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Razvoj sklopke s spremenljivim trenjem z uporabo delovnega sredstva

Development of the Variable Friction Clutch Applying the Functional Medium

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Razvit je bil nov funkcionalen material, poznan kot elektro-reološki gel (ERG), ki spreminja površinsko trenje glede na priključeno električno polje. Pričakovano je bilo, da lahko ERG uporabimo kot strojni element za prenos sile kakršna je sklopka, saj se lahko sila trenja na površini ERG električno uravnava. Enostransko vzorčene elektrode, ki so na izolacijsko osnovo urejene izmenično kot anode in katode, so v nedavni študiji o elektro-reološki tekočini (ERT) predlagane, da poenostavijo sestavo električne napeljave. V tej študiji so enostransko vzorčene elektrode uporabljene na ERG. Numerično in eksperimentalno je raziskan vpliv vzorca enostranske elektrode na učinek ERG. Na podlagi rezultatov vrednotenja elektrodnega vzorca, je razvit element sklopke ERG, ki uporablja enostransko elektrodo z optimalnim vzorcem elektrode. Značilka ERG sklopke je eksperimentalno ovrednotena. Sklopka ERG kaže odlično delovanje za statične in dinamične značilke pri prenosu vrtilnega navora. Enota ERG prikazuje odlično delovanje prenosa vrtilnega navora. Spremembe prenesenega vrtilnega navora so širokega območja in enakomerne v odzivu na variacije v priključenem električnem polju.

(Ključne besede: funkcionalni materiali, elektro-reološke tekočine, viskoelastične lastnosti, torne sklopke)

A new functional material known as electro-rheological gel (ERG) that shows variable surface friction according to an applied electric field has been developed. It was expected that ERG could be applied to a machine element to transfer force such as a clutch, because the frictional force of an ERG surface can be controlled electrically. The one-sided patterned electrodes, which arrange anode and cathode alternately on the insulating base, are proposed in a recent study of electro-rheological fluid (ERF) to simplify the structure of the wiring. In this study, one-sided patterned electrodes are applied to an ERG, and the influence of the pattern of the one-sided electrode on the ERG effect is numerically and experimentally investigated. Based on the results of the electrode pattern evaluation, an ERG clutch element, using the one-sided electrodes with an optimum electrode pattern, is developed and the performance of the ERG clutch is experimentally evaluated. The ERG clutch shows excellent performance for static and dynamic characteristics in torque transfer, and an ERG clutch unit shows excellent performance for torque transfer. The transferred torque changes widely and smoothly in response to the variation of the applied electric field.

(Keywords: functional materials, ER fluids, viscoelastic properties, friction clutch)

0 UVOD

Elektro-reološka tekočina (ERT) ([1] do [4]) je vrsta funkcionalne tekočine z viskoelastičnimi lastnostmi, ki se spreminjajo z intenzivnostjo priključenega električnega polja. Ob priključitvi visokega električnega polja (npr.: 1 kV/mm) delci, potopljeni v osnovno olje, težijo k oblikovanju verig, imenovanih grozdi [1]. To ovira prosti pretok osnovnega olja, kar povzroči strižne napetosti in

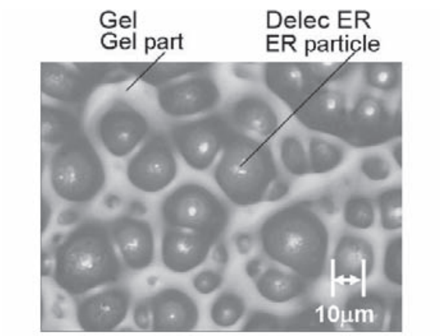
0 INTRODUCTION

Electro-rheological fluid (ERF) ([1] to [4]) is one type of functional fluid with viscoelastic properties that vary with the intensity of an applied electric field. When a high electric field (e.g., 1 kV/mm) is applied, the particles suspended in the base oil tend to form chains called clusters [1]. This inhibits the free flow of the base oil, causing the shear yield stress and the apparent viscosity to očitno povečanje viskoznosti. Lastnosti ERT so bile izkoriščene za nadzor delovanja strojnih elementov. ERT so bile uporabljene v strojnih elementih kot so spremenljivi blažilniki in sklopke ([5] in [6]). Vseeno pa imajo ERT pomanjkljivosti, namreč usedanje delcev ER in zahtevajo tesnilni mehanizem. Usedanje delcev ER zmanjšuje učinke ER in se odziva v majhni stabilnosti naprave ER. Z namenom obvladati usedanje in tako izboljšati delovanje naprav ERT smo s strjevanjem ERT razvili nov funkcionalni material imenovan elektro-reološki gel (ERG) ([7] do [11]). Razviti ERG ni tekočina, temveč trden material, podoben gumi. ERG, ki je sestavljen iz delcev ER in silikonskega gela, spreminja površinsko trenje glede na priključeno električno polje. Ta značilnost se imenuje učinek ERG.

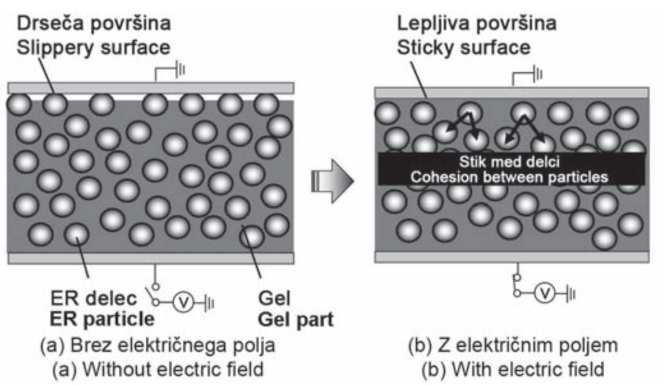
Učinek ER ERT izvira iz lastnosti, da delci ER, potopljeni v osnovno olje, v navzočnosti električnega polja oblikujejo verigo imenovano grozd. Po drugi strani se mehanizem učinka ERG pojavi zaradi sprememb v stičnih razmerah na meji med elektrodo in ERG kot odziv na spremembo jakosti električnega polja [11]. ERG je sestavljen iz delcev ER in silikonskega gela, kakor je prikazano na sliki 1. Mehanizem spremembe v površinskem trenju in adhezija sta ponazorjena na sliki 2. Začetno stanje sendvičev ERG med parom elektrod je prikazano na sliki 2(a). Strižna sila med zgornjo elektrodo in ERG je v odsotnosti električnega polja zelo majhna, ker je zgornja elektroda podprta z drsečimi delci ER, ki molijo iz površine gela. V primeru močnega električnega polja pa v nasprotju, zgornja elektroda ustvari stik z lepljivo površino gela, ker se plavajoči delci umaknejo v gel, kakor

