilnius (Leedu), 2020.

Lõputöö raames tehtud katsete käigus, nii tervete kui ka vigaste laagritega korral, selgus, et vibratsioonispekter võib näidata laagris kahjustuste olemasolu. Iga vigane laager annab mootori talitluse ajal teatud vibratsioonisignaali, mida saab võrrelda terve laagri vibratsioonispektriga. Plaanis on välja töötada kontseptsiooni, mis lubaks tuvastada defekti enne kui laager puruneb ja muutub kasutamiskõlbmatuks. Antud lõputöö eesmärgiks oli uurida harjavabade alalisvoolumasinate laagririkkeid. Selleks olid laagririkked tekitatud ja katsetuste teel selgitati välja rikete tuvastamise võimalused. Kokkuvõtteks, lõputöö eesmärgid saavutati. Töö käigus leiti vastused küsimustele, mis olid püstitatud lõputöö alguses.

SUMMARY

In this Master thesis, the main faults of brushless DC motors and their diagnostic possibilities were introduced. Special attention was paid to the most common bearing failures.

This research topic is very relevant and important, because nowadays brushless DC motors are used in many domectic and industrial applications abroad, and also in Estonia. It is also important to ensure their reliability because these types of motors have recently been used extensively in electric vehicles: hybrid ja electric cars, electric bycicles ja scooters. The growing number of applications makes the monitoring of the these motors condition very important, in order to avoid the negative consequences.

The first chapter of the work “Basics of Brushless DC motors ” introduced the nature of brushless DC motors: construction, operation principle and applications of these electric machines. In the second chapter, “Main Faults of Brushless DC Motors”, there were listed the main failures and damages, which can occur in this motor type. In the third chapter, "Bearings in brushless DC motors", there were listed possible bearing failures: the reasons and some recommendations on how to avoid them. The fourth chapter, "Fault Diagnostics Possibilities in Brushless DC Motors", introduced various diagnostic methods that are widely used in the world. The last and most important chapter "Practical part of the work" described the test bench: used in experiments measuring tools, motor and the softwares. The chapter also introduces the experiments performed in this work.

The vibration and FFT spectra of faulty bearings, which are not mentioned in the main part, are included in the appendices. In addition, in the appendices there were included papers, which had been written as both an author and a co-author during the Master's studies. These articles were presented at international scientific conferences and published (ETIS category 3.1):

- Research paper 1: K. Kudelina, B. Asad, T. Vaimann, A. Rassõlkin, A. Kallaste, D. V. Lukichev, D. V. “Main Faults and Diagnostic Possibilities of BLDC Motors”, 27th International Workshop on Electric Drives: MPEI Department of Electric Drives 90th Anniversary IWED2020 (1−6), IEEE, Moscow (Russia), 2020.
- Research paper 2: A. Rassõlkin, T. Vaimann, K. Kudelina, G. L. Demidova, D. V. Lukichev, S. Y. Perepelkina, “Modern Mechatronics and Robotics Education Program: Border

Cooperation between Estonia and Russia", IEEE Global Engineering Education Conference (EDUCON) (1272−1277), IEEE, Porto (Portugal), 2020.

- Research paper 3: K. Kudelina, B. Asad, T. Vaimann, A. Rassõlkin, A. Kallaste, "Effect of Bearing Faults on Vibration Spectrum of BLDC Motors", Open International Conference "Electrical, Electronic and Information Science" (eStream 2020), IEEE, Vilnius (Lithuania), 2020.

During the experiments wirh healthy as well as faulty bearings, which were performed in the framework of the research, it became clear that the vibration spectrum may indicate the presence of damage in the bearing. Each faulty bearing gives its certain vibration signal, which can be compared with the signal of the healthy bearing. For the future work it is considered to develop a concept that would allow a failure to be identified before the bearing breaks and becomes unusable. The aim of the Master thesis was to study the bearing failures of brushless DC motors. For this, the damages were inflicted to the bearings and the fault diagnostic possibilities were determined. In conclusion, the goals of the work were achieved and answers were found to the questions, which were raised at the beginning.

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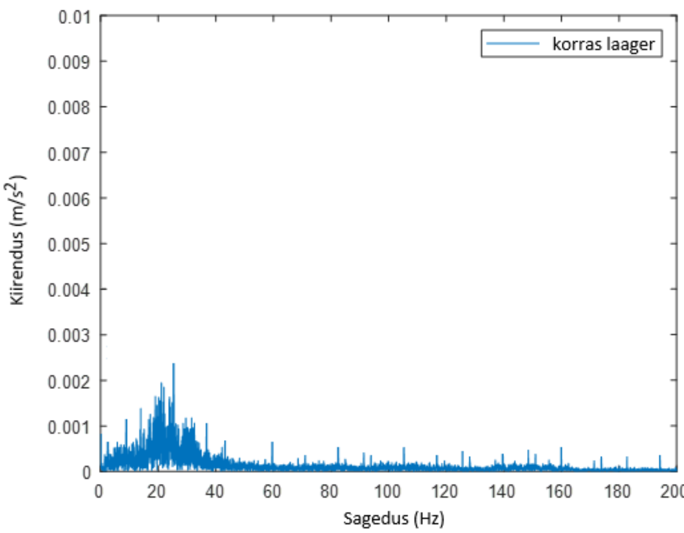
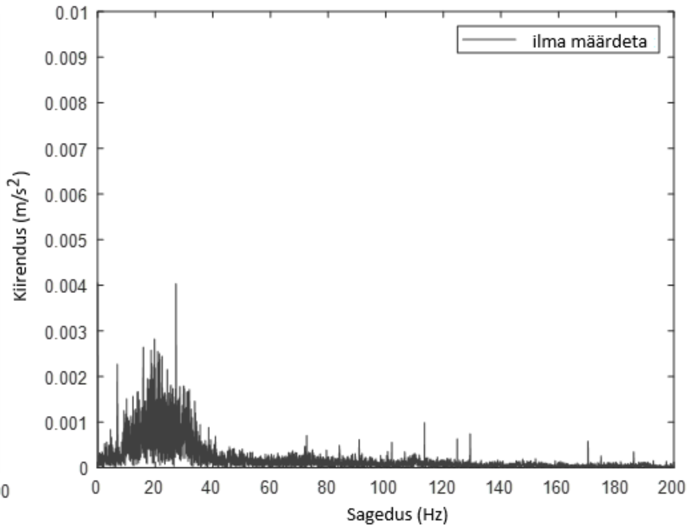
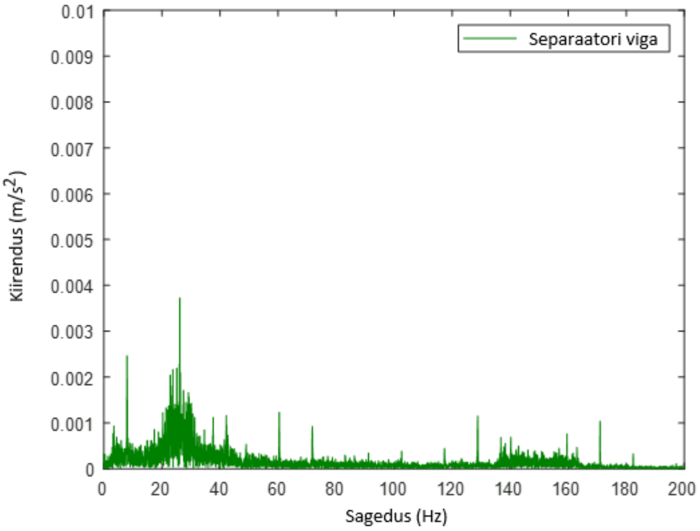
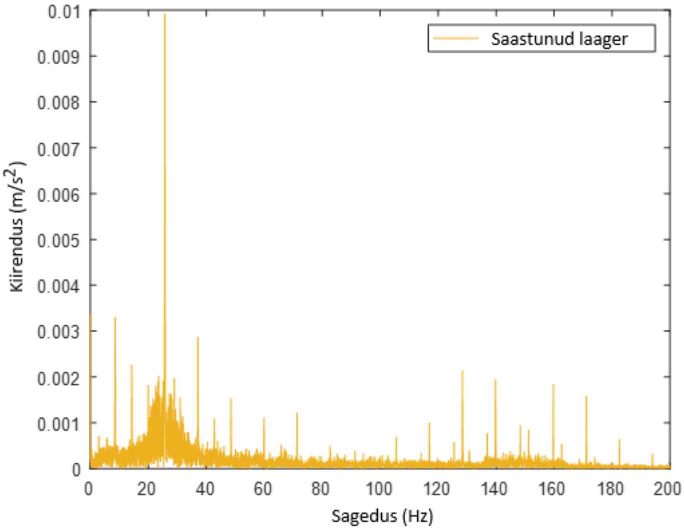
LISAD

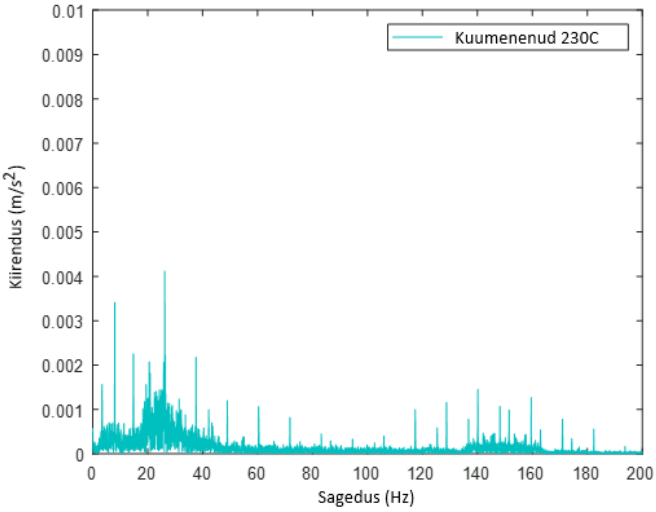
Lisa 1 Sensori 1 signaali põhjal tehtud FFT

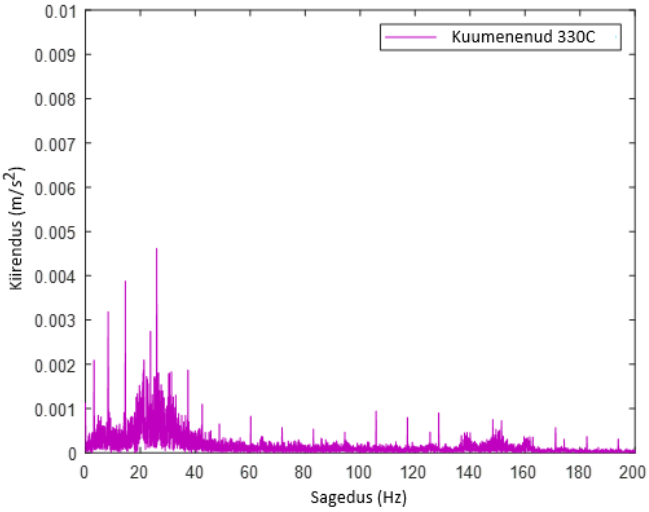









Kuumenenud 230C
Kiirendus (m/s^2)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
20
40
60
80
100
120
140
160
180
200
Sagedus (Hz)


Kuumenenud 330C
Kiirendus (m/s^2)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
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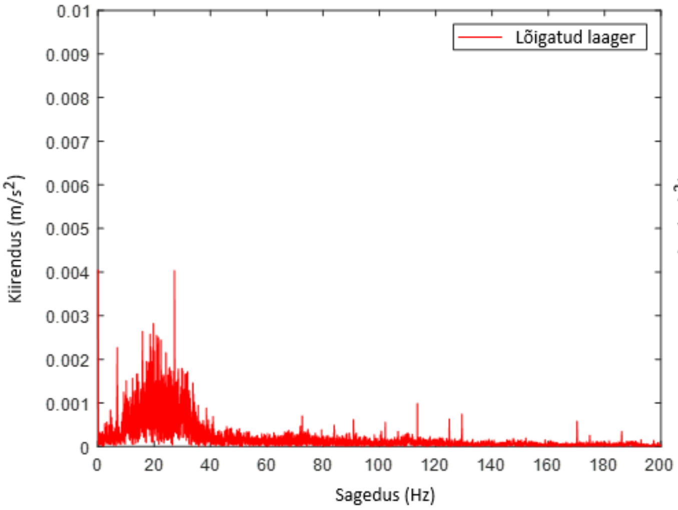
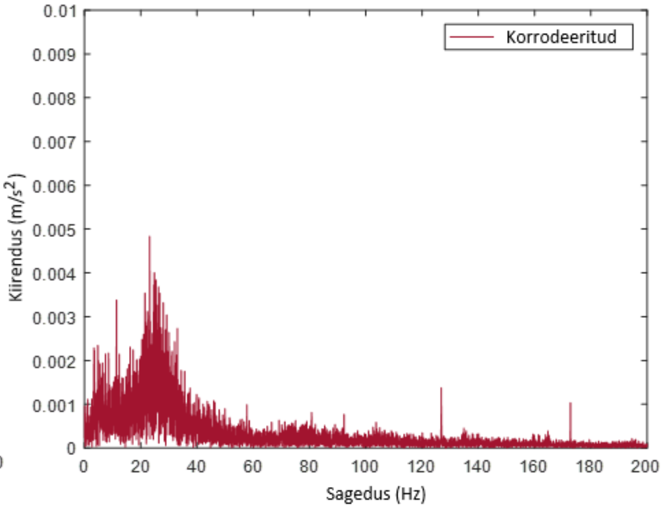
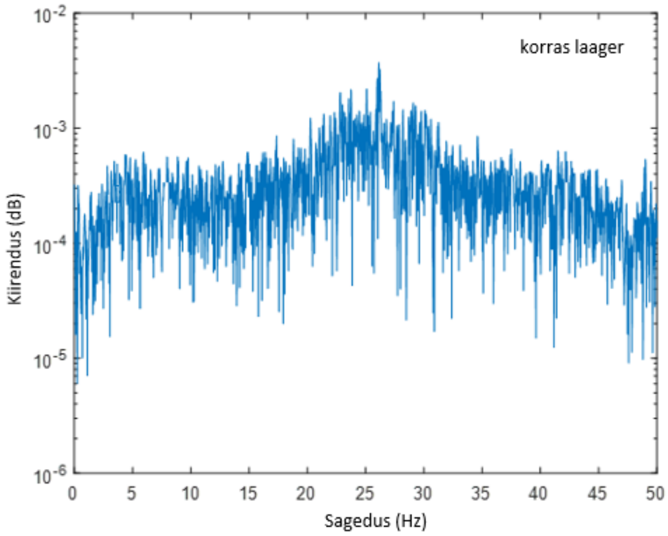
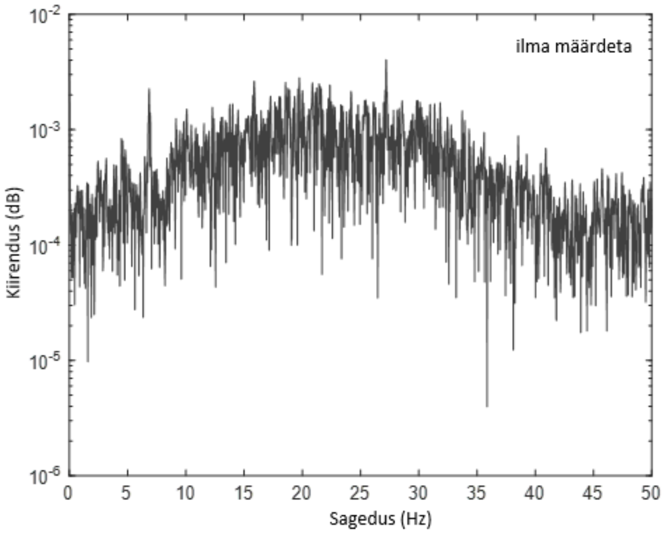
0.001
0
0
20
40
60
80
100
120
140
160
180
200
Sagedus (Hz)

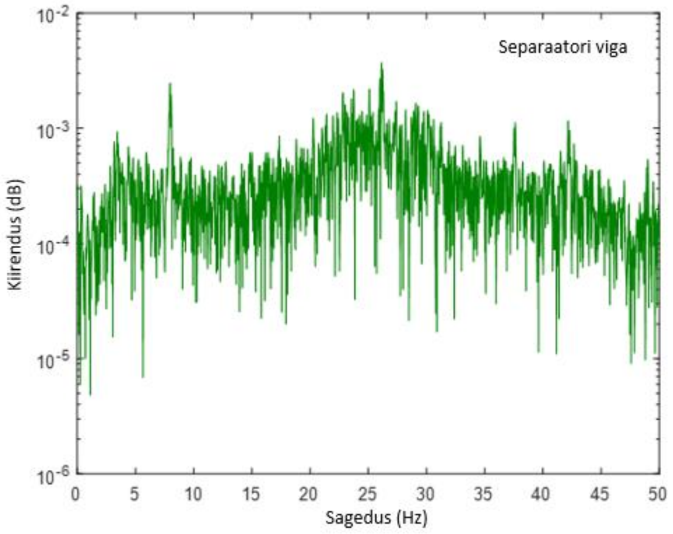

Lõigatud laager
Kiirendus (m/s^2)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
20
40
60
80
100
120
140
160
180
200
Sagedus (Hz)

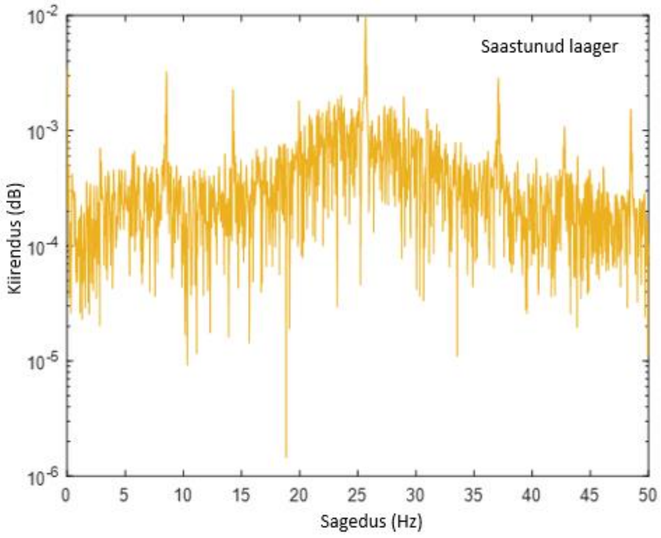

Korrodeeritud
Kiirendus (m/s^2)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
20
40
60
80
100
120
140
160
180
200
Sagedus (Hz)

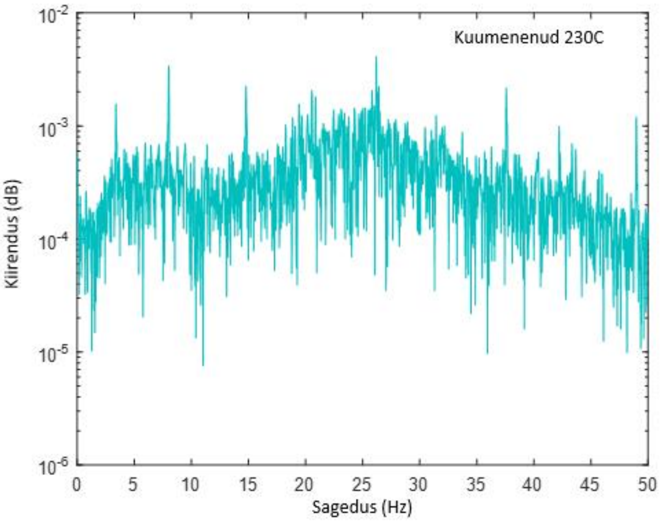
Lisa 2 Sensori 1 signaali põhjal tehtud FFT logaritmilises skaalas










Kuumenenud 230C
Kiirendus (dB)
Sagedus (Hz)
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10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
5
10
15
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40
45
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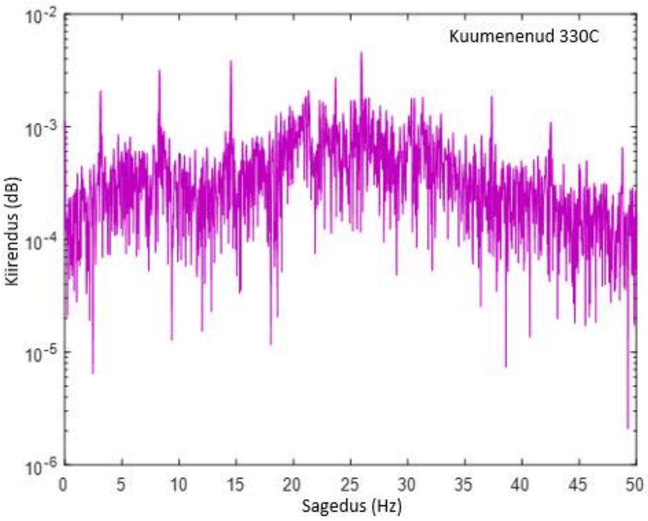
Kuumenenud 330C
Kiirendus (dB)
Sagedus (Hz)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
5
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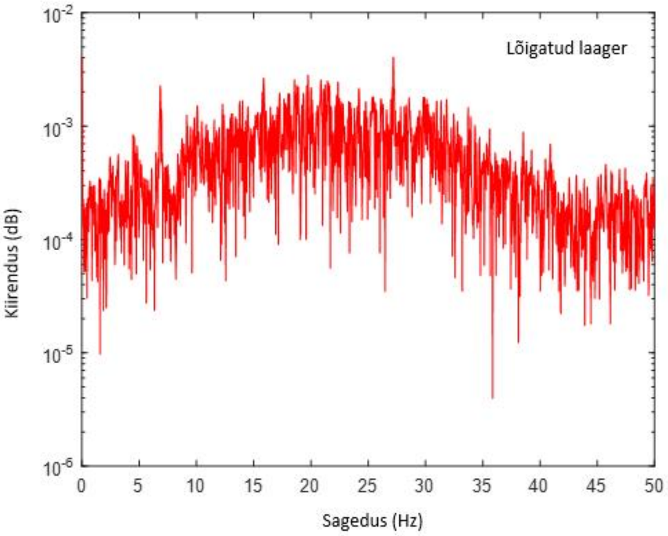
Lõigatud laager
Kiirendus (dB)
Sagedus (Hz)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
5
10
15
20
25
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35
40
45
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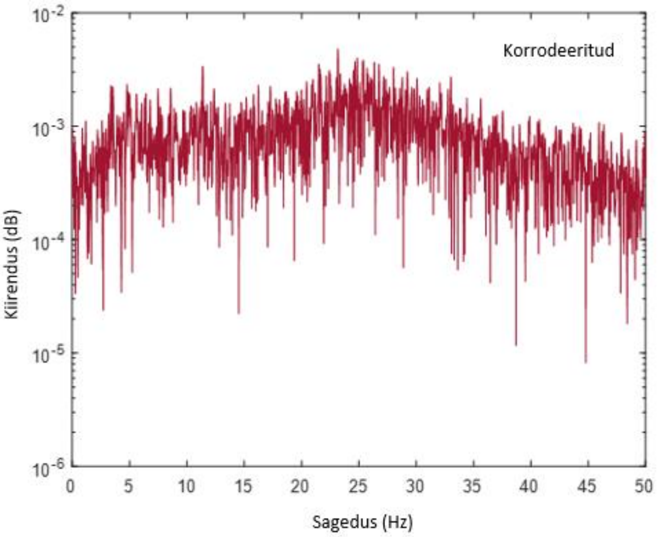
Korrodeeritud
Kiirendus (dB)
Sagedus (Hz)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
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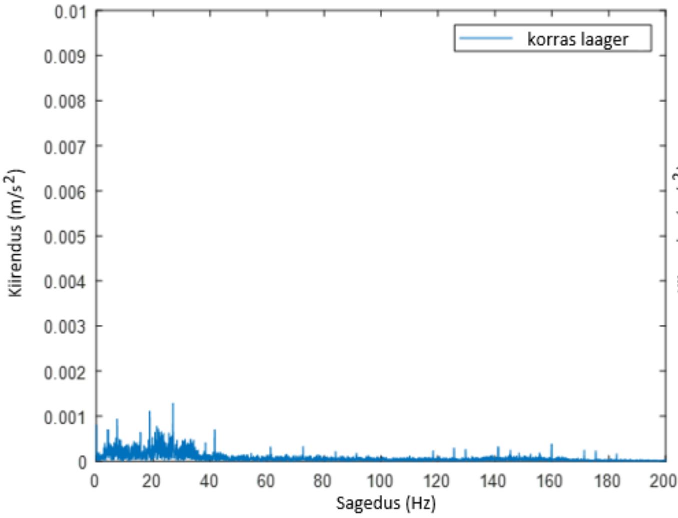
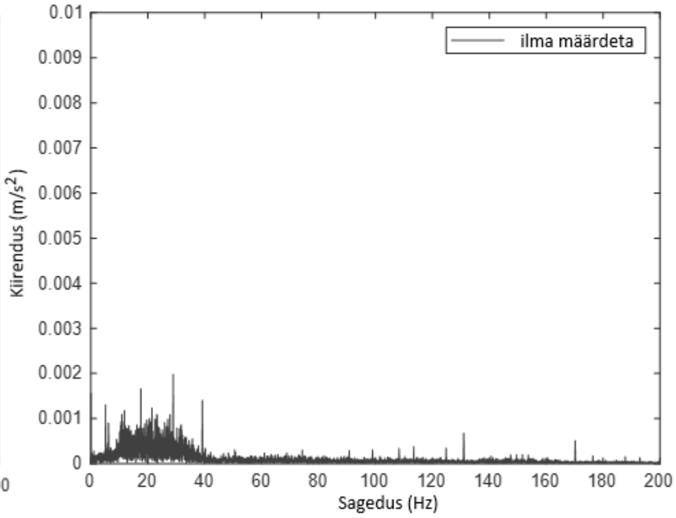
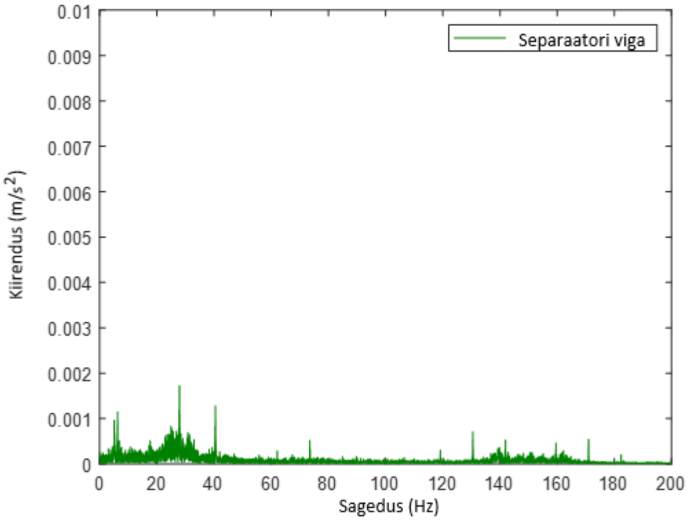
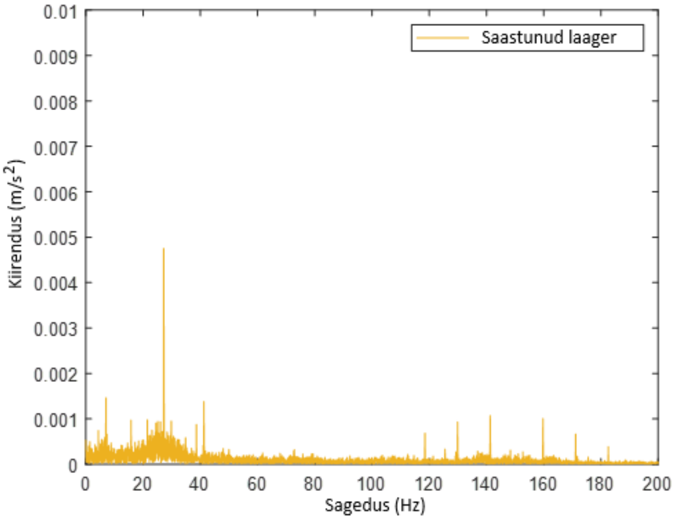
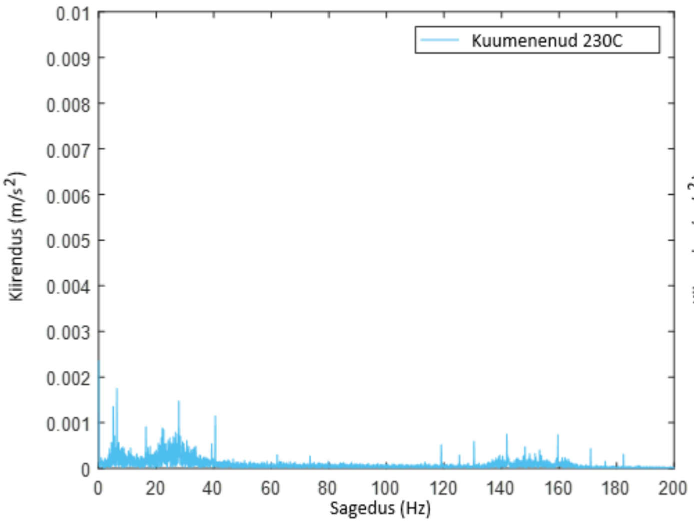
Lisa 3 Sensori 2 signaali põhjal tehtud FFT










Kuumenenud 230C
Kiirendus (m/s^2)
Sagedus (Hz)
0.01
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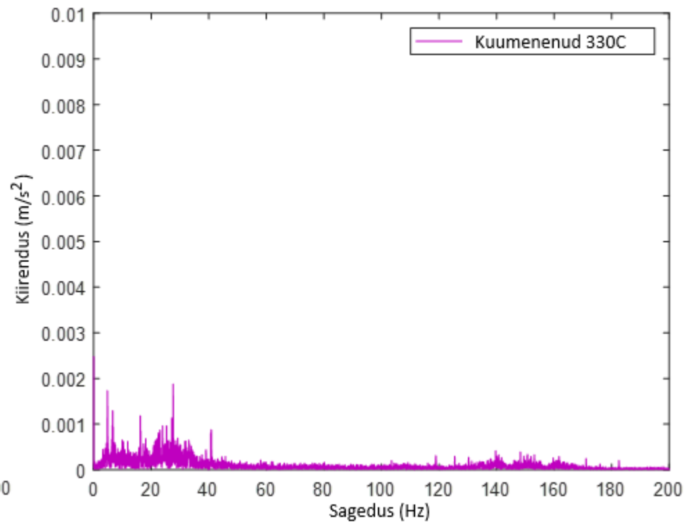
Kuumenenud 330C
Kiirendus (m/s^2)
Sagedus (Hz)
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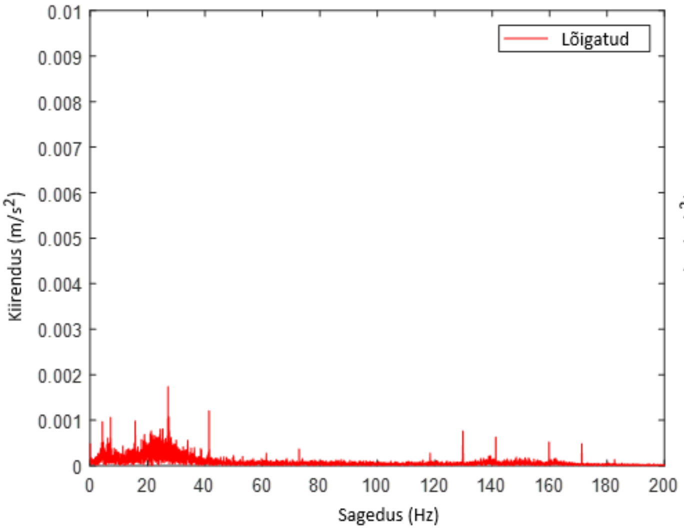
Lõigatud
Kiirendus (m/s^2)
Sagedus (Hz)
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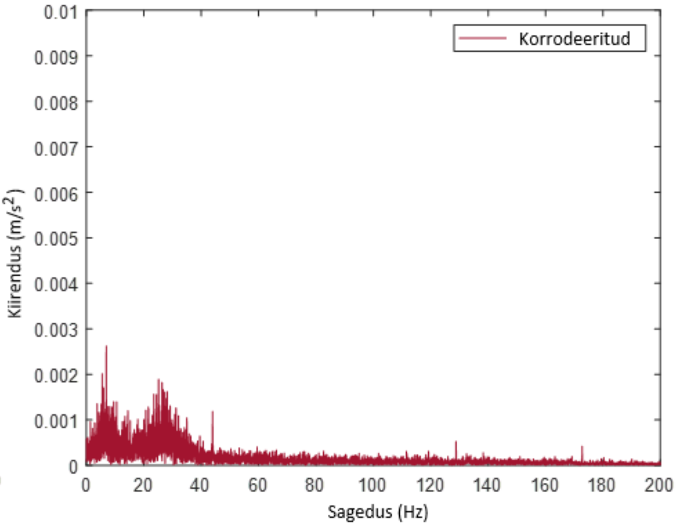
Korrodeeritud
Kiirendus (m/s^2)
Sagedus (Hz)
0.01
0.009
0.008
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0.006
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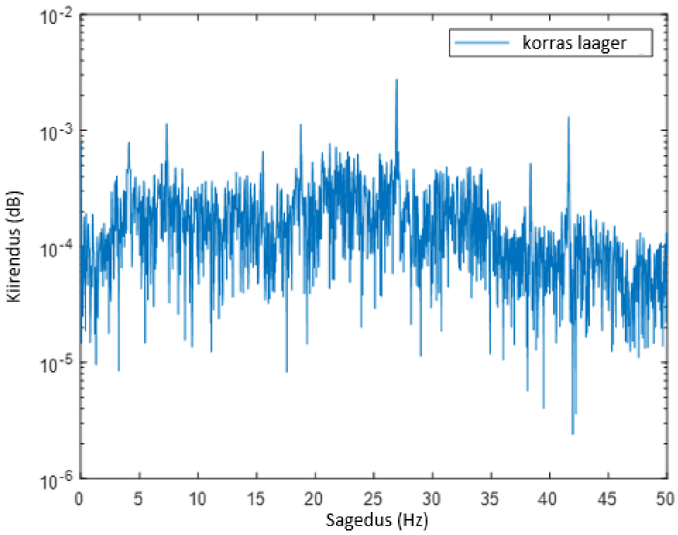
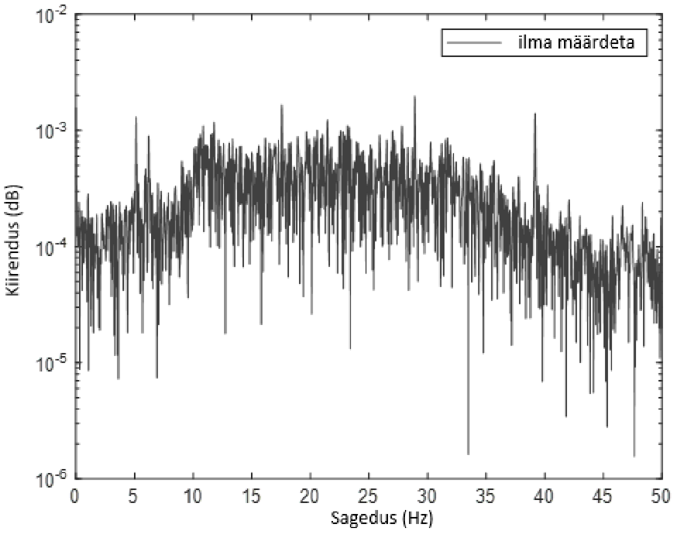
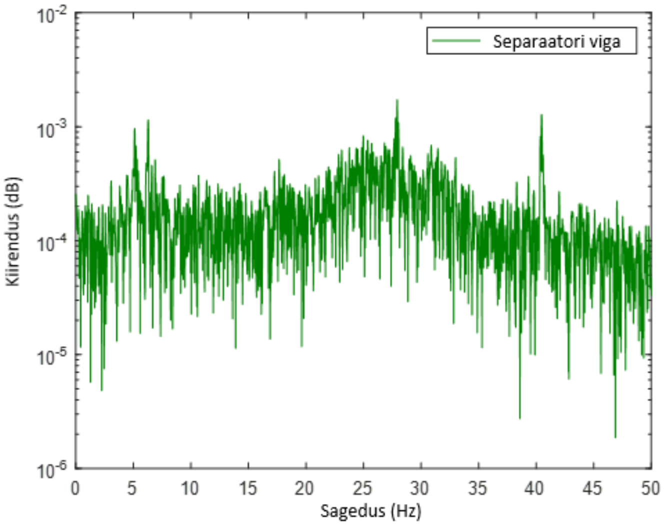
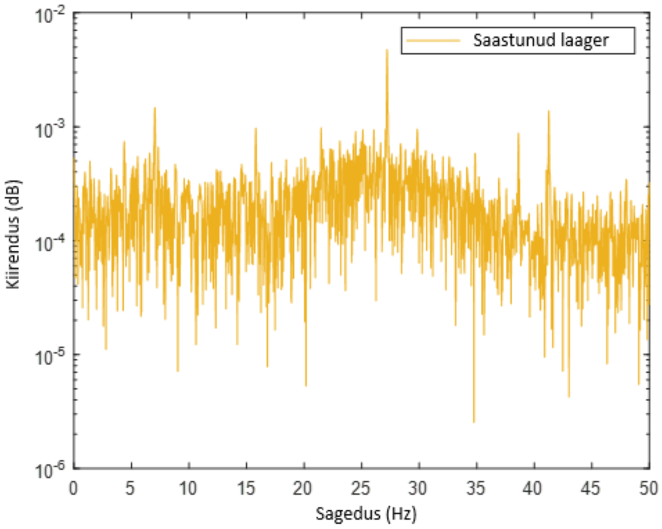
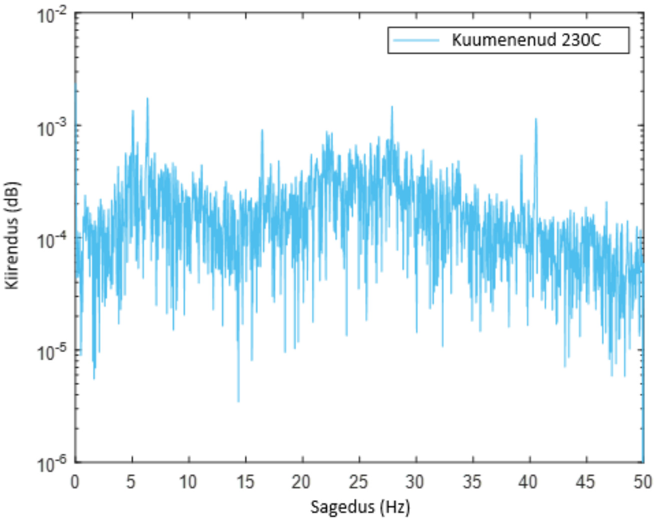
Lisa 4 Sensori 2 signaali põhjal tehtud FFT logaritmilises skaalas