increase. The properties of ERFs have been exploited to control the performance of machine elements, and ERFs have been applied to machine elements such as variable dampers and clutches ([5] and [6]). However, ERFs have disadvantages, namely, the sedimentation of the ER particles and the requirement for a seal mechanism. The sedimentation of ER particles reduces the ER effects and results in the poor stability of ER devices. In order to suppress the sedimentation and thereby improve the performance of ERF devices, we developed a new functional material called electro-rheological gel (ERG) ([7] to [11]) by gelling an ERF. The developed ERG is not a fluid but a solid material like rubber. The ERG, which is composed of ER particles and silicone gel, varies its surface friction according to an applied electric field. This characteristic is called the ERG effect.

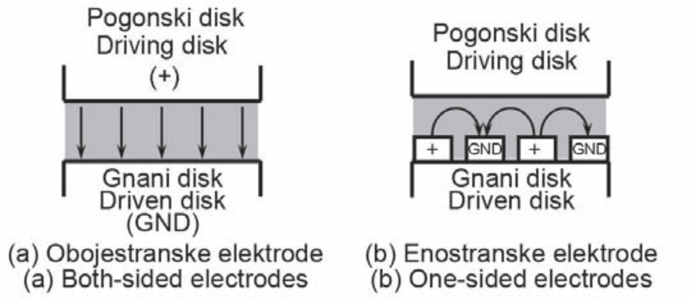
The ER effect of ERFs originates from the fact that the ER particles suspended in the base oil form a chain called a cluster in the presence of an electric field. On the other hand, the mechanism for ERG effect is due to the changes in the contact conditions at the interface between the electrode and ERG, in response to a change in the intensity of the electric field [11]. The ERG is composed of ER particles and silicone gel, as shown in Fig. 1. The mechanism for the change in the surface friction and adhesion is illustrated in Fig. 2. The initial state of the ERG, sandwiched between a pair of electrodes, is shown in Fig. 2(a). The shear force between the upper electrode and the ERG is very low in the absence of an electric field because the upper electrode is supported by slippery ER particles protruding from the gel's surface. In contrast, the upper electrode makes contact with the sticky gel surface in the presence of a high electric field because the protruding particles retract into the



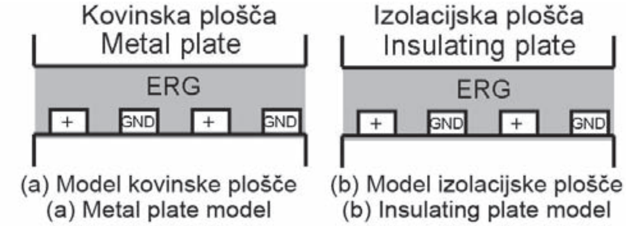
Sl. 1 *Površina ERG*
Fig. 1. *Surface of the ERG*



Sl. 2. *Mehanizem učinka ERG*
Fig. 2. *Mechanism of ERG effect*



Sl. 3. *Osnutek obojestranskih in enostranskih elektrod*
Fig. 3. *Concept of both-sided electrodes and one-sided electrodes*



Sl. 4. *Dva tipa modelov*
Fig. 4. *Two types of models*

je prikazano na sliki 2(b). Tako se zaradi adhezijskih sil gela, ki splava nad površino ERG, poveča strižna sila. Pričakuje se, da je ERG lahko uporabljen v napravi za prenos sile, ker je lahko sila trenja površine ERG električno nadzorovana [11].

Pričujoči prispevek predlaga razpored enostranske elektrode z ERG z namenom poenostaviti sestavo žičnih povezav in omogoča uporabo teh funkcionalnih materialov in različnih polj. Slika 3 prikazuje osnutek električnega polja z uporabo razporeda obojestranskih in enostranskih elektrod. V primeru obojestranskih elektrod nastanejo vzporedne električne silnice, kakor prikazuje slika 3(a). Po drugi strani v primeru enostranske elektrode nastanejo zapletene električne silnice. Učinek ER ERT je bil potrjen z uporabo enostranskih elektrod z ERT [12]. V primeru ERG lahko učinek ERG pridobimo z električnim poljem, ki potuje prek ERG, kar je prikazano na sliki 3(b). Sestava je lahko poenostavljena z uporabo enostranske elektrode, ko je ERG uporabljen v napravah z vrtilnim delom, kakršna je sklopka. V tem prispevku je numerično in eksperimentalno raziskan vpliv vzorca enostranske elektrode na učinek ERG. Na temelju rezultatov vrednotenja vzorcev elektrode je bil razvit element sklopke ERG z razporedom enostranske elektrode. Delovanje sklopke ERG je bilo ovrednoteno s preizkusi.

gel, as shown in Fig. 2(b). Therefore, the shear force increases because of adhesive force of the gel emerging at the ERG's surface. It is expected that the ERG could be used in a force-transfer device, because the frictional force of the ERG's surface can be electrically controlled [11].