Kuumenenud 230C
Kiirendus (dB)
Sagedus (Hz)
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10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
5
10
15
20
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30
35
40
45
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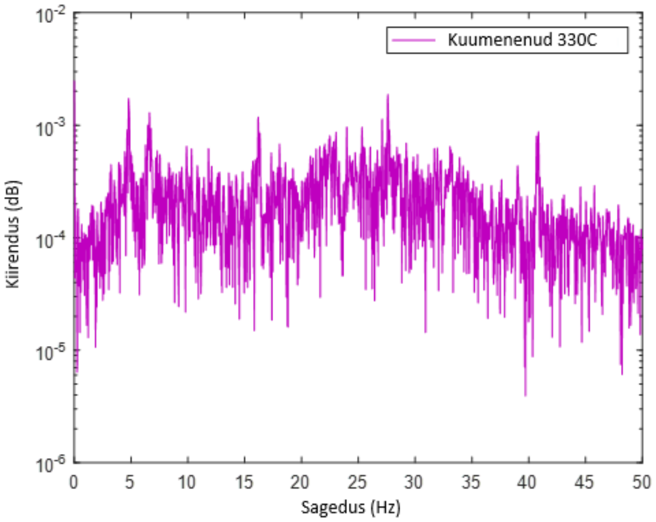
Kuumenenud 330C
Kiirendus (dB)
Sagedus (Hz)
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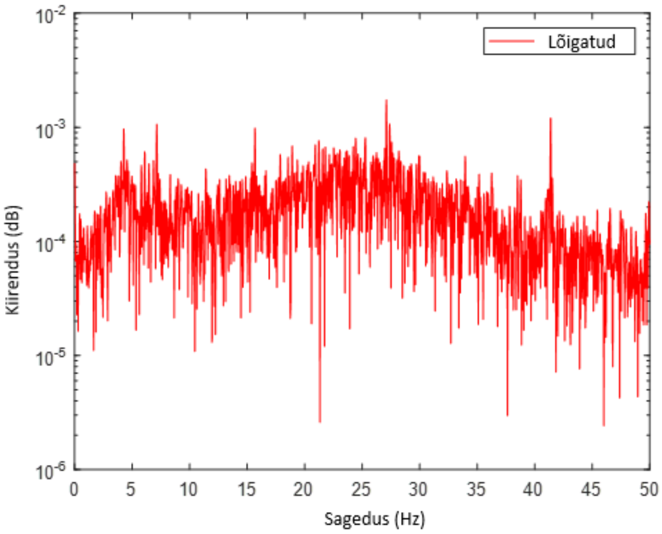
Lõigatud
Kiirendus (dB)
Sagedus (Hz)
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10^{-3}
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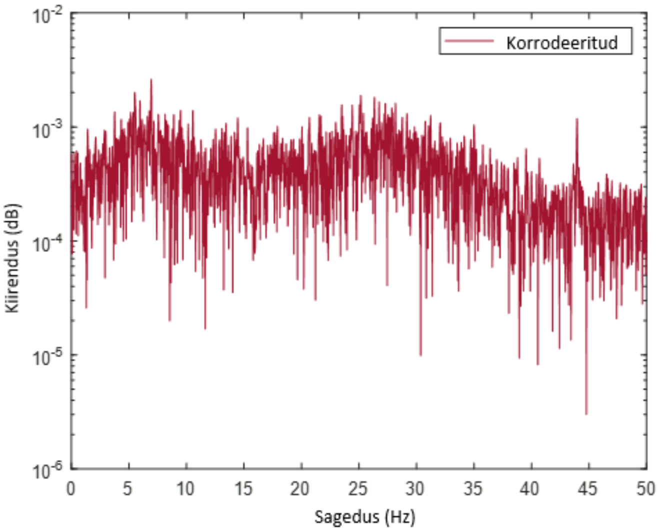
Korrodeeritud
Kiirendus (dB)
Sagedus (Hz)
10^{-2}
10^{-3}
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10^{-5}
10^{-6}
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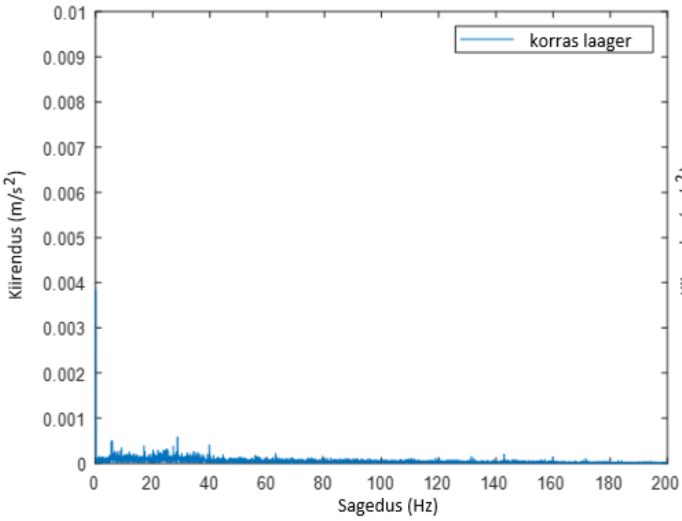
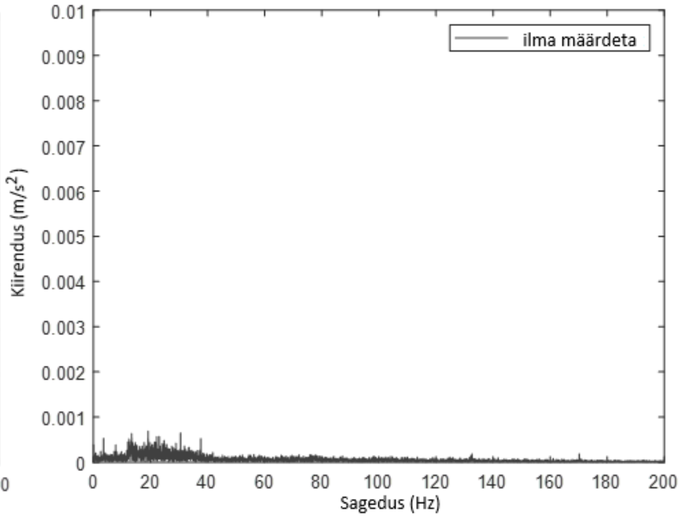
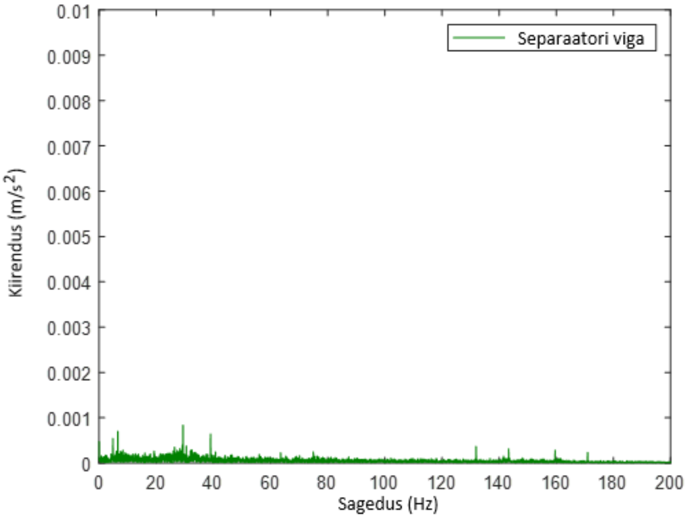
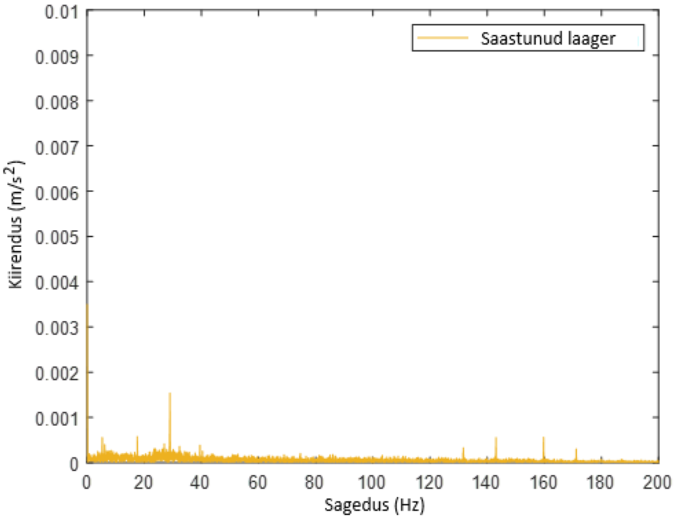
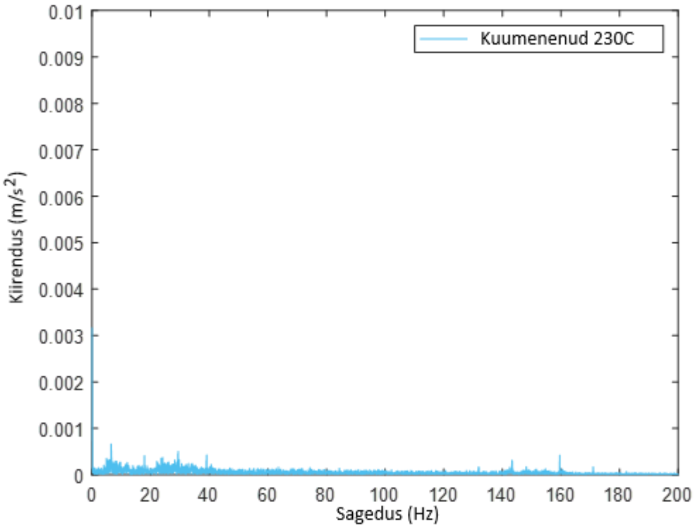
Lisa 5 Sensori 3 signaali põhjal tehtud FFT










Kuumenenud 230C
Kiirendus (m/s^2)
0.01
0.009
0.008
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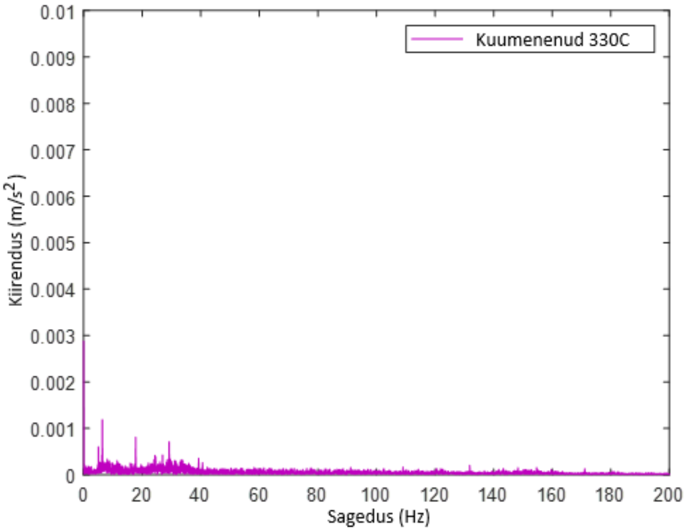
200
Sagedus (Hz)


Kuumenenud 330C
Kiirendus (m/s^2)
0.01
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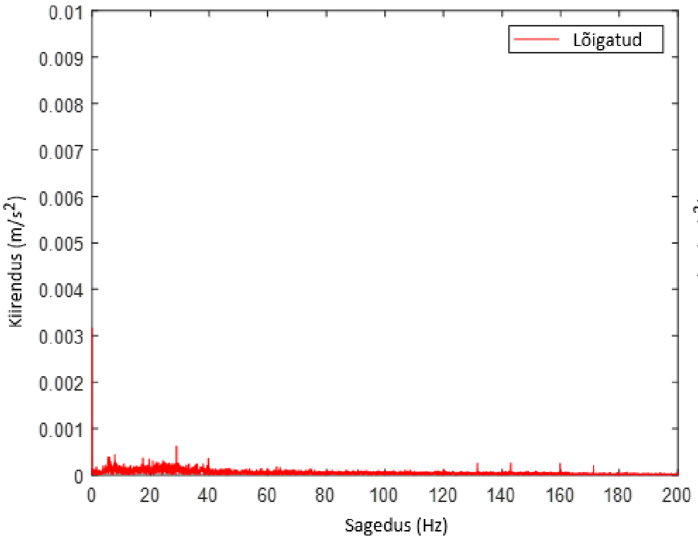
Sagedus (Hz)


Lõigatud
Kiirendus (m/s^2)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
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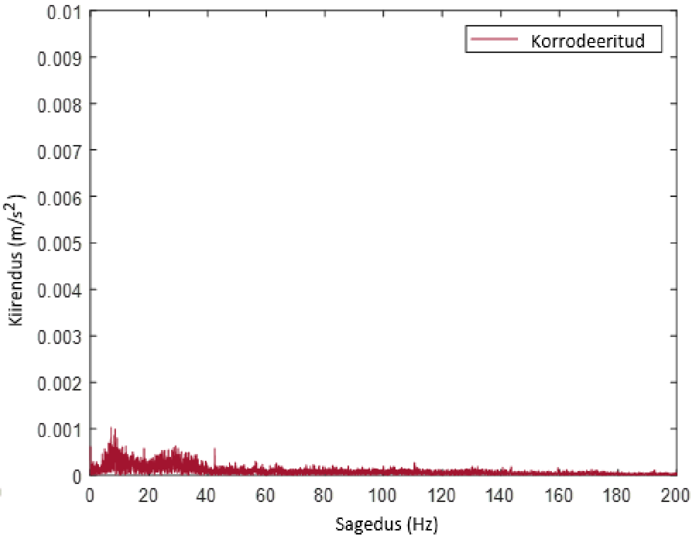
0
0
20
40
60
80
100
120
140
160
180
200
Sagedus (Hz)


Korrodeeritud
Kiirendus (m/s^2)
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0.002
0.001
0
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20
40
60
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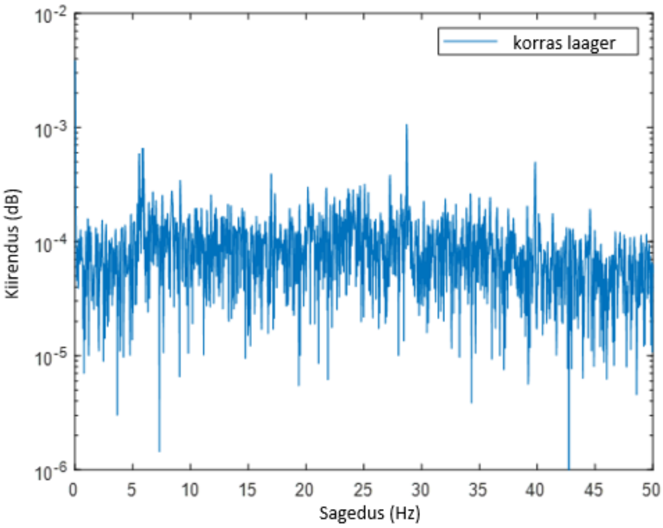
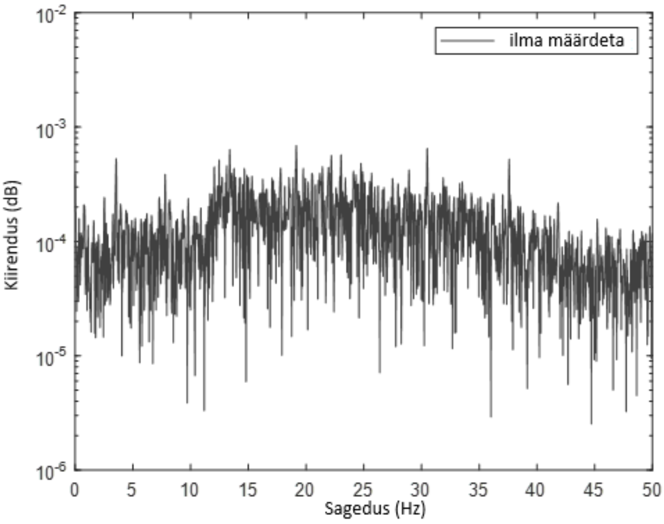
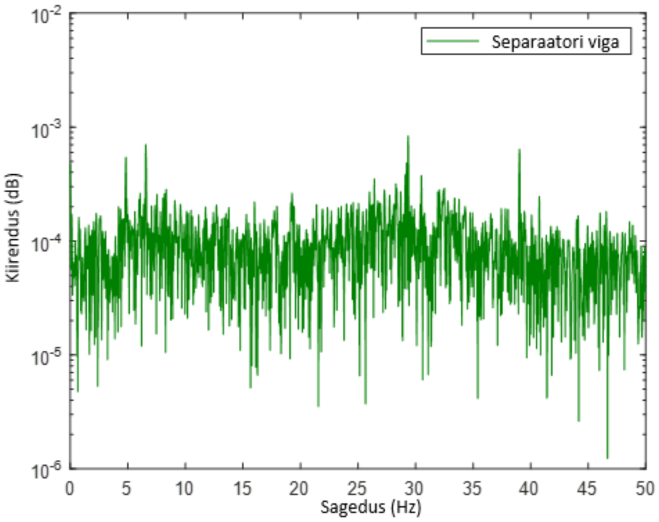
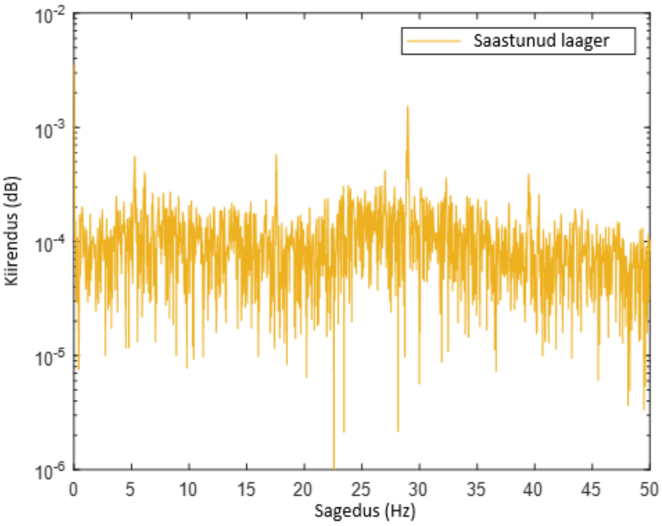
200
Sagedus (Hz)

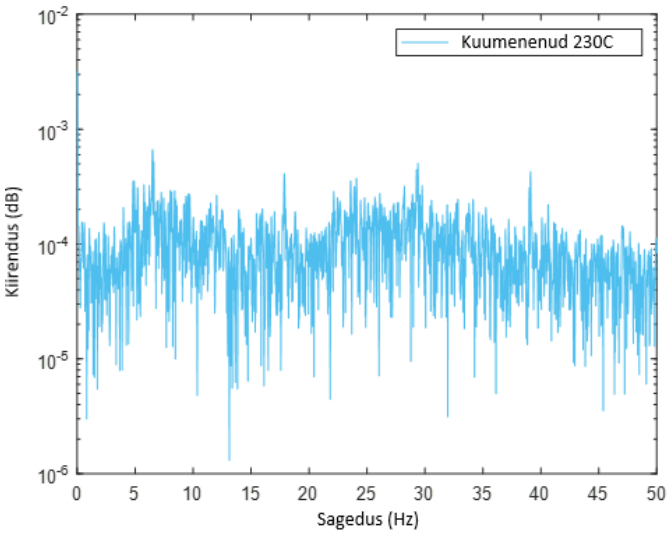
Lisa 6 Sensori 3 signaali põhjal tehtud FFT logaritmilises skaalas







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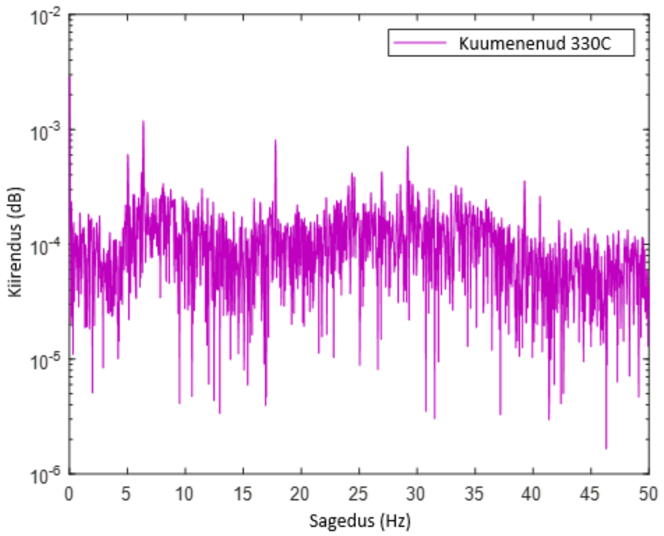
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0 5 10 15 20 25 30 35 40 45 50
Sagedus (Hz)


Kuumenenud 330C
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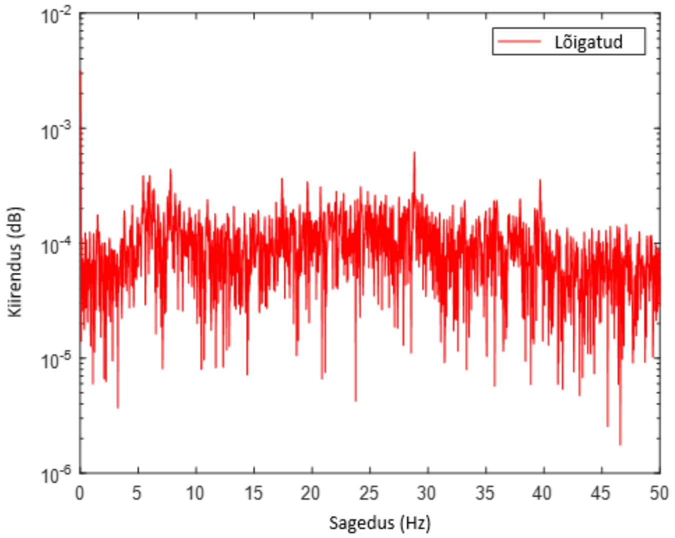
Sagedus (Hz)


Lõigatud
Kiirendus (dB)
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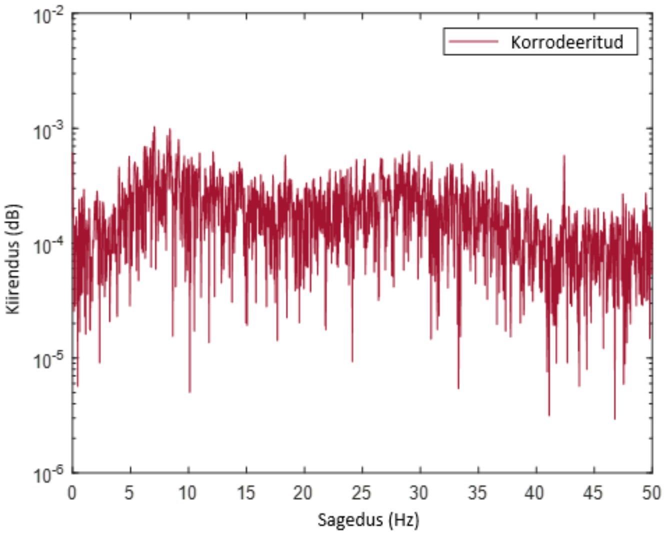
Sagedus (Hz)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10^{-3}
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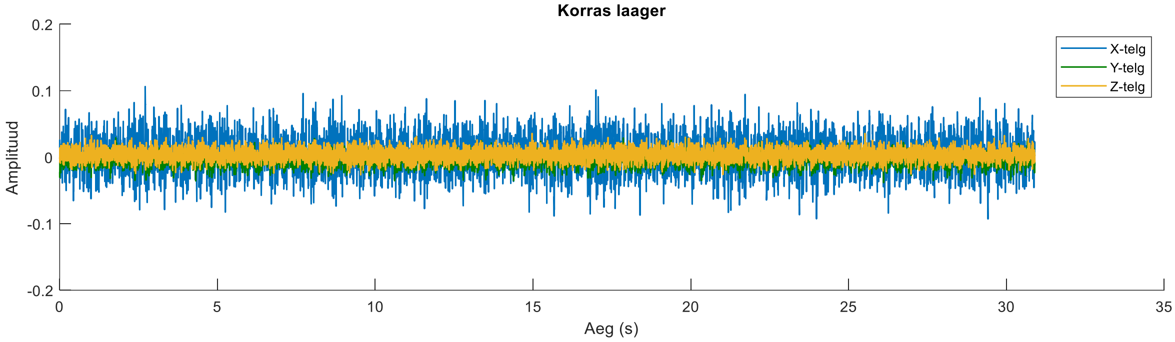
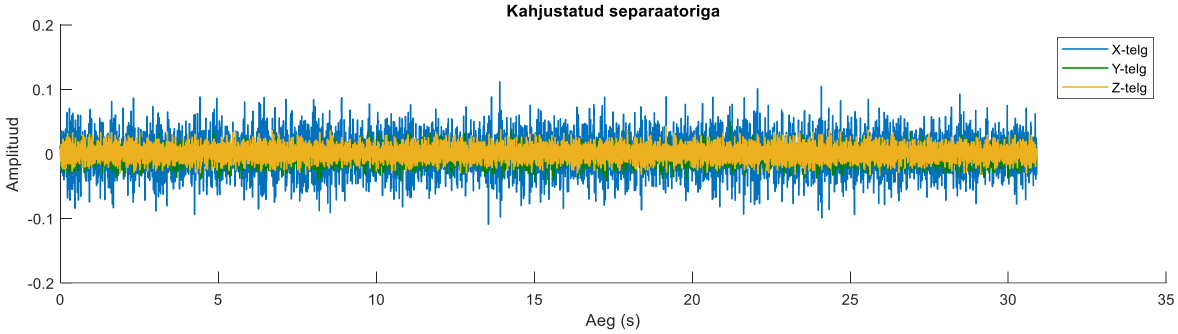
Sagedus (Hz)

Lisa 7 Sensori 1 vibratsioonisignaalid


Korras laager


Määrdeta laager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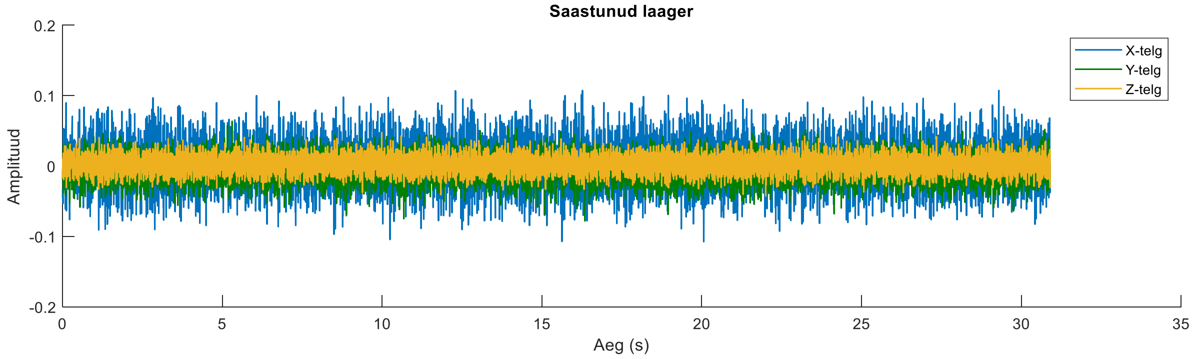
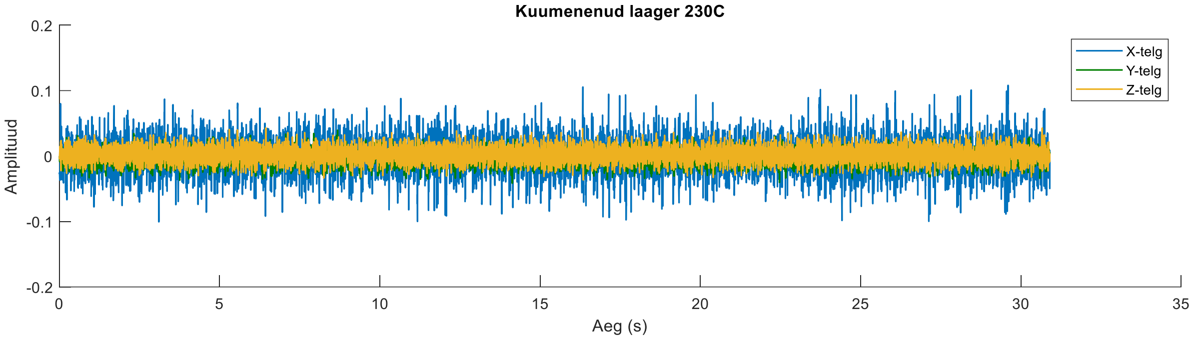

Saastunud laager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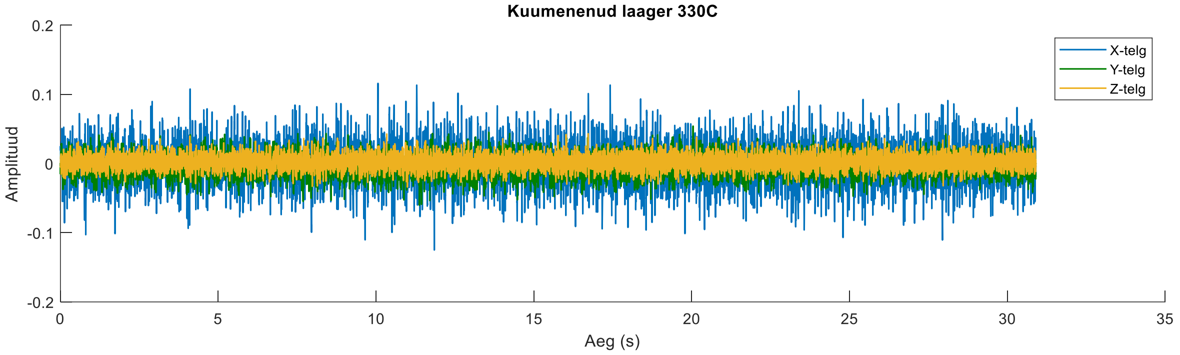
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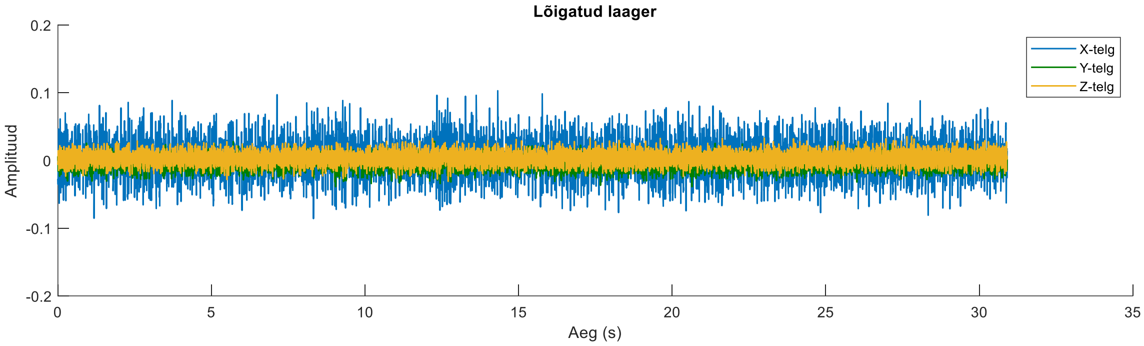
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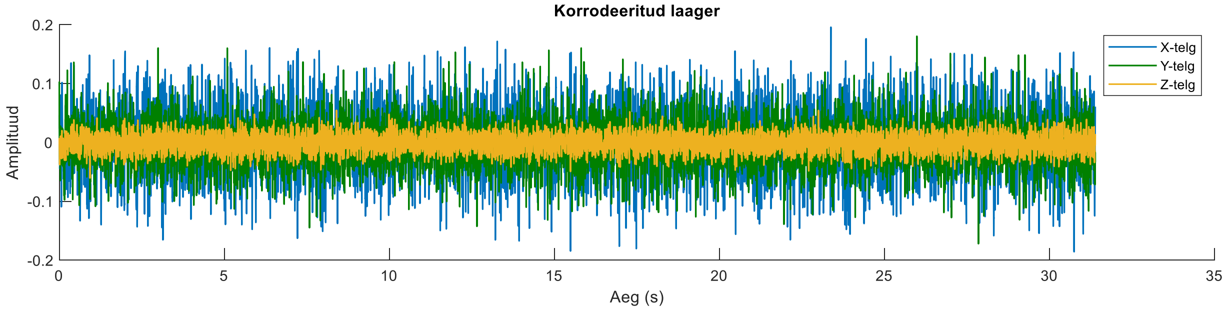
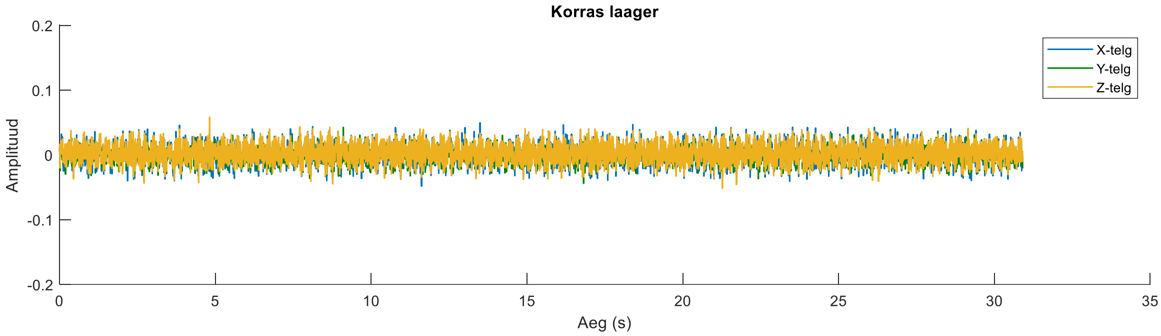
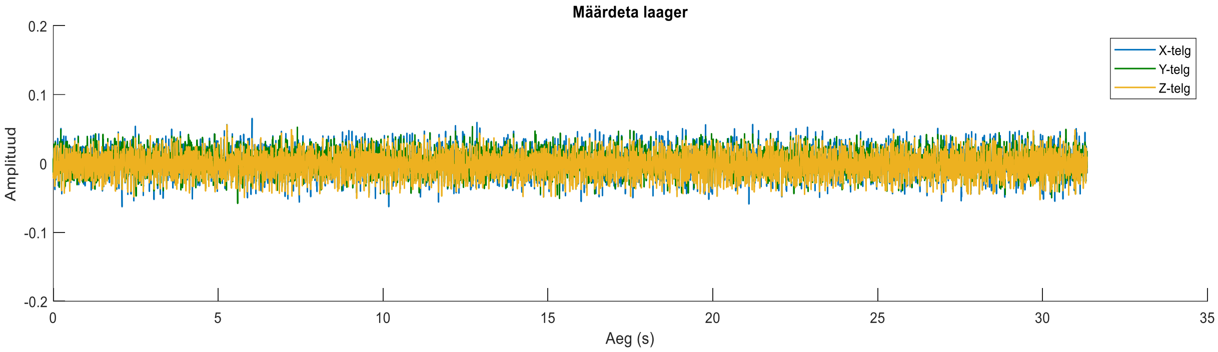
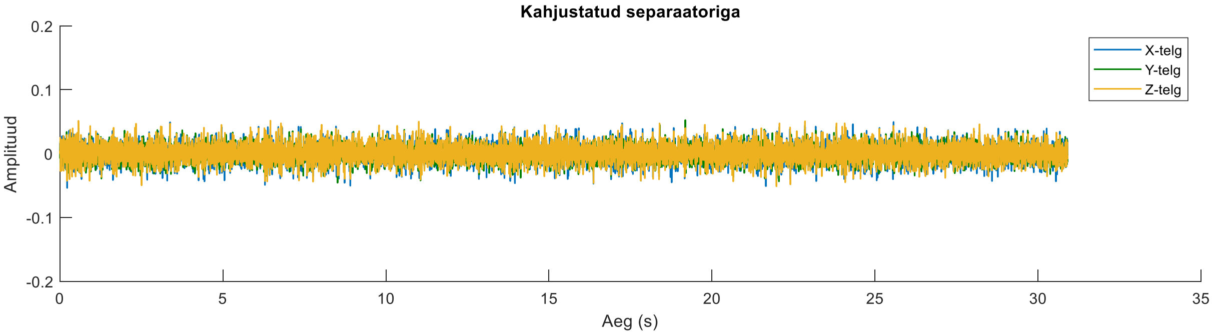
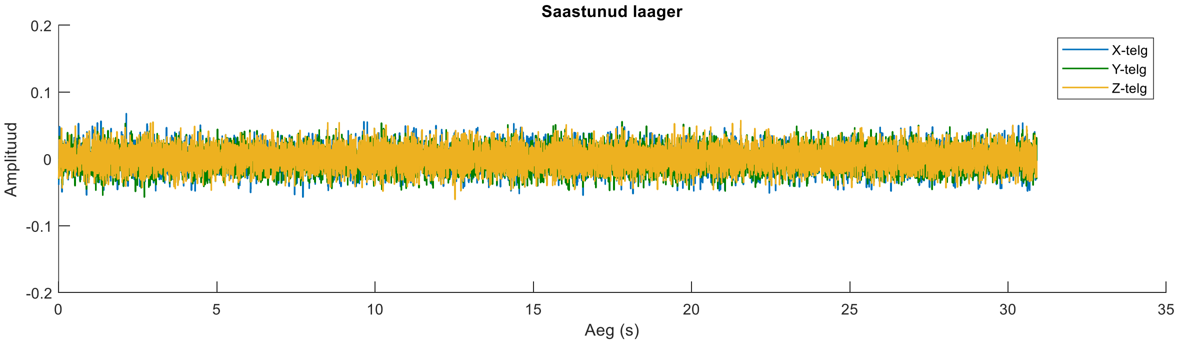