The present paper proposes that the one-sided electrode configuration is applied to the ERG in order to simplify the wiring structure and enable the application of this functional material in various fields. Figure 3 shows the concept of an electric field using both-sided and one-sided electrode configurations. As shown in Fig. 3(a), parallel lines of electric force are generated for both-sided electrodes. On the other hand, complicated electric lines are generated for the one-sided electrode configuration. The ER effect of the ERF has been confirmed using one-sided electrodes with an ERF [12]. In the case of the ERG, the ERG effect can be obtained when the electric field passes through the ERG, as shown in Fig. 3(b). When the ERG is used in a device with a rotating part, such as a clutch, the structure can be simplified by using the one-sided electrode configuration. In this paper, the relation between the pattern of the one-sided electrodes and the ERG effect is investigated numerically and experimentally. Based on the results of the electrode-pattern evaluation, an ERG clutch element with a one-sided electrode configuration was developed and the performance was evaluated experimentally.

1 ZVEZA MED NASPROTNIM MATERIALOM IN UČINKOM ERG

1.1 Model za numerično analizo

V predhodni študiji je bilo potrjeno, da je učinek ERG močno odvisen od priključenega električnega polja [11]. Električno polje v razporedu enostranske elektrode potuje prek ERG in je zahtevnejše kakor v primeru razporeda obojestranske elektrode. Poleg tega velja, da se porazdelitev električnega polja v ERG izredno spremeni v odvisnosti od lastnosti materiala plošče nasproti enostranske elektrode (nasprotne plošče) in vzorca enostranske elektrode.

Z namenom, da se razišče vpliv lastnosti materiala na porazdelitev električnega polja, je bila izvedena numerična analiza električnega polja za dva tipa modelov, prikazanih na sliki 4; prvi je *model kovinske plošče, drugi pa model izolacijske plošče*. Pri modelu kovinske plošče je za nasprotno ploščo uporabljen kovinski material, ki je električno neozemljen. V drugem primeru, tj. model izolacijske plošče, je za nasprotno ploščo uporabljen izolacijski material. Za numerično analizo je uporabljen ANSYS 9.0.

Model za analizo električnega polja je podrobno ponazorjen na sliki 5. Uporabljen je dvorazsežni model in opravljena je analiza z MKE. Specifična induktivna kapacitivnost ERG in izolacijske plošče iz bakelita so določene na 30,0

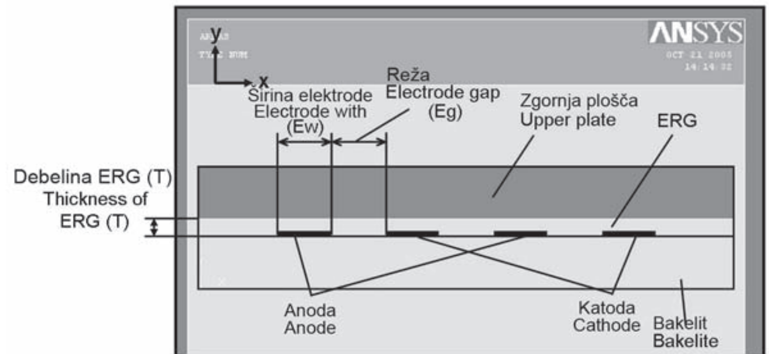
1 RELATION BETWEEN THE OPPOSITE MATERIAL AND THE ERG EFFECT

1.1 Model for numerical analysis

In a past study it was confirmed that the ERG effect relies strongly on the applied electric field [11]. The electric field in a one-sided electrode configuration passes through the ERG, and is more complex than that in a both-sided electrode configuration. In addition, it is considered to remarkably change the electric field distribution in ERG according to material properties of a plate opposite to the one-sided electrodes (opposite plate) and pattern of the one-sided electrodes.

In order to investigate the influence of the material properties on the electric field distribution, a numerical analysis of the electric field was performed for two types of models shown in Fig 4; one is *the metal-plate model* and the other is *the insulating-plate model*. In the metal-plate model, a metallic material is used as the opposite plate, which is electrically floated from ground. On the other hand, in the insulating-plate model, insulating material is used as the opposite plate. ANSYS 9.0 was used for the numerical analyses.

The detail of the model for the electric field analysis is illustrated in Fig. 5. A 2-dimensional model was used and a FEM analysis was carried out. The specific inductive capacity of the ERG and the insulating plate of bakelite was set to 30.0 and 3.0 respectively, which was measured using an



Dielektrična konstanta/Dielectric constant: $\varepsilon_{ERG} = 30$, $\varepsilon_{Bakelit/Bakelite} = 3$
T = 0,3 Ew = 1 mm; Eg = 1 mm
Število elementov/Number of elements: 20580
Analiza stanja zgornje plošče: (a) Kovina: konstanta površina poteciala
Analysis condition of upper plate: (a) Metal: surface potential constant
(b) Izolator: zgornja plošča $\varepsilon = 3$
(b) Insulator: upper plate $\varepsilon = 3$

Sl. 5. *Dejanski model za analizo električnega polja*
Fig. 5. *Actual model for the electric-field analysis*

mm oz. 3,0 mm, in so merjene z metodo elektrodne kapacitivnosti. Debelina ERG je določena na 0,3 mm. Širina elektrode in reža med njimi je 1,0 mm. Istosmerna napetost 900 V je priključena na anodo, medtem ko je katoda ozemljena (0 V).

1.2 Vpliv lastnosti materiala nasprotne plošče na porazdelitev električnega polja

Porazdelitev električnega polja v ERG za enostranske elektrode je ponazorjena na sliki 6. Pri modelu kovinske plošče, prikazanem na sliki 6(a), električna silnica nastane pravokotno iz anode do nasprotne kovinske plošče in prav tako iz nasprotne plošče do katode. Potrjeno je, da ima nasprotna kovinska plošča polovico medelektrodnega potenciala, ko je plošča električno neozemljena. V modelu izolacijske plošče, prikazanem na sliki 6(b), električne silnice nastanejo iz anode do katode ukrivljene oblike in gredo tudi skozi izolacijsko nasprotno ploščo. Vseeno pa gre večina električnih silnic vodoravno na površino ERG in ne more vstopiti na nasprotno ploščo pravokotno, ker je specifična induktivna kapaciteta ERG znatno večja od nasprotne plošče.

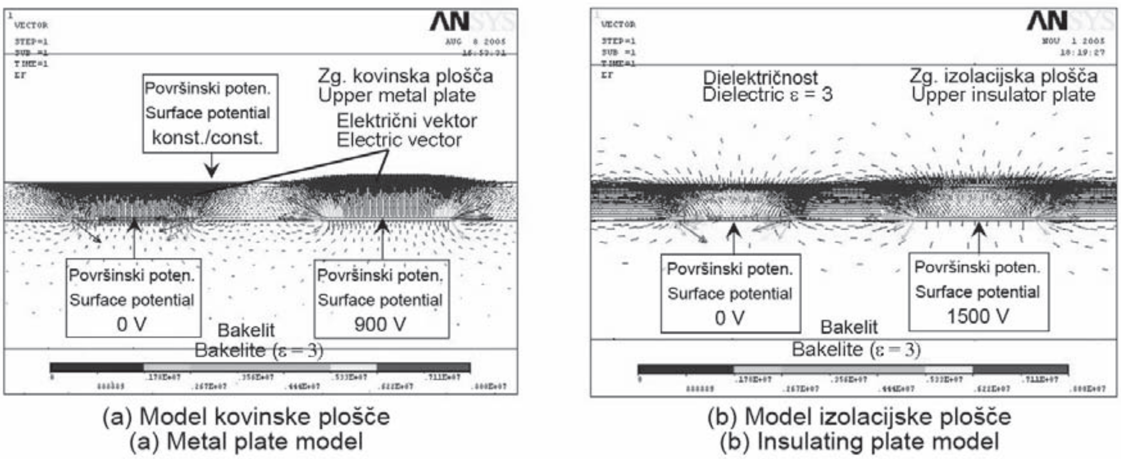
Povprečno električno polje je dobljeno iz rezultatov numerične analize v pravokotni smeri za oba primera modelov, kakor je povzeto v preglednici 1. Domneva se, da je učinek ERG, še posebej komponenta, pravokotna na površino ERG (komponenta y), odvisen od intenzivnosti električnega polja, ker je ta učinek medploskovni pojav med površino ERG in nasprotno ploščo.

electrode-capacitance method. The thickness of the ERG was also set to 0.3 mm. The width and the gap of the electrodes was fixed to 1.0 mm. A DC 900 volts was applied to the anode, while the cathode was connected to ground (0 V).

1.2 The influence of the material property of the opposite plate on the electric-field distribution

The distribution of the electric field in the ERG for the one-sided electrode is illustrated in Fig.6. In the metal-plate model shown in Fig. 6(a), the electric line of force is generated perpendicularly from the anode to the opposite metal plate, and also from the opposite plate to the cathode. It was confirmed that the opposite metal plate had half of the inter-electrode's potential when the plate was electrically floated from ground. In the insulating-plate model, shown in Fig. 6(b), the electric lines of force in the arched shape were generated from the anode to the cathode, and also go thorough the insulating opposite plate. However, most of the electric lines of force go horizontally on the surface of the ERG and cannot enter the opposite plate perpendicularly because the specific inductive capacity of the ERG is set much higher than that of the opposite plate.

From the result of the numerical analysis, the average electric field in the perpendicular direction is obtained in both models, as summarized in Table 1. The ERG effect is supposed to depend on the intensity of the electric field, especially the component perpendicular to the ERG's surface (the y component), because this effect is an interfacial phenomenon



Sl. 6. *Porazdelitev električnega polja za oba modela*
Fig. 6. *Distribution of electric field in each model*

Povprečna intenzivnost električnega polja komponente y na površini ERG v kovinskem modelu je bistveno večja kakor v izolacijskem modelu.

1.3 Preizkusno ovrednotenje učinka ERG

Z namenom ovrednotenja veljavnosti rezultatov numerične analize je učinek ERG za oba modela preizkusno potrjen. Enostranske elektrode so narejene iz plošč za tiskana vezja (TV - PCB). TV se množično uporabljajo v elektroniki in računalniški industriji. Tanke bakrene črte na izolacijski plastični plošči omogočajo povezave med elektronskimi komponentami v obtoku. Enostranske elektrode s postopkom jedkanja preprosto izdelamo z uporabo TV. Enostranske elektrode so oblikovane tako, da je razmik med elektrodami 1 mm. Vsaka elektroda je 1 mm široka s površino elektrode 70×50 mm, kar je prikazano na sliki 7(a). 0,3 mm debela plošča ERG je pritrjena na enostransko elektrodo, kakor je prikazano na sliki 7(b). Osnovno delovanje ERG na enostranski elektrodi je ovrednoteno s preprostim preizkusom, shematično prikazanim na sliki 8. Plošča ERG na enostranski elektrodi je pritrjena na osnovno ploščo in nasprotna plošča je postavljena na ERG ploščo. Nasprotna plošča je aluminijasta oz. bakelitna plošča. Strižno gibanje nasprotne plošče je ustvarjeno z mikrometrskim vijakom z motornim pogonom. Strižna sila je merjena z uporabo obremenilne celice z merilnikom napetosti, ki je pripeta na drsno ploščo. Premik nasprotne plošče je merjen z vrtilnim tokovnim zaznavalom pomika. Obnašanje strižne sile je ovrednoteno s spreminjanjem jakosti električnega polja od 0 do 1,5 kV/mm. Strižna dolžina je nastavljena na 600 μm, medtem ko je strižna hitrost naravnana na 30 μm/s.

Povezava med nastalo strižno napetostjo in spremenljivo jakostjo električnega polja je prikazana na sliki 9, kjer je strižna napetost

between the ERG's surface and the opposite plate. The average electric field intensity of the y component at the surface of the ERG in the metal model is considerably higher than in the insulating model.