Korrodeeritud laager

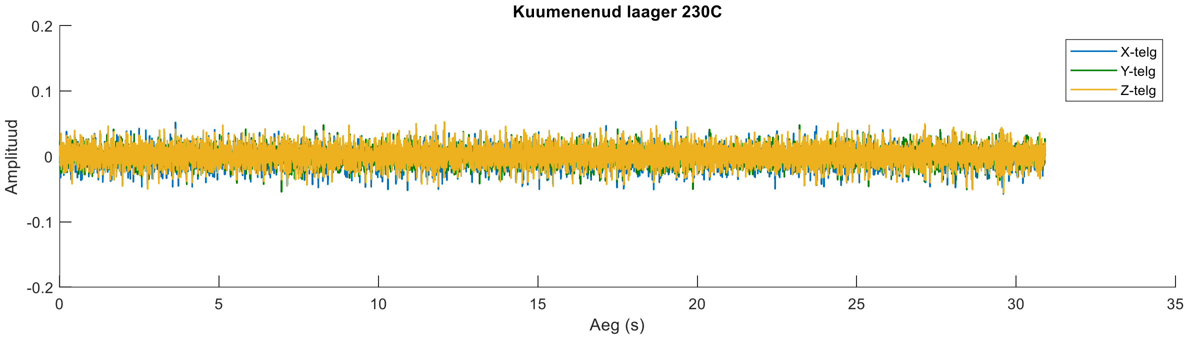
Lisa 8 Sensori 2 vibratsioonisignaalid










Kuumenenud laager 230C
Amplituud
0.2
0.1
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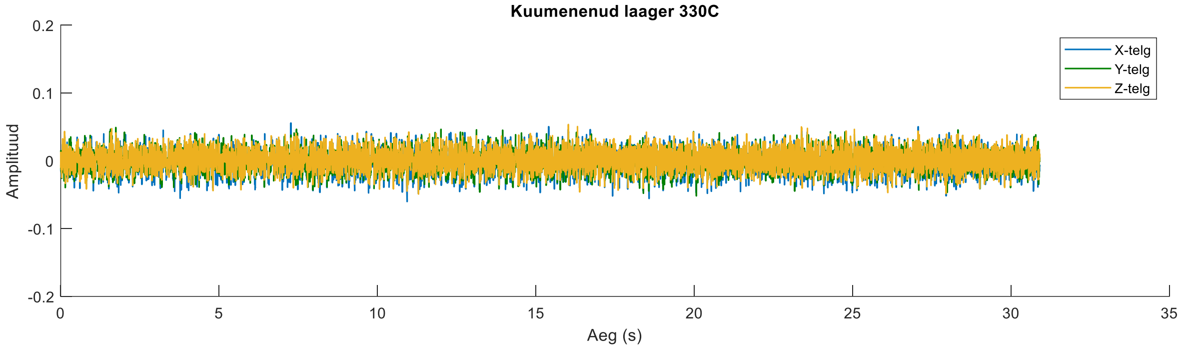
35
Aeg (s)
X-telg
Y-telg
Z-telg


Kuumenenud laager 330C
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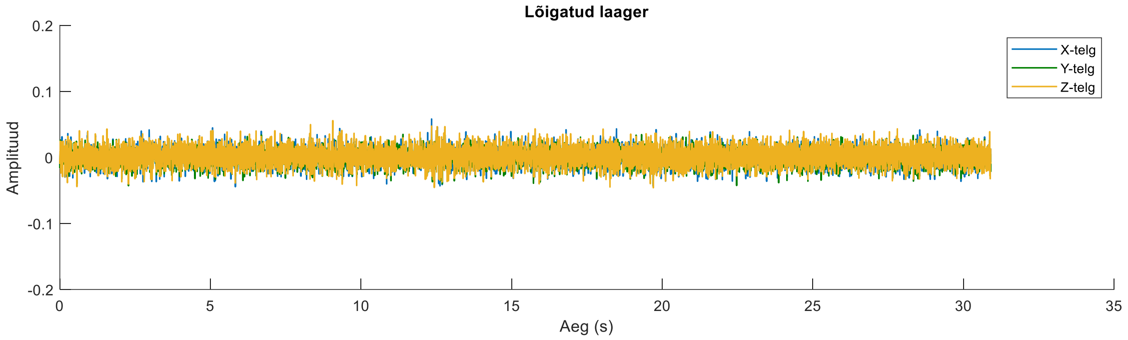
Aeg (s)
X-telg
Y-telg
Z-telg


Lõigatud laager
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Aeg (s)
X-telg
Y-telg
Z-telg


Korrodeeritud laager
Amplituud
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0.1
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-0.1
-0.2
0
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Aeg (s)
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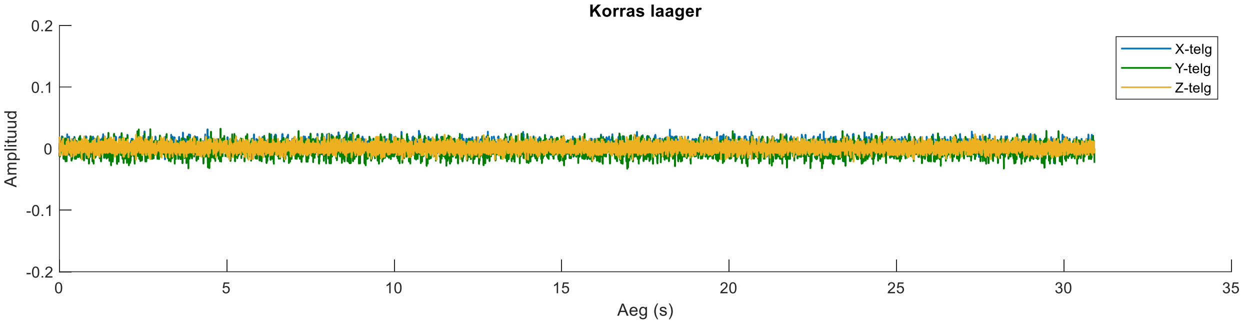
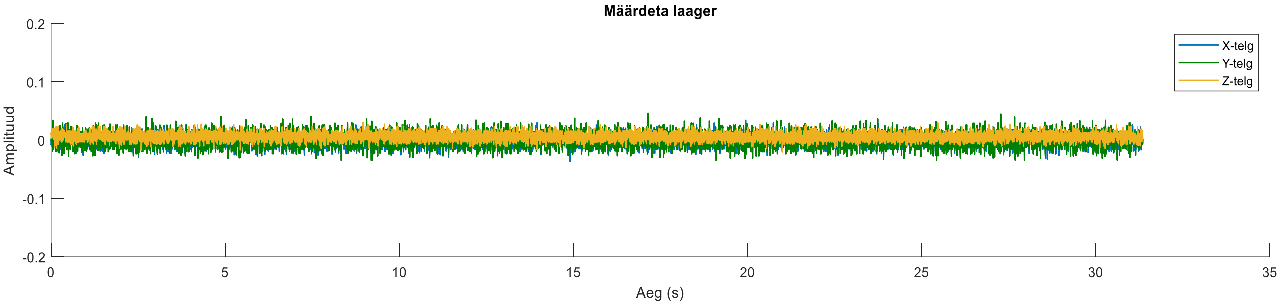
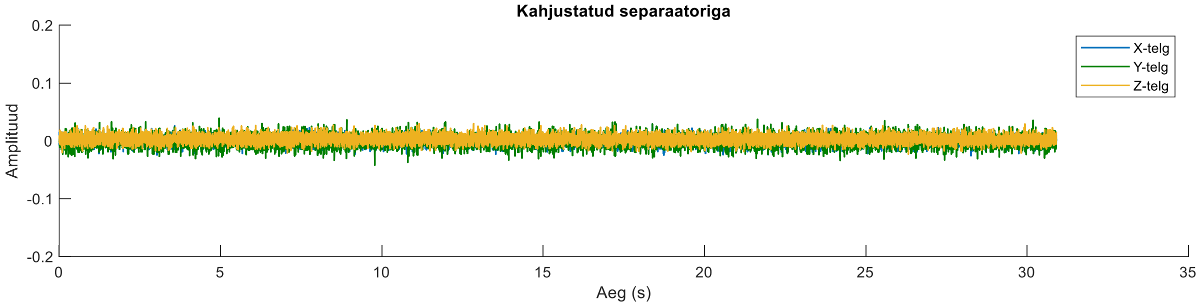
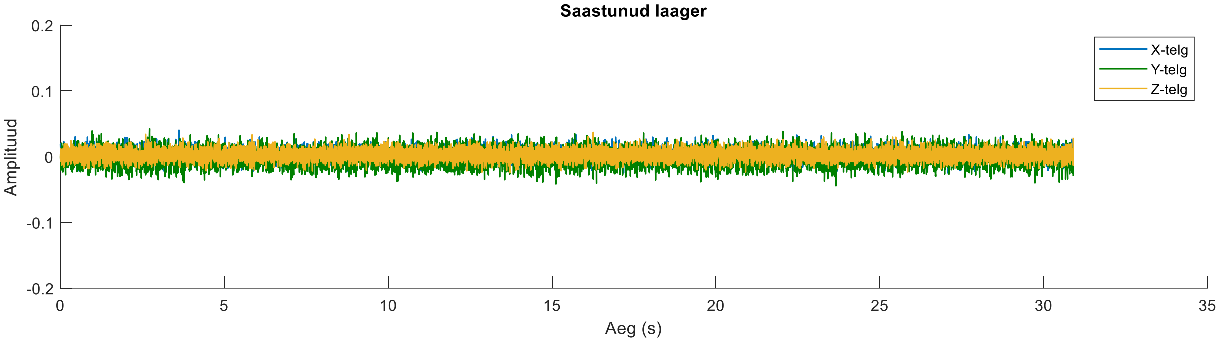
Y-telg
Z-telg

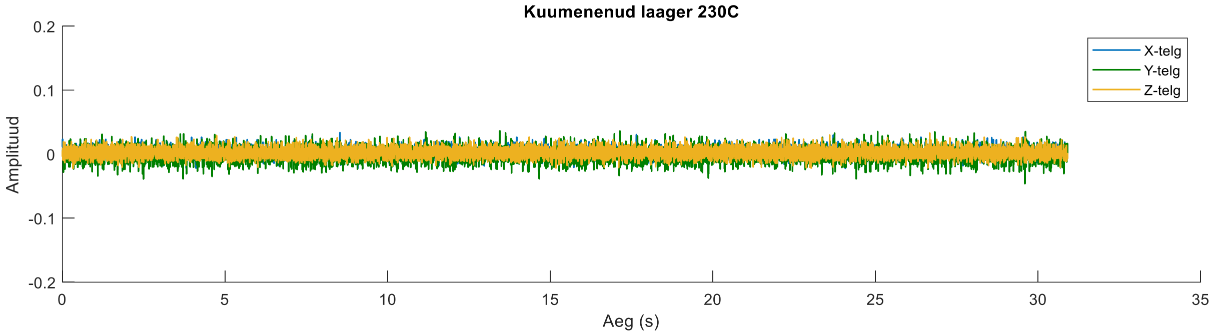
Lisa 9 Sensori 3 vibratsioonisignaalid











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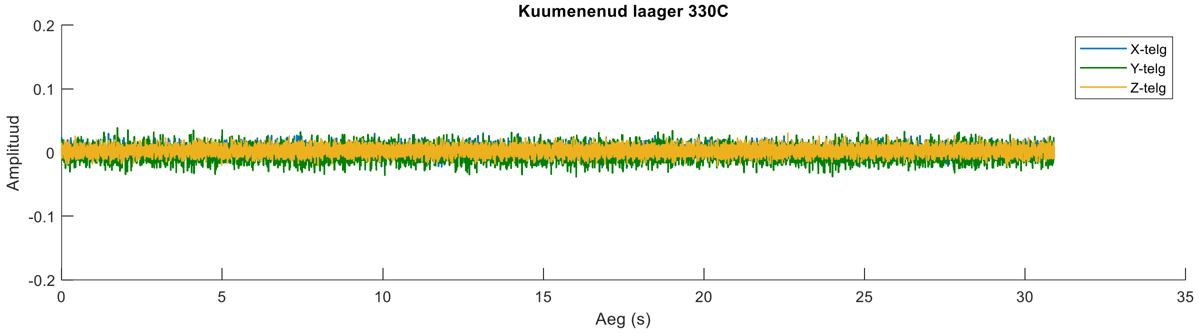

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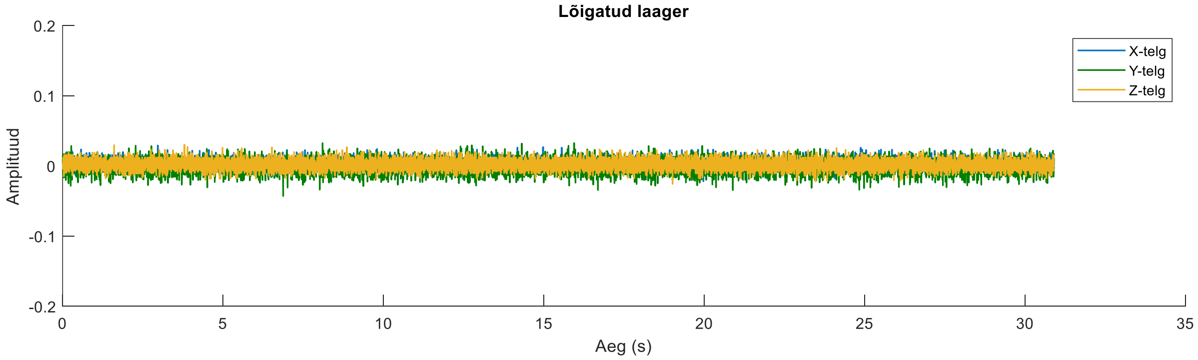

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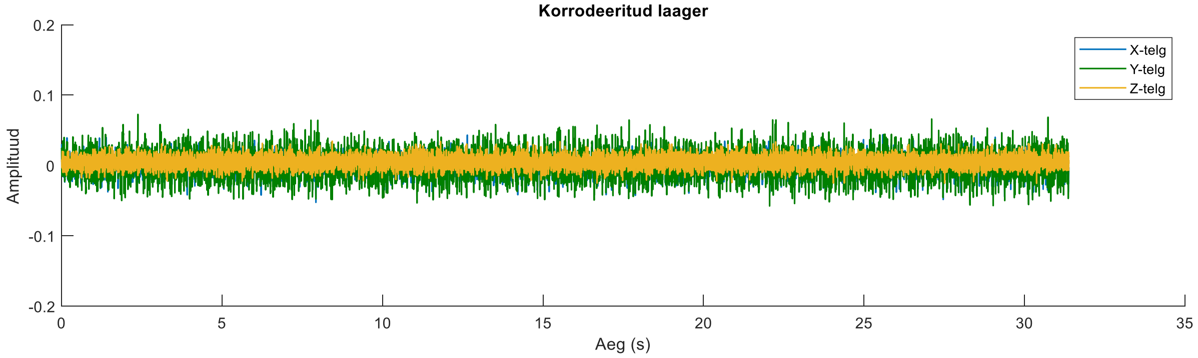

Korrodeeritud laager

Lisa 10 Teadusartikkel 1

2020 27th International Workshop on Electric Drives: MPEI Department of Electric Drives 90th Anniversary (IWED), Moscow, Russia. Jan 27 – 30, 2020

Main Faults and Diagnostic Possibilities of BLDC Motors

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Abstract—**This paper presents the main faults of brushless DC motors and their diagnostic possibilities. Due to the popularity gain of such devices in the past decade, the maintenance and diagnostic of such machines is getting more important. As the machines are used in various applications, they are often critical parts of devices. Due to this, the unexpected failures of such machines are undesired and are to be avoided. The main faults of the machines are listed, some possibilities of their monitoring and diagnostics have been addressed. The necessity of further study has been pointed out.**

Keywords*—permanent magnet motors, brushless motors, failure analysis.*

I. INTRODUCTION

Brushless direct current (BLDC) motors have been widely used in different industrial and domestic applications over the past decade. This is one of the motor types, which gains rapid popularity today. Based on the structure, direct current (DC) motors can be classified as:

- brushed DC motors (BDC),
- brushless DC motors (BLDC).

BLDC motors were developed on the base of BDC motors [1]. All BDC motors are made of the same basic components: stator, rotor, brushes and commutator. BDC motor has a simple design and operating principle. The disadvantages of BDC motors mostly lies in the usage of brushes. Brushes cause the noise and shorten the motor lifespan. Also, brushes need regular replacement.

To make the motor operation more reliable and efficient, BLDC motors were developed, in order to overcome the problems caused by brushes. BLDC motors are electronically commutated, and due to the absence of brushes, they do not produce sparking. This feature of BLDC motors allows them to be suitable for the use in applications, where sparks are dangerous (for example gas environment). In addition, removal of the brush on the BLDC motor, overcomes the problems associated with the mechanical friction and electrical erosion [2].

Using permanent magnets, combined with power electronics, allows BLDC motors to generate more power than the BDC motors. In addition, the BLDC motors are smaller and lighter than BDC motors with the same output power, making it valuable in applications, where size and weight are the critical factors. Over the BDC motors, the BLDC motors offer the following advantages [3]:

- Increased efficiency,
- Higher speed ranges,
- Reduced noise,
- Better speed-torque characteristics,
- Smaller size and weight for a given power,
- Increased reliability,
- Longer lifetime.

II. APPLICATIONS OF BLDC MOTORS

With the increasing demand on energy efficiency in appliances, the high-performance permanent magnet motors are being increasingly employed by replacing the induction motors [4]. Due to the lower energy consumption and maintenance, BLDC motors have gained wide attention in different industrial and domestic applications: automotive, household, aerospace, renewable energy, industrial automation, etc.

Special attention has been paid to BLDC motors in automotive and transportation applications. Nowadays, there are four types of motors, which are used for electric vehicles [5]:

- BDC motor,
- induction motor,
- switched reluctance motor,
- BLDC motor.

However, the BLDC motor is more reliable for electric vehicles than the BDC motor, as there is an electric commutator instead of a mechanical one [6]. BLDC motors are extremely appropriate for electric vehicles due to the wide speed and power ranges. Also, the brushless mechanism leads to reduced vehicle size and increased reliability.

Another noticeable trend in the transportation industry are the electric scooters. The main requirements for the electric scooter are the high power density and starting torque, high cruising speed, reliability, noise-free and minimum maintenance [7]. The BLDC motors meet these requirements better than the other motor types.

In addition, the BLDC motors are frequently used in domestic applications: washing machines, air conditioners, water pumps. A good example of the integration of BLDC motors into the household are the ceiling fans. Before the usage of BLDC motors, the construction of ceiling fans was based on induction motors. Due to the induction motors physics, there are problems related to pulsating torque. For the energy-saving reasons, the BLDC motor is a choice to use in an application like the fan. The energy can be saved at least

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50%, compared to the ceiling fan based on the induction motor [8].

III. CONSTRUCTION AND OPERATING PRINCIPLE OF BLDC MOTOR

The construction of BLDC is similar to the permanent magnet synchronous motor. The magnetic fields of the rotor and the stator rotate at the same frequency. BLDC motors can be single-phase, two-phase or three-phase. Depending on phase configuration, the stator has an according number of windings. At Fig. 1 a three-phase BLDC motor is shown.

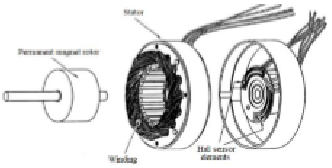

Fig. 1. Disassembled view of a BLDC motor [9].

The operating principle of a BLDC motor is based on the force interaction between the permanent magnet and the electromagnet. By applying DC power to the coil, it energizes and becomes an electromagnet.

A. Stator

The stator of the BLDC motor is similar to the one of an induction motor. The main difference consists in the distribution of the windings. In general, the three star-connected stator windings are widely used in BLDC motors. There are also possibilities of delta-connection. Comparing these two connections, star-connection is used to get higher output torque and delta-connection to get higher rotational speed [10].

B. Rotor

The rotor of BLDC motor consists of the shaft and the hub with permanent magnets. It varies from two to eight pole pairs, where north and south poles are alternated. Rare earth magnetic material alloys are preferred in permanent magnet industry nowadays, especially in the magnets used for applications such as electrical machines [11]. Over the last years, mostly NdFeB and SmCo are being chosen as the desired permanent magnet material. NdFeB is used to get higher power density and SmCo is used due to the wide temperature range [12]. There are different configurations of rotor magnet cross-sections. The main options are shown in Fig. 2 [13].

C. Rotor Detection Sensors

Differently from the BDC motors, the operation of BLDC motors is electronically controlled. To get a continuous rotation of the rotor, the stator windings must be energized in a sequence.

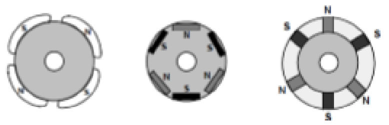

Fig. 2. Rotor magnet cross section [11].

Hall-effect sensors, embedded into the stator, are used in motors for determination of rotor position. The Hall-effect sensors indicate the north or south poles, when the magnetic pole passes the sensor. A sensor determines the position of the rotor. Based on this information, the controller decides, which stator coil to energize. The signal measured from this sensor can also be used as a potential candidate to detect the defects in the permanent magnets, such as cracks and demagnetization. However, a stator embedded coil can be used to study a variety of faults in steady state regime.

IV. MAIN FAULTS OF BLDC MOTORS

The faults that occur in BLDC motors can be classified as mechanical faults (bearings and eccentricity), electrical faults (drive and winding failures) and magnetic faults (demagnetization) [14].

A. Mechanical Faults

Almost 50% of all failures in BLDC motors are related to mechanical faults [15]. The most frequent failures are the bearings related failures. The bearing failure can be indicated by increased noise and vibration [16]. The reasons for bearing failures can be different environmental or manufacturing factors [14]:

- Overload,
- Wrong emplacement,
- Material fatigue,
- Bad lubrication,
- Environmental pollution,
- Bearing and/or shaft currents.

a) Material fatigue: Fatigue of the material is usually caused by the cyclic load. The cyclic and continuous load causes cracks on the surface of the material. If fatigue cracking progressively expands to a larger surface, the bearing eventually becomes unsuitable for further operation.

b) Bad lubrication: Bad lubrication can consist of either scarce or surplus lubrication. Scarce lubrication can be caused by either low viscosity grease or small amount of the lubricant. Surplus grease can lead to the shaft slipping, which also leads in turn to crack progression. In addition, incorrect lubricant selection contributes to lubricant contamination.

c) Environmental pollution: The grease can become contaminated when water or other chemically active substances pollute the lubricant. This causes bearing corrosion, as the lubricant properties are deteriorated. The contamination can occur in hand with wrong bearing gasket selection.

d) Shaft currents: The bearing can be affected by stray currents. Defects in bearing surfaces due to the stray currents are clearly different from any other typical bearing damage, making it very easy to detect them visually. The type and the view of this defect depend on the operating conditions of the motor. Fig. 3 shows common effects on shaft currents on the bearing surface.

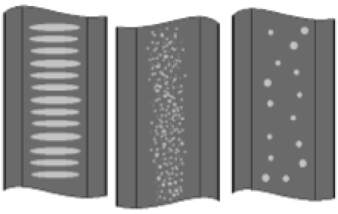

Fig. 3. Effects of shaft currents on bearings track surfaces (fluting, frosting, pitting).

Fluting occurs in the combination of low voltage and constant rotational speed. When the motor runs at varying speeds, another well-detectable fault called frosting will appear. Pitting is caused by high voltage and low rotational speed.

Another frequently occurring fault in BLDC motors is eccentricity. The unequal air gap between rotor and stator causes eccentricity faults in electric machines. The air gap eccentricity exceeding 10% is considered as a fault [14]. This conduces to stray currents in stator windings, which in turn heat the motors and lead to losses.

There are two main types of eccentricity: static and dynamic [16]. In the case of static eccentricity, there is a displacement of the rotation axis. This can be caused by stator ovality or misaligned mounting of bearings, rotors or stators. In the case of dynamic eccentricity, the stator axis and the rotation axis of the rotor are identical, however, the centerpoint of the rotor is displaced to some extent. In some cases, elliptic eccentricity can be found, where the center points of the rotor and stator symmetry are matching, but the eccentricity is caused by either rotor or stator circumferential tolerance error [17].

B. Armature Faults

This type of machine faults is usually caused by winding insulation failure. The conditions that can occur due to the armature failures are [16]:

- High temperature (stator core or windings),
- Electrical discharges,
- Environmental pollution,
- Short circuit.

As shown in Fig. 4 [17], there are five most common winding failures.

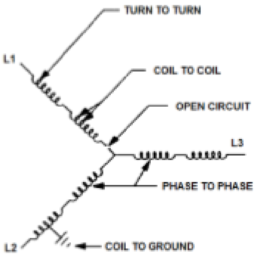

Fig. 4. Stator possible failure modes [18].

Also, these failure modes can occur in different combinations. The fault usually starts with a turn-to-turn short circuit. Then it can progress to a phase-to-phase short circuit or a ground fault. It can damage the motor eliminating further operation.

C. Permanent Magnet Faults

The most frequent permanent magnet fault is its demagnetization [16]. The demagnetization means partial or complete loss of magnetization. Overheating and overload are frequent causes for permanent magnet demagnetization. Apart from demagnetization, corrosion decreases useful properties of the magnetic material. Another factor that can influence the magnet properties is a short circuit. The most dangerous electrical fault for the magnet is the phase-to-phase short circuit of the machine.

V. FAULT DIAGNOSTIC POSSIBILITIES FOR BLDC MOTORS

During recent years, the diagnostics of electrical machines has received reasoned importance. Nowadays, there are many possibilities for fault diagnostics [19] . The majority of them can be divided into the following categories:

- Temperature measurement,
- Electromagnetic field monitoring,
- Radio-frequency emissions monitoring,
- Chemical analysis,
- Acoustic noise measurement,
- Motor-current signature analysis (MCSA),
- Noise and vibration monitoring,
- Model, artificial intelligence and neutral-network based techniques.

Additionally, there are two large groups under which all the diagnostic techniques can be classified – invasive and non-invasive techniques.

A. Invasive Diagnostic Techniques

In the case of invasive diagnostic techniques, the sensors are built into the motor. These types of diagnostic techniques can be more accurate but at the cost of more complexity and difficult maintenance if the sensors are failing.

B. Non-invasive Diagnostic Techniques

In non-invasive techniques, there are no embedded sensors in the machine. Although, non-invasive methods are less accurate, as compared to the invasive techniques, they possess advantages, such as, the machine structure does not need to be changed, the measurement of global parameters open a vast domain of signal analysis techniques, which can be used depending on the nature of the machine and its application. Almost all kind of signal processing techniques depend on the Fourier transformation and its variants.

C. Fourier Series

The idea of the Fourier series is that any periodic function of time can be represented as a series of sinusoids and cosines. The Fourier series deals only with periodic signals. This means that signals repeat themselves in a certain interval of time (time period). The complex formulas of Fourier series can be avoided by using fast Fourier transform (FFT), which is an algorithm to solve them in a faster and simpler manner.

a) Fast Fourier transform (FFT): The Fast Fourier transform converts time domain signal into a frequency domain signal. Compared to the Fourier series, it can deal with both periodic and aperiodic signals. According to the data type, the Fast Fourier transform can be divided into two categories:

- CTFT (continuous time Fourier transform)

$$\text{CTFT } X(\omega)=\int_{n=-\infty}^{\infty} x(t)e^{-j\omega t}dt \tag{1}$$

where x(t) is a major function in continuous time domain.

- DTFT (discrete time Fourier transform)

$$\text{DTFT } X(\Omega)=\sum_{n=-\infty}^{\infty} x[n]e^{-j\Omega n} \tag{2}$$

where x(n) is a major function in discrete time domain.

This technique requires less computational power. However, there are also several disadvantages and limitations of FFT. Firstly, the small sampling rate can lead to a wrong signal. This occurrence is called aliasing. Secondly, the signal time limitation can lead to spectral leakage. Spectral leakage is an energy leakage of the main frequency component into the side lobes. The FFT is intended for the measuring signal with infinite length. Practically, the signals have a finite length. Spectral leakage can be fatal for frequencies having very small amplitude. This will make algorithm difficult to measure fault frequencies at an incipient stage. The length of the signal should be long enough to measure the harmonics correctly. The main drawback of FFT is that this algorithm works only with stationary signals and fails when the signal is non-stationary. Moreover, the signals with discontinuities are difficult to be handled using this technique. A lot of work related with fault diagnostic of electrical machines can be found in literature. The authors in [20]used to investigate the broken rotor bars for inverter fed induction machines. [21]used it along with infinite impulse response filter to improve the legibility of spectrum. The researchers in [22] used this technique to detect principal slot harmonics in motor's current spectrum. Despite being very easy, comprehensive and compatible with various other signal processing techniques, it fails if the signal is in transient condition or un-stationary. It means that it is not possible to locate the time of the particular harmonic using this technique. In this case, the solution is short time Fourier transform.

b) Short time Fourier transform (STFT): The algorithm of this transform is based on dividing the original signal into short segments. Due to the shortening window, the signal can be considered as a stationary signal, making it able to calculate the FFT from each segment separately. This application provides better time-frequency representation. There is also a possibility to analyze data by 3D plots (time-frequency-amplitude) for more efficient data acquisition. However, the short-time Fourier transform has also the same drawbacks referred to the fast Fourier transform, such as aliasing and spectral leakage. The clever use of windowing function for truncation of the signal is very important to reduce the above mentioned problems. Another emerging signal processing algorithm to get time frequency response of almost every kind of signals is the wavelet. The equation of wavelet transform is as follows:

$$X\ (m,\ \omega)=\sum_{n=-\infty}^{\infty} x[n]w\ [m-n]e^{-j\omega n} \tag{3}$$

where x[n] is complete signal and w[m-n] is the truncation window which moves and take a portion of the signal at a time. This technique is being used widely for the fault diagnostic of electrical machines in the literature. A good comparison of STFT with other time-frequency methods can be found in [23]. The shaft fault diagnostic using time-frequency maps is presented in [24]. While the authors in [25] used fractional Fourier transform to detect rotor fault. Since the STFT inherits the problems of FFT and leakage of windowing functions, the wavelet transform can be a better solution.

c) Wavelet transform: While in FFT the signals are decomposed in sinusoids and cosines of infinite duration, the signals in wavelet transform are decomposed into wavelets of finite duration. In the wavelet transform, the signals are deconstructed with the same wavelet with different scales. There are many types of wavelets. The main of them are shown at Fig. 5 [26]. The algorithm of this technique is based on taking one of the mother wavelets and comparing it with the measured original signal. The mother wavelet with certain frequency is swiped across the entire signal and its translation and scaling parameters are recorded, where it is in best correlation. These parameters of mother wavelet are changed and the process is repeated until all frequencies are recovered. This technique is accurate enough. Also, comparing to the Fourier transform, the time-frequency resolution is better. The leading drawback of wavelet transform is the requirement of bigger computational power and memory to save the information. The wavelet transform equation is as follows:

$$W\ (a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}\psi\left(\frac{t-b}{a}\right)f(t)dt \tag{4}$$

where a is the translation parameter, b is the scaling parameter, $\frac{1}{\sqrt{a}}$ normalization constant, $\psi\left(\frac{t-b}{a}\right)$ is the mother wavelet.

The variety of wavelet based applications for fault diagnostics are available in literature. [27] used it to detect the rotor rub fault, while the authors in [28] used it to detect bearing faults of induction motor. The broken rotor bars fault detection under transient regime is presented in [29]. This technique can be considered as a reliable diagnostic technique. However, there are two main disadvantages: increased complexity of this technique and its cost. The dynamic eccentricity in BLDC motors is studied in [30].

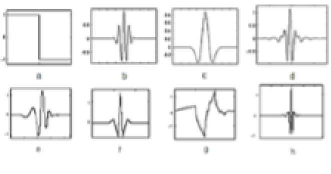

Fig. 5. The main types of wavelet transform [26]: a) Haar wavelet b) Morlet wavelet c) Mexican hat wavelet d) Meyer wavelet e) Daubechies wavelet f) Biorthogonal wavelet g) Symlets wavelet h) Coiflets wavelet.

TABLE I. THE DISCRIPTION OF DIAGNOSTIC TECHNIQUES

Technique	**Technique attributes**	
	Advantages	*Drawbacks*
FFT (DTFT, CTFT)	Work with aperiodic signals Small losses of information Requires less computational power Easy to implement in on-board processors	Unable to analyze the non-stationary signals Time-frequency representation is not possible Aliasing Bad resolution Spectral leakage Bad for discontinuities in the signal
STFT	Work with aperiodic signals Ability to work with non-stationary signals Time-frequency representation is possible 3-D (time-frequency-amplitude) plots can be more informative	Spectral leakage Aliasing Bad time-frequency resolution Compromise between time and frequency More computational power is required as compared to FFT
Wavelet	Very precise technique Better time-frequency resolution Ability to analyze non-stationary signals A variety of mother wavelets makes it more flexible	More memory is required to save intermediate results Requires more computational power as compared to STFT The better precision requires more iterations
Advanced techniques	More efficient analysis More presice results	Modern and sophisticated technology is required Requires a lot of computational power

d) Advanced diagnostic techniques: Due to the fact that computer science has moved foward and has become a growing industry over the last years, it is reasonable to focus on the integration of advanced techniques into the diagnostics of electrical machines. Nowadays, many advanced diagnostic techniques are used, such as neural networks, fuzzy logic or pattern recognition. Also, some analytical advanced techniques can be used in diagnostics, such as inverse problem theory, machine learning, parameters estimation. These advanced techniques can provide more efficient and precise results. The most of these techniques depend on the mathematical models of the system, which makes them more complicated. A good number of references regarding advanced fault diagnostic techniques can be found in [31].

VI. CONCLUSION

The use of BLDC machines is increasing day by day in electric and hybrid vehicles, electric bicycles, computer hard drives, industrial robots, CNC machine tools, conveyer belt systems, compressors and small power supply fans, etc. The increasing number of applications makes their condition monitoring very important to avoid any catastrophic situation.

In this paper all possible fault types associated with BLDC machines are first summarized and the signal processing techniques are discussed in the perspective of their advantages and disadvantages. The main benefits and drawbacks of possible diagnostic technique for BLDC motors are shown at Table 1. Because of the involvement of the controller, the clever choice of the diagnostic technique is very important. The practical implementation of these techniques on the signals taken from test rig with different types of faults will be considered as future work.

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Modern Mechatronics and Robotics Education Program: Border Cooperation between Estonia and Russia

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***Abstract*—The paper describes the interaction between Tallinn University of Technology (TalTech, Tallinn, Estonia) and ITMO University (St. Petersburg, Russia) based on recently signed agreement. The purpose of the agreement is to record the intention of TalTech and ITMO University to cooperate on implementing a double master's degree program, which involves confirmation of the master's educational level absorption and the award of master's degree and obtention of two diplomas, and to outline the organizational form, principles and terms of the implementation. The double degree Program is a two-year Master's program of 120 ECTS credit points. Its structure and content meets the requirements that both TalTech and ITMO University have established for their master's programs, in accordance with the government standards. Development and approval of the double degree Program is held by the Parties in accordance with the procedures established by them. This paper describes the procedure of implementation of a double-degree master program in mechatronics engineering.**

Keywords— Educational programs, Engineering education, Mechatronics

I. INTRODUCTION

The international cooperation between academic institutions is one of the main aspects in boarder cooperation between many countries. Such cooperation helps to improve the quality of the didactic and give the students a more wider experience and better opportunities in the labor market. Double-degree programs in engineering fields are widely used worldwide [1], there is number of double-degree programmes successfully implemented between middle-east and European Union (EU) countries [2]–[4], at the same time Russia is also one of the major partner for EU countries [5]–[7].

Usually, it is a great challenge to try to establish a common ground and propose courses for the new program that would fit the needs of all parties and an industrial enterprise, complement each other and be mutually beneficial. An example of distance degree presented in [3], the agreement consists in the creation of a double degree in ICT (Information and Communication Technologies) Engineering, delivered in e-learning modality. The use of e-learning didactic allows students to study at home or in home university and to take a double degree, that may be recognized in both countries. A double degree study program with only one obligatory semester abroad is presented in [5]. One interesting case of joint master degree of different practice-oriented and theory-oriented curricula's is presented in [6]. Very important that the parties agree to the mutual recognition of credits for the in-coming students from the university participating in the double degree program.

In [4] authors attempts to investigate the personality development of engineering students who embarked in a double degree programme, study shows that the students who have been exposed internationally may articulate the qualities that are expected to be highly regarded by an employer and the environment that they have experienced has helped them to be an adaptable person who could communicate with people of different backgrounds and enriched with creative thinking.

Financial support plays important role in creation of any double degree program. It is important that parties are following their national policies and regulations regarding tuition fees. Both parties must agree that they do not have reciprocal claims regarding compulsory tuition fees. Usually, international programs that encourages higher education institutions mobilities are involved. In [2] double degree master program in mechatronics was developed based on the TEMPUS (Trans-European Mobility Programme for University Studies) bachelor curriculum (within ca 800 students enrolled). In [4] DAAD (German Academic Exchange Service) supports joint double degree program between Malaysia and Germany. Moreover, a number of activities in Europe is supported by Erasmus+ actions, as [8] for example.

To extend cooperation between Tallinn University of Technology (TalTech) and ITMO University in the field of Mechatronics the agreement on cooperation in the framework of a double master's degree program has been signed. The main purpose of the agreement is to ensure master's theses counseling and to conduct quality assurance of the double degree Program. The full-time double degree Program in Mechatronics and Robotics, program Intelligent Technologies in Mechatronics aims at training of highly qualified specialists with cultural, linguistic and unique professional skills by coordinating the content of the double degree Program and integration of resources of TalTech and ITMO University in this academic field with including a compulsory mobility period in the degree requirements for the students of both universities.