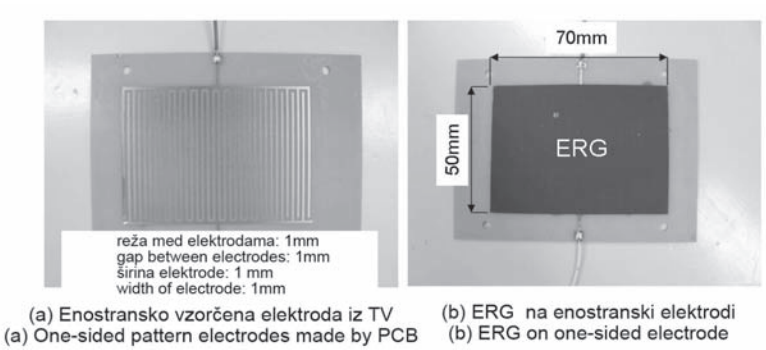
1.3 Experimental evaluation of the ERG effect

In order to evaluate the result of the numerical analysis for its validity, the ERG effect in both models was evaluated experimentally. One-sided electrodes were made from printed circuit boards (PCBs). PCBs are widely used in the electronics and computer industries. Thin copper lines on an insulating plastic board enable the connection between electronic components on the circuit board. One-sided electrodes using PCB plates can be fabricated easily by the process of etching. The one-sided electrode is designed to have a 1-mm gap between the electrodes. Each electrode is 1-mm-wide and the electrode area is 70×50 mm, as shown in Fig. 7(a). A 0.3-mm-thick ERG sheet was molded on the one-sided electrodes as shown in Fig. 7(b). The basic performance of the ERG on a one-sided electrode was evaluated by the simple test schematized in Fig. 8. The ERG sheet on the one-sided electrodes was fixed on the baseplate and the opposite plate was placed on the ERG's sheet. An aluminum plate and a bakelite plate were prepared as the opposite plates. A shear motion was applied to the opposite plate using a micrometer screw with a motor drive. The shear force was measured using a strain-gauge load cell attached to the slider plate. The displacement of the opposite plate was measured using the eddy-current displacement sensor. The behavior of the shear force was evaluated by varying the electric-field intensity from 0 to 1.5 kV/mm. The shear length was set to 600 μm, while the shear speed was adjusted to 30 μm/s.

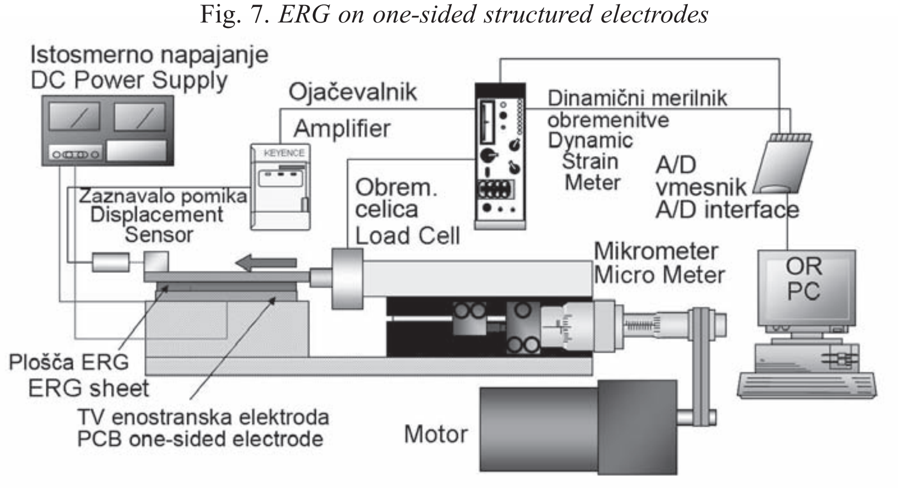
The relationship between the generated shear stress and the variable electric-field intensity is summarized in Fig. 9, where the shear stress is

Preglednica 1. *Povprečno električno polje komponente y [numerično]*
Table 1. *The average electric field of the y component [numerical]*

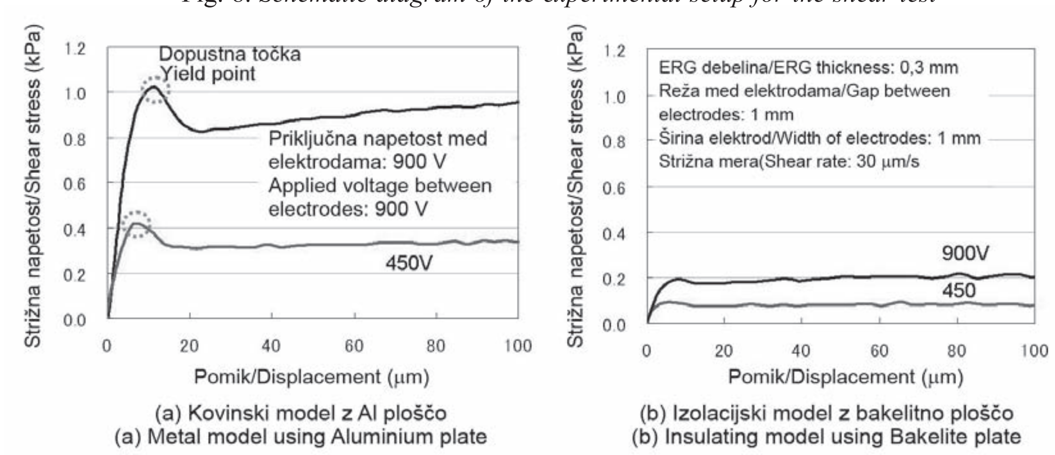
	model kovinske plošče metal plate model	model izolacijske plošče insulating plate model
povprečna jakost električnega polja komponente y [V/mm] average electric field intensity of y component [V/mm]	1000	70



Sl. 7. *ERG na enostransko sestavljeni elektrodi*
Fig. 7. *ERG on one-sided structured electrodes*



Sl. 8. *Shema preizkusa za strižni test*
Fig. 8. *Schematic diagram of the experimental setup for the shear test*

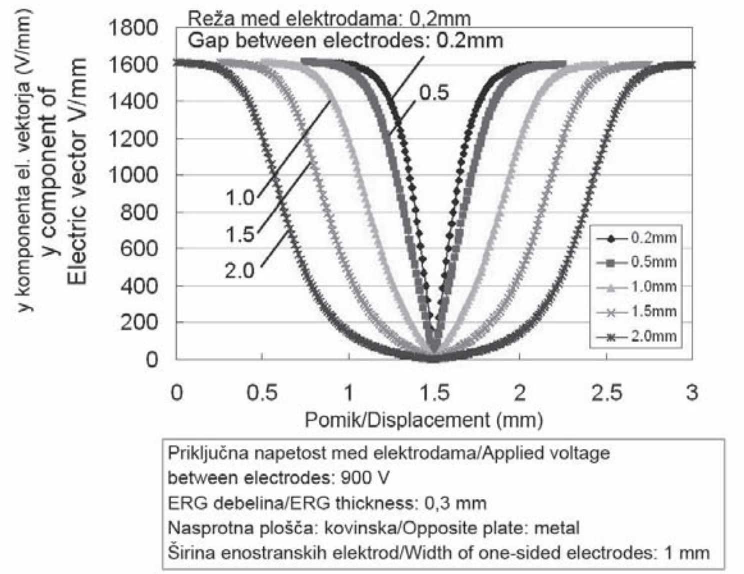


Sl. 9. *Povezava med strižno napetostjo in električnim poljem [s preizkusom]*
Fig. 9. *Relation between the shear stress and electric field [experimental]*

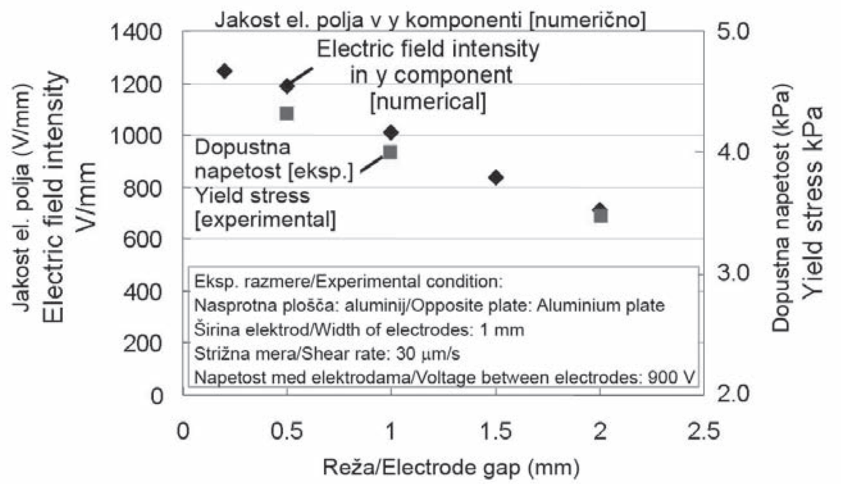
izračunana s količnikom med izmerjeno strižno silo in površino ERG. Razumljivo je, da je učinek ERG ustvarjen v enostranskih elektrodah. Ob premiku nasprotne plošče za vrednost okrog 15 μm plošča ERG popusti. Višje dopustne napetosti so dobljene pod večjimi jakostmi električnega polja. Ustvarjena

calculated by dividing the measured shear force by the surface area of the ERG. Clearly, the ERG effect is generated in one-sided electrodes. When the displacement of the opposite plate exceeds a certain value of about 15μm, the ERG sheet yielded. Higher yield stresses were obtained with higher electric-dopustna napetost je skoraj sorazmerna priključenemu električnemu polju. Ko je priključeno električno polje višje od 2 kV/mm nastane dielektrični zlom. Do dopustne točke se strižna napetost spreminja linearno s pomikom. Nad to točko se strižna napetost le malo poveča. To zaradi zdrsa med površino nasprotne plošče in ploščo ERG. Ob primerjavi kovinskega modela z izolacijskim, je pri kovinskem modelu nastala strižna napetost bistveno večja, kakor v primeru izolacijskega modela pri enaki velikosti priključene napetosti. Zaradi tega je odločeno, da je model s kovinsko ploščo uporaben za element sklopke ERG,

field intensities. The generated yield stress is almost in proportion to the applied electric field. However, when the higher electric field above 2kV/mm was applied, the dielectric breakdown occurred. Up to the yield point, the shear stress varies linearly with displacement. Above the yield point, the shear stress increases only gradually. This is due to the slip between the surface of the opposite plate and the ERG sheet. Compared with the metal model and insulating model, the generated shear stress in the metal-plate model is much higher than in the insulating model under the same applied voltage. Consequently, it is clear that the metal-plate model



Sl. 10. *Porazdelitev y komponente električnega vektorja v primeru različnih rež med elektrodami [numerično]*
Fig. 10. *Distribution of y component of electric vector in case of various electrode gap [numerical]*



Sl. 11. *Razmerje med električnim poljem in dopustno napetostjo kot funkcija reže elektrod*
Fig. 11. *Relation between electric field and yield stress as function of electrode gap*

saj ob priključitvi električnega polja lahko pričakujemo širše spremembe prenesenega vrtilnega navora.

Numerični in preizkusni rezultati kažejo, da je nastala strižna napetost zaradi učinka ERG odvisna od povprečne jakosti električnega polja v smeri komponente y na površino ERG.

2 OBLIKA REŽE ELEKTRODE

2.1 Postopek

Povezava med vzorcem enostranske elektrode in nastalim električnim poljem na površini ERG je raziskana z namenom določiti potrebno obliko za učinkovit vpliv ERG. Numerična analiza je bila izvedena tudi v primeru raziskovanja vpliva reže elektrode na porazdelitev električnega polja v ERG. Numerični model je pokazal enako kakor na sliki 5. Širina elektrode je nespremenjena, 1,0 mm, medtem ko se širina reže spreminja med 0,2 mm in 2,0 mm. Priključen medelektrodni potencial med anodo in katodo je 900 V.