II. MASTER STUDY ADMISSION

A. Tallinn University of Technology (TalTech)

TalTech is a promoter of science, technology and innovation and a leading provider of engineering and economic education in Estonia since 1918. The university's vision is innovative Estonia in a developing world. The core values of TalTech are professionalism and reliability, entrepreneurship and innovation, openness and cooperativeness. The university pursues these values in all of its fields of activity. Today, more than 10 000 students from nearly 100 countries are studying at the TalTech. One of the goals of the university is internationalization and the proportion of international staff has increased year by year: from 7% in study year 15/16 to 11% in 18/19 [9].

Study and teaching at TalTech is based on internationally recognized research and the graduates are highly rated on the labor market. The University's approximately 70,000 alumni have shaped the economic landscape of present-day Estonia. Number of master students at TalTech in last decade is shown at Fig.1. As it can be seen from the diagram the number of graduates students has positive trend, in despite of total number of master students is decreasing in last five years. Decreasing of total number of the master students at TalTech that started five years ago may be explained by general demographic situation in Estonia, however, today the number of students in general education started to grow according to [10]. Unfortunately, there are still a high number of students that interrupt their master studies, around 15% of all master students.

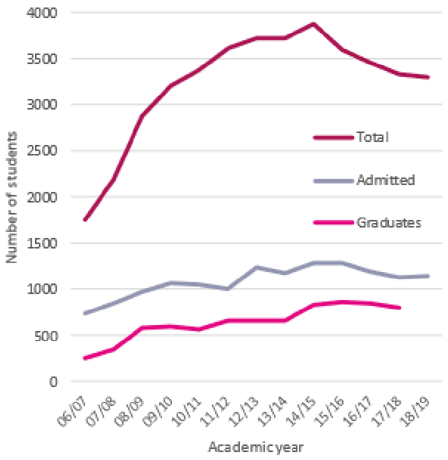

Fig. 1. Number of master students at TalTech

With a total number of students 1144 admitted in 2018/19 to TalTech majority were chosen engineering and business fields of study, as shown in Fig.2.

At TalTech in the academic year 2018/19, the total of 18 master's programmes taught in English were opened for admission [9], five of which were joint study programmes with other Estonian universities (the University of Tartu, Tallinn University and the Estonian Academy of Arts) and one was an international study programme with parter universities: the Catholic University of Leuven (Katholieke Universiteit Leuven) from Belgium and the University of Münster(Universität Münster) from Germany.

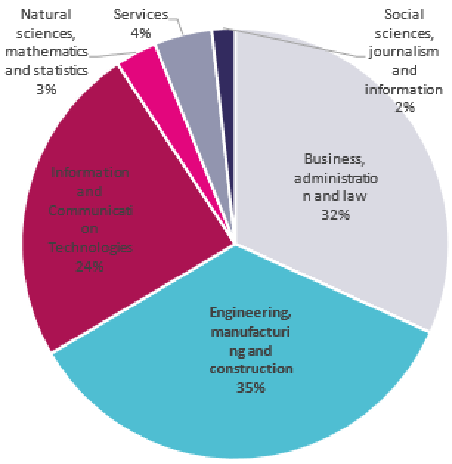

Fig 2. Aggregated indicators by master studies at TalTech for admission 2018/19

B. *ITMO University*

ITMO University was founded in 1900 and it is one of the oldest engineering educational establishments in Russia and is recognized as the leader in informational technologies and optics. ITMO University celebrates its 120th anniversary in 2020. Today ITMO University is one of the most well-known, fashionable and popular universities in Russia. The mission of ITMO University is to open up opportunities for the harmonious development of a competitive personality and inspire to solve global problems. The strategic goal of ITMO University: the generation of new knowledge, markets, businesses and human navigation in the world of information, providing a balance of physical and virtual realities. During the last decade ITMO University's programming team was five times the world champion in the ACM International Collegiate Programming Contest [5].

In education, much attention is paid to:

- digital culture and digital ethics, forming competencies and skills necessary for life and work in the digital world; students are taught to work with big data, with artificial intelligence technologies, realizing their role in solving socially significant problems;
- entrepreneurial culture and competencies to respond to uncertainties and challenges of the external environment and solve non-standard problems; students are taught to see positive experiences in failures and not be afraid to take risks, going beyond the limits of template decisions; we develop creativity and enterprise;
- analytical, critical and systemic thinking, necessary for navigating the world of information and highlighting the main from the multitude, for critical understanding of reality and recognition of differences in its physical and virtual manifestations.

Therefore, the goal of ITMO University is to help students become a high-class and advanced programmer, scientist, engineer, businessman, choose the profession of the future at the junction of new directions.

ITMO University has a unique scientific and educational profile: information technology, robotics and photonics, their convergence.

ITMO University is the world's only seven-time champion of the ACM ICPC International Collegiate Programming Contest [6]. Winner of the international programming competitions Google Code Jam, Facebook Hacker Cup, Yandex.Algorithm and others. In the field of Cyberphysical systems ITMO University has three-time champions of the World Robot Olympiad (WRO), winners and finalists of international and national, competitions in robotics - Robocup, Robotex, Robofest and computer security – CTF.

Currently, ITMO University is in the TOP-100 of the world's best IT universities in the Times Higher Education Computer Science ranking (71st place); TOP-400 in THE Engineering and Technology; 436th place in QS WUR, 76-100th place in the ARWU by Subject Automation & Control, 201-250th place in QS WUR by Subject Electrical & Electronic Engineering.

Currently, 15,000 students are studying at the university. These are bachelor's students (ca 6700 students), specialists (ca 300 students), master's students (ca 5100 students) and PhDs (ca 900 students). ITMO University is one of the few universities in Russia who is given the right to independently develop and approve educational standards.

Every year the number of applicants to the University for master's programs is significantly increasing (Fig.3). In 2019 67% of them did not study at ITMO previously – from 35 countries 321 universities.

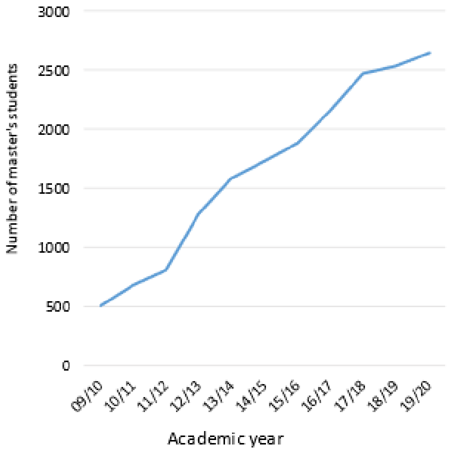

Fig.3. Number of master students at ITMO University

Most of the master's degree programs are in IT and engineering, business fields of study, as shown in Fig.4. To promote and increase the efficiency of academic and scientific activity of Master and PhD students and to diversify research and development in ITMO University, eScience Research Institute was created in 2007 [5].

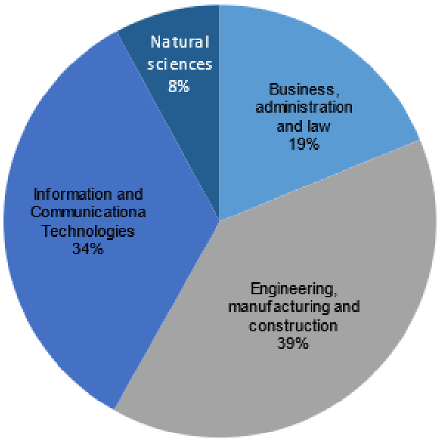

Fig.4. Aggregated indicators by master studies at ITMO University for admission 2019/20

III. COLLABORATION

Strategically, TalTech strives to internationalise its educational activities and build ties with knowledge institutions in Russia - the region that has a long history of strong Basic Science, excellent mathematicians and a rich pool of young research talent. TalTech [1], the only technological university in Estonia, is the flagship of Estonian engineering and technology education. Here, the synergy between different fields (technological, natural, exact, economic and health sciences) is created and new ideas are born. TalTech strives to become one of the leading technological universities in the Baltic Sea region.

What makes ITMO[2] a desirable partner for TalTech is the fact that ITMO is one of the best engineering schools in Russia. Unlike many other Russian universities, ITMO has a broad range of courses taught by professors with worldwide recognition in English, which makes it possible for TalTech to set up a high-quality exchange scheme - develop joint research projects and exchange students at Master's and PhD levels.

In 2015, representatives of TalTech participated in ITMO International Days and had high-level meetings between the university managers. In 2017 and 2018, ITMO's students participated in the final round of Robotex - the largest robotics competition in Europe organized by TalTech and the University of Tartu. In 2017, ITMO team had won the first prize of the competition.

In terms of joint curricula development, TalTech and ITMO have been working on an interdisciplinary educational module "Internet of Things". During 2016-2019, this project

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[1] https://taltech.ee/en/

[2] https://en.itmo.ru/en/

has been supported by the grant Erasmus+ Strategic Partnership for Higher Education (http://iot-open.eu). Thanks to the long-term cooperation, the partner departments have made necessary adjustments to the curricular within their Master's degree programmes delivered in English, which makes the exchange of students between the programmes in the two universities possible.

What is also important for cooperation between universities the number of common research works is growing. According to official statistic by Estonian Ministry of Education and Research number of joint publications with foreign authors is increasing. Fig.5 shows last 15 years statistic of Estonian authors and joint publications with foreign authors. The scientific publications take into account the Estonian publications in the Thomson Reuters Web of Science (SCI-EXPANDED, SSCI, A & HCI databases), conference abstracts and corrections are excluded. Collaborative publications take into account all publication types. Only Estonian authors mean those publications which have been written only in co-operation with Estonian authors.

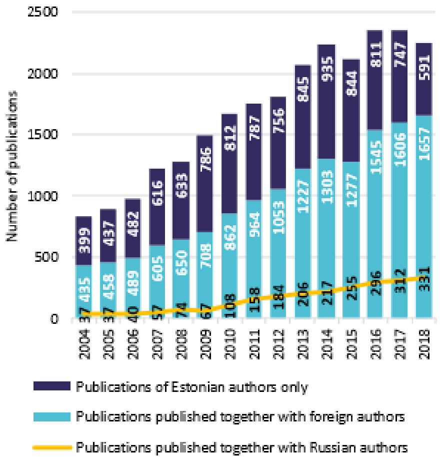

Fig. 5. Number of publications of Estonian authors and joint publications

IV. DOUBLE DEGREE PROGRAMM

The double degree Program is a two-year Master's program of 120 ECTS credit points. Its structure and content (Table I and Table II) will meet the requirements that both TalTech and ITMO University have established for their master's programs, in accordance with the government standards. Development and approval of the double degree Program take hold by the parties in accordance with the procedures established by them. The study process under the double degree program has to be carried out in accordance with the jointly approved study plan before the mobility of the student.

Both partners have committed to taking on clearly defined responsibilities. The sending institution nominates students/staff based on a transparent selection procedure. The criteria for the students are based on grades, motivation and knowledge of the English language. The host institution has the right to examine the quality of the students (eg. by a skype interview), and to reject the candidacy if they think the student does not fit the required profile. In that case the sending institution has the right to propose another student. The staff will be selected on who is the most beneficial for the purpose of this particular mobility. Once the nominations have been accepted, the host institution will provide information to the students/staff on insurance and it will offer pre-departure guidance. It will also offer visa support and assistance in finding accommodation. At TalTech, the practical support will be divided between the specialized central units (accommodation, insurance, visa support, etc) and the Faculties. TalTech pays the scholarships to all grantees and reports on the mobilities in the Mobility Tool+.

The concerned TalTech's Faculties will inform their students about this mobility project through its normal communication channels: the website, information sessions, and emails. Individual lecturers who are involved in this mobility will also address individual students who might benefit from this mobility. ITMO will assist visiting staff and students with finding accommodation, enrolling into courses, and obtaining necessary insurances. Medical, accident, travel, repatriation and civil liability insurances will remain the responsibility of visiting scholars and students. Visa invitation letters will be provided to visiting staff and students by ITMO's Visa Department. In the framework of the project, all efforts, responsibilities, and the budget will be distributed as equally as possible taking into account differences in hourly rates of staff members. Organisational Support grant will be split equally between the two universities.

In addition to an existing Cooperation Agreement signed by the Higher Education Institutions (HEIs) in December 2017, both parties will sign a new Inter-Institutional Agreement (IIA), in which they will agree that a merit-based selection of participants will be organised at both HEIs, it will be supervised by the International Student Coordinator from the School of Engineering; all exchange students will pay fees only to their home universities in accordance with their regulations; all academic credits obtained during the credit mobility exchange project at the host HEIs will be recognized by the home HEIs upon return of each student; all participating staff members will remain employed and paid by their home universities through the project lifetime; for monitoring purposes, HEIs' reports will be provided in the EU's Mobility Tool+ on a monthly basis; English language will be the language of instruction in both HEIs, however the HEIs will be ready to provide complementary language courses upon students' request; a common procedure for the recognition and transfer of credits is established between HEIs.

Measuring learning outcomes of the credit mobility project: students will be required to submit a written report after the conclusion of the project to their supervisors at both host and home universities; students will be asked to fill out questionnaires at mid-point and at the conclusion of their semester abroad to evaluate the quality of their mobility experience, including learning outcomes, on-site experience, engagement with peers and staff, accommodation. This will help the institutions to evaluate the quality of the project implementation and make necessary improvements, if required, during the project. Upon their return home, students will go through a re-entry orientation and will be encouraged to contribute their new skills in their learning environment as well as share their experience through university's publications, website and social media.

V. Conclusions and Discussions

Nowadays a number of universities encourage opening of internationally attractive study programmes taught in English, in particular at master's level, and study programmes, the graduates of which will receive the graduation certifcates of several partner universities (double degrees).

The opening of attractive international study programs taught in English, in particular at the master's level, graduates of which receive double diplomas from several partner universities, can increase the competitiveness of engineering education in Russia and Estonia, educating graduates who have skills and abilities from different fields and are able to use these skills to solve specific tasks of real life. This article describes the educational cooperation of the two largest universities in Russia and Estonia in the field of mechatronics and robotics (industrial robots, technologies for robot/human interaction, unmanned vehicles, service robotics, etc). The features that laid the foundation of this cooperation, as well as the features and advantages of this double educational program are shown. These features include:

- two diplomas from the leaders of engineering education in Russia and Estonia for 2 years provide world-wide recognition of education in mechatronics and robotics;
- one of the best master's programs to prepare an engineer of international level for a successful career in the global world;
- international teaching staff of international qualifications;
- study in Estonia and modern teaching methods;
- talented and ambitious students;
- a unique university international communication environment for students, teachers, researchers;
- external exams provide an independent double procedure for assessing students' knowledge and the highest international quality standards;
- bright, rich student communication, ideas, initiatives student life;
- graduates successfully withstand international competition, both when entering the best foreign universities and when hiring;
- a variety of forms of financial support provide the best applicants and students with access to the program, regardless of the income of their families.

After 5 years of activities of the full-time double degree Program in Mechatronics and Robotics between TalTech and ITMO University more than twenty unique international mechatronics experts have been trained to meet the rapidly changing global labour market based on a synthesis of scientific and professional knowledge and experience of universities partners.

The experience recieved in implementing this double degree Program shows that the Program requires continuous monitoring, renewal and updating not only the content of the disciplines, but also the educational technologies used. Due to mutual responsibility, the quality of education increases, which, in turn, increases the status of the program and the competitiveness of partner universities as a whole.

Acknowledgment

Authors thanks all contributing partners, particularly Mart Tamre (TalTech) and Svetlana Perepelkina (ITMO).

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TABLE I. Curriculum for students from TalTech who Apply to go to ITMO University

Semester	Course title	Number of credits	University
1	MLE0010 Estonian Language and Culture*	6	TalTech
	MLI0010 English for Science and research*	6	
	IAS0430 Microprocessor Systems (obligatory course)	6	
	EEM0090 Mechatronics Systems Modeling and Control (obligatory course)	6	
	IAS0065 Control Instrumentation (obligatory course))	6	
	IAS0410 Object Oriented Programming**	6	
	IEE1720 Data Acquisition Means and Methods**	6	
	IEE1550 Electronics**	6	
	EEM0020 Dynamics of Robots and Machines**	6	
2	TMJ3300 Entrepreneurship and Business Planning (obligatory course))	6	TalTech
	EEM0080 Advanced Robotics (obligatory course)	6	
	IEP1010 Prototyping - project	6	
	UTT0110 Mechatronics and smart systems - project	6	
	EEM0050 Industrial Internship	6	
	IHB0160 Biomedical Sensors	6	
	EIS4080 Fundamentals of Sustainable Energy Engineering	6	
	IAS0060 Robotics	6	
	IAS0031 Process Modeling and Identification	6	
3	Optimal control	3	ITMO
	Control of four-wheel drive robots	3	
	Programming control systems	3	
	Modeling and control of electromechanical systems	3	
	Biomechatronics and biomimetics	6	
	Man-machine interface	3	
	Robot programming	3	
	Design of mechatronic and robotic systems	3	
	Machine vision	3	
	Programming industrial controllers	3	
	Research work	7	
4	Engineering practice	15	ITMO/ TalTech
	Undergraduate practice	9	
	Defense of master's thesis	6	

* at least 6 ECTS must be selected
** at least 18 ECTS must be selected

TABLE II. Curriculum for students from ITMO who Apply to go to TalTech University

Semester	Course title	Number of credits	University
1	University-wide discipline of a world outlook module (Creative Technologies; Project Management Methodology; Thinking)	4	ITMO
	Elective discipline Soft Skills (Negotiations, conflict management and techniques of influence; Emotional intelligence; Business and scientific ethics, organization of scientific research; Personal effectiveness and time management; Internationalization of scientific research; Effective team management)	4	
	Foreign language in professional activities	2	
	Data processing and analysis	3	
	CAD systems	3	
	Dynamics of robotic systems	3	
	Research work	11	
2	Foreign language in professional activities	2	ITMO
	Applied Artificial Intelligence	3	
	Cyber-physical systems and technologies	3	
	Modeling and control of robotic systems	3	
	Design of biomechatronic systems	3	
	Robot Sensing Systems	3	
	Modeling and control in mechatronic systems	3	
	CAD systems	3	
	Research work	7	
3	EEM0110 Mechatronics Master Seminar	6	TalTech/ ITMO
	IAS0051 Applied Data Communication	6	
	EEM0040 Machine Vision and control	6	
	IAS0023 Intelligent Control Systems	6	
	EMT8130 Advanced Manufacturing Planning and Control Systems	6	
	IEE1630 Networks of Smart Things	6	
	Engineering practice	6	
4	Engineering practice	15	ITMO/ TalTech
	Undergraduate practice	9	
	Defense of master's thesis	6	

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Effect of Bearing Faults on Vibration Spectrum of BLDC Motor

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***Abstract*— The topic of this paper is the brushless DC motors' bearing faults. Such motors have been gaining popularity during the past years due to the specific nature of the usage of the machines. Bearing faults are the most common failures emerging in the machines. The paper presents the most common bearing fault types, related to brushless DC machines. In addition, it presents the case study, where these faults are implemented to healthy bearings, in order to further test the impact on machine performance. Laboratory experiments of the setup with healthy as well as faulty bearings are explained and presented. Possibilities of monitoring and diagnostics, as well as the necessity of further study, have been pointed out.**

***Keywords*—ball bearings, brushless motors, fault diagnosis, vibrations**

I. INTRODUCTION

Brushless DC (BLDC) motors have gained wide attention in the electrical machine industry during the last decades. As there are no brushes used for magnetic field creation in those machines, the operation of the BLDC motors is more reliable. Also, brushless construction leads to reducing the overall dimensions of the motor. The combination of permanent magnets and power electronics allows generating more power. A three-phase BLDC motor is shown in Fig. 1.

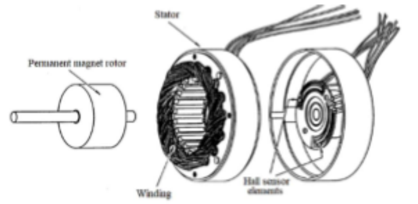

Fig. 1. Disassembled view of a BLDC motor [1]

The operating principle of a BLDC motor is based on the force interaction between the permanent magnet and the electromagnet. The coil energizes and becomes an electromagnet when DC power is applied to it. For sequential energizing of the coils, generally, Hall-effect sensors embedded into the stator are used.

This branch of the industry develops constantly and during the last years, the researchers have found many options on how to improve the reliability and increase the efficiency of the BLDC motors. Many works related to diverse design and analysis methods of electrical machines can be found in the literature. The authors in [2] present and compare different control methods for BLDC motors, such as PI controller, Fuzzy Logic controller, hybrid (PI controller and Fuzzy Logic) and Grey Wolf Optimization (GWO) algorithm.

The BLDC motor is a perceptible trend in transportation applications, particularly in electrical scooters, bicycles, airplanes, boats, etc. The BLDC motors meet most of the requirements for electrical vehicles, such as high power density and starting torque, high cruising speed, and reliability, noise-free and minimum maintenance [3]. Nowadays, this industry develops rapidly. The researchers in [4] present a prototype of the electrical machine with improved energetic performances, which was used for electrical scooter application. Besides, authors in [5] introduce PID-Fuzzy speed-control design for BLDC motors in dynamic electric vehicles to improve steady-state performance.

Additionally, the given type of motors has gained wide attention in different domestic applications. The researchers in [6] propose improvements of the new structure of a BLDC motor for the ceiling fan, which can save at least 50% of energy, compared to the conventional fan based on the induction motor. In [7] the starting characteristics of the plunger pump hydraulic system driven by BLDC motor were analyzed, where the speed of motor and pressure of the hydraulic system were studied. While the authors in [8] present a reliable water pumping based on the solar PV fed BLDC motor drive through a PV-utility grid interface.

Because the operation of BLDC motors is controlled electronically, the BLDC motors overcome problems related to sparking, which makes the machines suitable for the application, where sparks could be a critical factor, for example, in dangerously explosive environments. The researchers in [9] present the comparison of the slotted and slotless stator core design for BLDC motors in the oil and gas industry. While the authors in [10] outline the designs and the experience of the applications of special brushless synchronous motors for a special use in oilfield pumps.

This paper deals with common fault types of BLDC motor bearings. The main core of this work is to present a study of fault diagnostic and monitoring possibilities for BLDC motors, implementing the most spread types of bearing failures.

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II. COMMON BEARING FAULTS IN BLDC MOTORS

The faults that occur in BLDC motors can be divided into three main groups [11]:

- mechanical faults (bearings and eccentricity),
- electrical faults (drive and winding failures),
- magnetic faults (demagnetization).

Within the framework of the given paper, the typical and the most spread mechanical faults related to BLDC motors, such as bearings related faults were studied.

A. Material Fatigue

One of the common bearing failures is material fatigue. Fatigue is material weakening caused by the cyclic load. As a result, damage to the material structure is inflicted and the growth of the cracks is rising.

B. Material Corrosion

Differently from fatigue, corrosion is a process between metal and environment, which results in material consumption or dissolution. The corroded bearing will generate additional vibrations due to the products of corrosion that interfere with the balls during the rotation of the shaft [12]. The usage of the bearings in an aggressive environment leads to the more rapidly developing corrosion of the material. The material corrosion can be caused by excessively high or low temperature, humidity or moisture.

C. Bad Lubrication

Lubrication provides a thin coating between the contact surfaces of a bearing to reduce friction and heat. Besides, lubricant facilitates inhibit corrosion on balls and raceways. Bad lubrication can mean either scarce or surplus lubrication. Scarce lubrication can lie in either a small portion of the lubricant or its low viscosity. Surplus grease leads to shaft slipping, which in turn can lead to material corrosion and structural damage. Incorrect lubricant selection can affect bearing operation and its lifespan.

D. Shaft Currents

Another well-detected bearing fault is the shaft currents. Due to the currents, this damage can ideally be detected visually, as it leaves a recognizable print on the bearing surface as shown in Fig. 2.

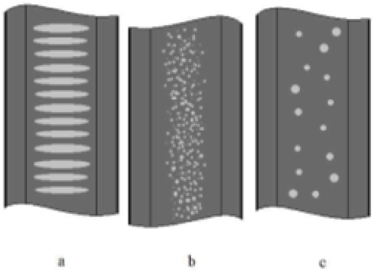

Fig. 2. Effects of shaft currents on bearings track surfaces [13]
a) fluting b) frosting c) pitting

E. Environmental Pollution

As water or other chemically active substances pollute the lubricant, it can become unusable. The properties of the grease become deteriorated. It can lead to bearing corrosion. Additionally, the bearing can be polluted by sand, dust or other abrasive particles, which in turn interferes with bearing operation and leads to scratches, cracks or other structural damage.

III. COMMON DIAGNOSTIC METHODS

Most of the diagnostic techniques, which are based on the signal-processing algorithm, relate to the Fourier series.

a) Fast Fourier transform (FFT): Differently from the Fourier series, FFT is used to process either periodic or aperiodic signals. Depending on the signal nature, FFT can be divided into two categories:

- CTFT (Continuous-time Fourier transform)

$$\text{CTFT } X(\omega)=\int_{n=-\infty}^{\infty} x(t)e^{-j\omega t}dt \qquad (1)$$

where x(t) is a major function in the continuous-time domain.

- DTFT (Discrete-time Fourier transform)

$$\text{DTFT } X(\Omega)=\sum_{n=-\infty}^{\infty} x[n]e^{-j\Omega n} \qquad (2)$$

where x(n) is a major function in the discrete-time domain. The majority of machines related fault diagnostic techniques depend on FFT analysis of its global parameters, such as currents, voltages, speed, torque and vibration signals.

A lot of research work based on FFT can be found in literature, e.g. in [14] authors use current and voltage spectrum analysis of induction motor to detect the broken bars under different operating conditions. The authors in [15] investigated the broken bars by doing the spectrum analysis of a motor's active and reactive currents. The use of FFT in conjunction with Park's vector was investigated in [16] to make ants clustering of frequencies. The authors in [17] used the auto regressive method relying upon DTFT and adaptive Notch filter. The use of band-stop filters to improve the legibility of the spectrum can be found in [18] The authors in [19] used FFT to investigate the broken bars based on mechanical vibrations measurement of induction motor. However, for the implementation of FFT, the signal must be stationary. If the signal is not stationary, the Short-Time Fourier transform can be used.

b) Short-Time Fourier transform (STFT): The idea of this signal processing technique is based on dividing the signal into short segments. After that it could be considered, that the signal in the segment is stationary, making it able to apply the FFT on each of the segments. The equation of the transform is as follows:

$$X\,(m,\omega)=\sum_{n=-\infty}^{\infty} x[n]w\,[m-n]e^{-j\omega n} \qquad (3)$$

where x[n] is the complete signal and w[m-n] is a window that moves and takes a signal segment at a time. Despite advantages,

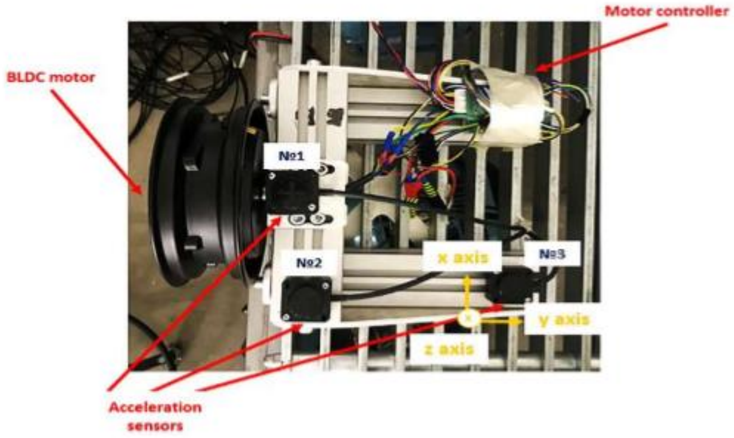

Fig. 3. Experimental setup: BLDC motor, motor controller, acceleration sensors

the STFT also meets the same drawback and limitations as the FFT, such as aliasing, bad resolution, and spectral leakage.

c) Wavelet transform: The main core of the wavelet algorithm lies in taking one of the mother wavelets and comparing it with the original signal. Each mother wavelet has a certain form and a certain frequency. As the mother wavelet is swiped across the measured signal and parameters are recorded, where it is in the best correlation in the frequencies. Then parameters of mother wavelet are changed and the process is repeated until all frequencies are recovered. This technique is quite precise. However, compared to the FFT and STFT, more memory and computational power are required [20].

d) Advanced techniques: As computer science is developing day by day, it is sensible to focus on advanced techniques for the diagnostics of electrical machines. Advanced techniques can give more precise results, but for their implementation, modern and sophisticated technologies are required.

IV. EXPERIMENTAL SETUP DESCRIPTION AND DATA ACQUISITION

The motor used in the experiments is shown in Fig. 3. This is a three-phase BLDC intended for electric scooter application. The test motor has 15 poles and 27 slots. The main electrical parameters of the motor are shown in Table I.

As a measuring tool in the setup, three acceleration sensors with three-axis horizontal mounting (X, Y, Z) were used. The sensors were placed at different distances from the motor. Sensor 1 was placed over the shaft of the motor. Sensor 2 was mounted near to the first sensor but beyond the shaft. The last, sensor 3, was placed on the most distant edge from the motor. Within the framework of given research, the measuring results were taken from the acceleration sensor 1, where the noise and

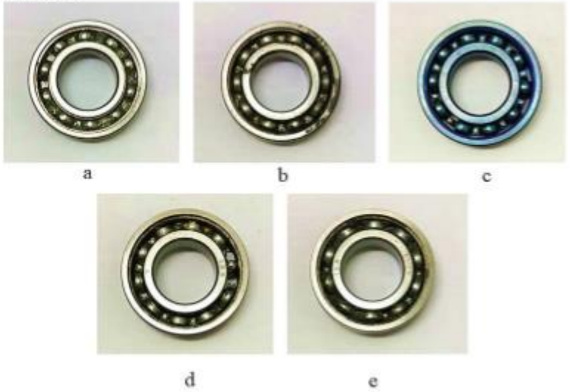

Fig. 4. Bearings used in the experiment
a) Healthy bearing b) Corroded bearing c) Bearing tempered at 300°C d) Bearing with damaged separator e) Contaminated bearing

vibrations are higher and more tangible due to the vicinity of the motor shaft.

TABLE I. Motor Performance Parameters

Parameter	*Data*	*Unit*
Rated voltage	54	V
Rated rotating speed	600±10	rpm
Rated current	8±0.5	A
No-load current	≤1	A
Rated power	350	W

In the motor, ball bearings (type 16003-2RS) with dimensions 17 x 35 x 8 mm were used. As the given motor is been used in transportation and as shown in Fig. 4, five typical bearing failures were chosen, which can occur during the usage of the electric scooter.

a) Healthy bearing – new bearing without modifications,
b) Corroded bearing – bearing, which was placed into an aggressive alkaline environment and after some time was tested with obvious sign of corrosion,
c) Tempered bearing – bearing, which was heated up to the temperature 300°C,
d) Bearing with the damaged separator,
e) Contaminated bearing.

Each of faulty bearings gives its certain vibration pattern during the motor operation that can be compared to the vibration signal of the healthy bearing. As the signal is stationary and the no-load motor has been rotating with maximum constant speed, according to the previously discussed diagnostic methods, FFT was chosen to analyze the results. For more precise and accurate data processing, wavelet transforms analysis or one of the advanced techniques could have also been used. However, it will lead to complicated mathematical models and more computational data requirements.

As a data acquisition tool, the measurement of software OXYGEN was used in the experiments. This software allows acquiring data, recording the measurements and analyzing the results. Additionally, OXYGEN software has an analysis module, which allows measuring of the noise and vibration, during the motor operation.

V. Result Analysis

For the result analysis, two comparison methods were chosen: vibration spectrum analysis and FFT analysis. Fig. 5 shows the vibration signals taken from the acceleration sensor in three different axes at the same time. As seen in Fig. 5, the vibration amplitudes of the faulty bearings are much higher in each of the cases. The distinctions in the amplitudes are noticeable in all three axes.

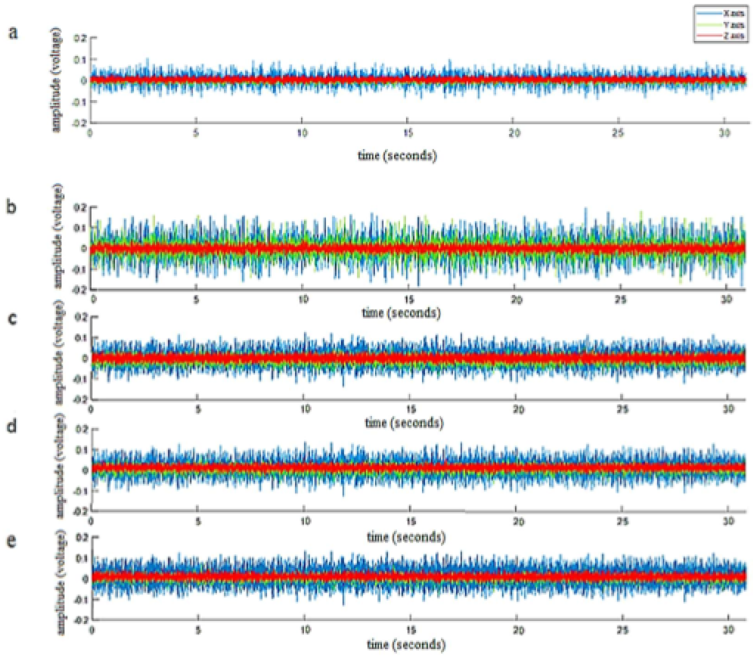

Fig. 5. Vibration signals taken from the acceleration sensor 1
a) Healthy bearing b) Corroded bearing c) Bearing tempered at 300°C d) Bearing with damaged separator e) Contaminated bearing

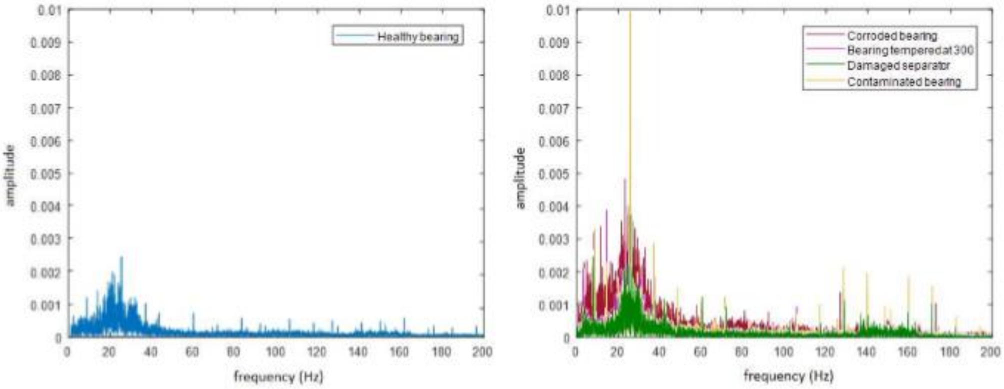

Fig. 6. FFT spectra
a) FFT spectrum of the healthy bearing b) FFT spectra of the faulty bearings

Fig. 6 shows the FFT analysis applied to the acceleration signal. It is visually detectable that each frequency spectrum of the faulty bearings is much higher than in the case of the healthy bearing.

For comparison, one of the perceptible examples was taken. As shown in Fig. 7, compared to the frequency spectrum of the healthy bearing, frequency peaks in the spectrum of the contaminated bearing are much higher.

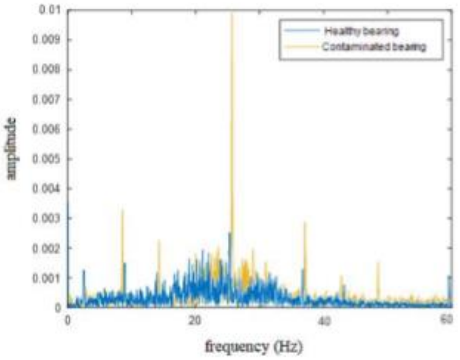

Fig. 7. Comparison of FFT spectra of healthy and contaminated bearing in the range of 0-60 Hz

The main diagnostic feature is the presence of a specific manifestation of bearing defects in the spectrum of vibrational signals. The signs of the defect appear in the spectrum when it grows to such a level that the energy released by it becomes relatively noticeable in the total vibration energy of the bearing and will be presented on the spectrum. For detecting early bearing problems, special attention must be given to the FFT spectrum's and bearing defect frequencies [21]. On the first stages of defect development, there appears a clearly noticeable frequency peak, as it is seen in the case of contaminated bearing in the given research. It makes possible to identify accurately the defective element, especially if the harmonic amplitude is represented on a logarithmic scale.

As the defect develops, the first pair of side harmonics appear in the spectrum on the left and right side of the main peak, as shown in Fig. 8. The more developed the defect is, the more side frequencies near the main peak will appear. The reason behind this phenomenon is that the failed rolling body shifts so much that the adjacent rolling bodies already bear the main load to support the shaft of the mechanism. On this stage, the bearing fulfills its functions and can operate, but requires replacement in a short time because of added stresses.

In the last stage, the bearing has already degraded and ceased to fulfill its functions. Practically, this stage is characterized by appearing of additional harmonics, which have a random nature. This case has not occurred in the given experiment.

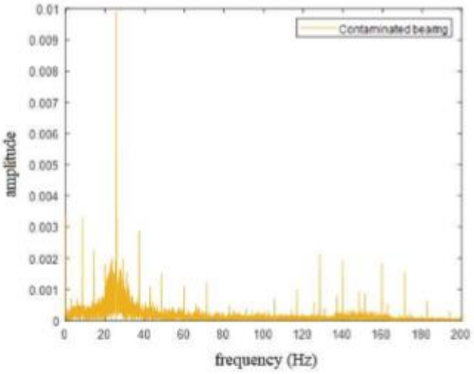

Fig. 8. FFT spectrum of contaminated bearing in the range of 0-200 Hz

VI. CONCLUSION

In this paper, possible bearing faults of BLDC motors are pointed out and the diagnostic techniques are discussed. The faults were inflicted on the bearings on purpose to investigate the failure effect on the vibration spectrum. The faults that have been implemented to the bearings are the typical bearing faults, which can occur in an electric scooter, as the test motor is intended for this application. Experiments with healthy and faulty bearings show that the vibration spectrum can indicate the presence of the damage in the bearing. Measurement results show that when applying FFT to the acceleration signal of faulty bearings, visible harmonic changes, related to the faulty conditions, appear. The research of detecting bearing faults through the vibration spectrum and the implementation of this research into practice will be considered as future work.

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