Trije tipi enostranskih elektrod, katerih reže med elektrodami so 0,5, 1,0, 2,0 mm, so bili izdelani. Nastali učinki ERG v vsaki enostranski elektrodi so ovrednoteni s preizkusi pri enaki priključeni napetosti.

2.2 Povezava med režo elektrode in učinkom ERG

Intenzivnost električnega polja komponente y z različnimi režami med elektrodami je bila ovrednotena. Slika 10 prikazuje obnašanje intenzivnosti električnega polja na površini ERG med dvema elektrodama. Intenzivnost električnega polja nekaj nad središčem elektrode (položaj = 0, 3,0) postane velika, ker se intenzivnost električnega polja v sredinski točki med dvema elektrodama zmanjša skoraj na 0 V/mm. Dobljeno razmerje med povprečno vrednostjo električnega polja in režo elektrode je predstavljeno na sliki 11. Z manjšanjem reže elektrode se jakost električnega polja na površini ERG poveča. Strižni test s preizkusno postavitvijo, prikazano na sliki 8, je bil uporabljen tudi za raziskovanje razmerja med dopustno napetostjo in režo elektrode. Aluminijasta plošča je uporabljena za nasprotno ploščo. Preostale preizkusne razmere so enake, kakor so opisane v odstavku 1.3. Potrjeno je, da dopustna strižna

is useful for the ERG clutch element since a wider change of transferred torque with the applied electric field can be expected.

These numerical and experimental results indicate that the generated shear stress due to the ERG effect depends on the average electric field intensity of the y component at the surface of the ERG.

2 DESIGN OF THE ELECTRODE GAP

2.1 Procedure

The relation between the pattern of one-sided electrodes and the generated electric field at the ERG's surface is investigated in order to determine the design necessary to obtain an efficient ERG effect. To investigate the influence of the electrode gap on the distribution of the electric field in the ERG a numerical analysis was also carried out. The numerical model is the same as the one shown in Fig.5. The width of the electrodes was fixed at 1.0 mm, while the gap was varied from 0.2 mm to 2.0 mm. The applied inter-electrode potential between the anode and cathode was 900 V.

Three types of one-sided electrodes, with electrode gaps of 0.5, 1.0, 2.0mm, were prepared and the generated ERG effects in each one-sided electrode under the same applied voltage were evaluated experimentally.

2.2 Relation between the electrode gap and the ERG effect

The electric field intensity of the y component was evaluated for various electrode gaps. Figure 10 shows the behavior of the electric-field intensity on the ERG's surface between the two electrodes. The electric-field intensity just above the center of the electrodes (position=0, 3.0) becomes high while the electric field intensity at the middle point between the two electrode decreases to almost 0 V/mm. The relationship obtained between the average value of the electric field and electrode gap is presented in Fig. 11. As the electrode gap decreases, the electric-field intensity at the ERG's surface increases. To investigate the relation between the yield stress and the electrode gap, the shear test was also carried out using the experimental setup shown in Fig.8. An aluminum plate was used as the opposite plate. Other experimental conditions were the same as described in Section 2.3. It was confirmed that the napetost kaže enako težnjo kakor jakost električnega polja. Ponovljivost numerične analize v tem prispevku je velika.

yield shear stress shows the same tendency as the intensity of the electric field. The repeatability of the numerical analysis in this paper is high.

3 RAZVOJ ENOTE SKLOPKE ERG

3 DEVELOPMENT OF THE ERG CLUTCH UNIT

3.1 Sestava sklopke ERG

Elektroda za predlagano sklopko ERG je razvita na temelju rezultatov numerične analize električnega polja. Sestava enostranske elektrode za sklopko ERG je prikazana na sliki 12 in ima elektrodno režo 0,2 mm in elektrodo širine 1,0 mm. Premer enostranskih elektrod je 30 mm. Slika 13 prikazuje sestavo naprave s sklopko ERG. Sklopka ERG je sestavljena iz dveh osi z diskoma na eni strani. ERG na enostranski elektrodi je povezan z diskom na podrejeni osi. Vneseni vrtilni navor je iz glavne strani prenesen na podrejeno stran prek ERG. Dolžina obeh osi je 50 mm s premerom 12 mm, premer obeh diskov pa je 40 mm. Razmere v stiku med površino ERG in glavnim diskom so pomembne, če želimo dobiti učinkovit vpliv ER. Zaradi tega je na glavni disk vstavljena malo elastična guma, tako da ima glavni disk enakomeren stik z ERG, postavljenim na podrejeni strani. Ko se glavna os vrti z indukcijskim motorjem, je lahko vrtilni navor, ki je prenesen iz glavne strani na podrejeno, spremenjen v odvisnosti od priključenega električnega polja na ERG.

3.1 Structure of the ERG clutch

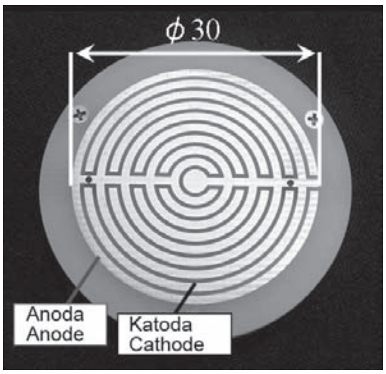
The electrode for the proposed ERG clutch was designed using the results from the numerical analysis of the electric field. The one-sided electrode configuration for the ERG clutch is shown in Fig. 12, and has a 0.2-mm electrode gap and an electrode width of 1.0 mm. The diameter of the one-sided electrodes is 30 mm. Figure 13 illustrates the structure of the ERG clutch device. The ERG clutch is composed of two shafts with the disks on one side. The ERG on the one-sided electrode is set up with the disk of the slave shaft. The input torque is transferred from the master side to the slave side through the ERG. The length and the diameter of the master and slave shafts are 50 mm and 12 mm, respectively, and the diameter of each disk is 40 mm. To obtain an efficient ER effect, the condition of the contact between the ERG's surface and the master disk is important. Thus, a low elastic rubber is inserted at the master disk, so that the master disk has uniform contact with the ERG, placed on the slave side. When the shaft of the master side is rotated by the induction motor, the transferred torque from the master side to the slave side can be changed in response to the applied electric field to the ERG.

3.2 Preizkusna postavitev in postopek

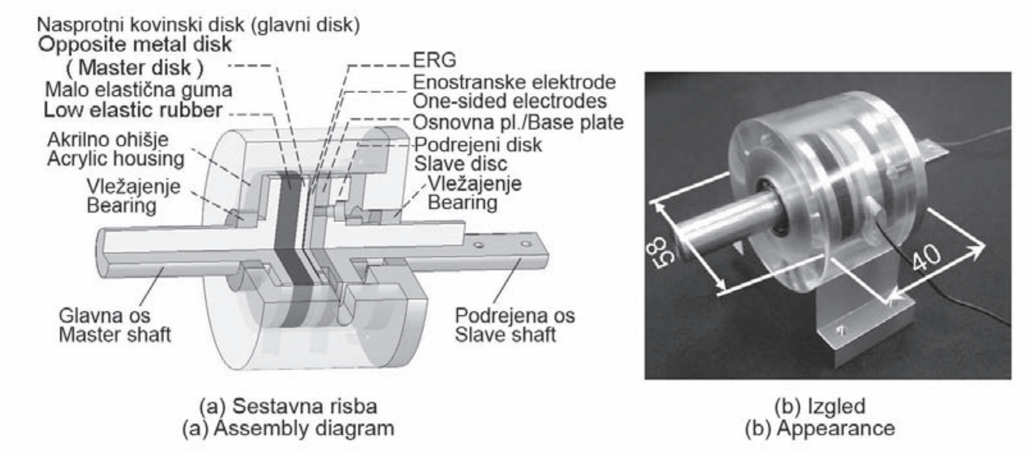
Statična značilka sklopke ERG je vrednotena tako, da je preneseni vrtilni navor merjen ob priključitvi stalne napetosti. Shema

3.2 Experimental setup and procedure

To evaluate the static performance of the ERG clutch, the transferred torque was measured under an applied constant voltage. A schematic of



Sl. 12. *Enostranske elektrode s širino 1mm in režo 0,2 mm*
Fig. 12. *One-sided electrodes with 1mm width and 0.2 mm gap*



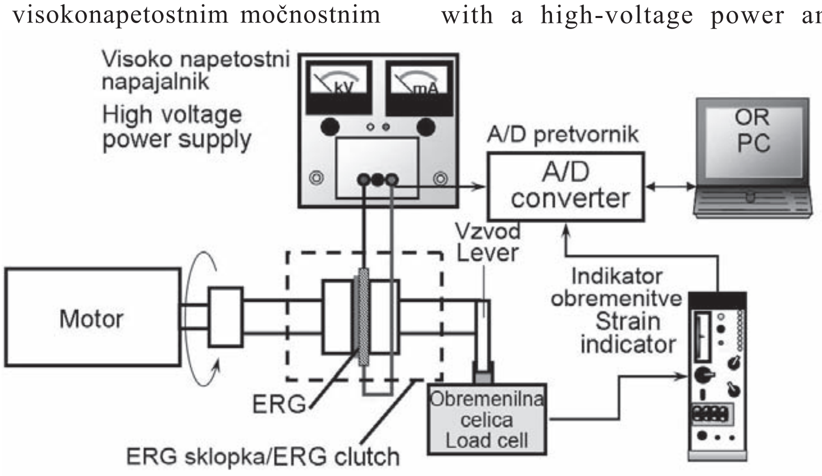
Sl. 13. *Sestava sklopke ERG*
Fig. 13. *Structure of the ERG clutch unit*

preizkusne postavitve je podana na sliki 14. Glavna os je prek spoja povezana z osjo motorja. Vzvod za merjenje vrtilnega navora je pritrjen na podrejeno os in nameščen na obremenilno celico. Ko se glavna os vrti s stalno hitrostjo, je na ERG priključeno električno polje, preneseni vrtilni navor pa je zaznan z obodno silo na koncu vzvoda. Preneseni vrtilni navor lahko izračunamo iz zmnožka zaznane sile in dolžine vzvoda (46,5 mm).

Dinamična značilka naprave za prenos vrtilnega navora s sklopko ERG je prav tako ovrednotena z merjenjem induciranega prenesenega vrtilnega navora ob priključitvi spremenljive napetosti, npr. sinusni ali pravokotni signal vhodne napetosti. Namesto visokonapetostnega vira uporabljenega pri statičnem testu, je bil v tem primeru uporabljen funkcijski generator v kombinaciji z visokonapetostnim močnostnim

the experimental setup used is shown in Fig. 14. The master shaft is connected to a motor shaft through a coupling. The lever used for measuring the torque is attached to the slave shaft, and is set on a load cell. When the master shaft is rotated at constant speed and an electric field is applied to the ERG, the transferred torque is sensed as the tangential force at the top of the lever. The transferred torque can be calculated by multiplying the sensed force by the length of the lever (46.5 mm).

The dynamic performance of the torque-transfer device with the ERG clutch is also evaluated by measuring the induced transferred torque under an applied variable voltage, e.g., a sinus or square wave of the input voltage. Instead of the high-voltage power supply used in the static test, a function generator was used in combination with a high-voltage power amplifier. The



Sl. 14. *Eksperimentalna postavitev za merjenje vrtilnega momenta*
Fig. 14. *Experimental setup for measuring torque*

ojačevalnikom. Preneseni vrtilni navor je merjen z merilnimi lističi obremenilne celice.

3.3 Statična značilka sklopke ERG

Slika 15 prikazuje rezultate statičnega testa, ko je na enostransko elektrodo priključena napetost, ki se zvišuje v korakih po 300 V od 0 do 900 V. Zelo jasna razlika je opažena med vsakim povišanjem napetosti. Višje ko je priključeno električno polje, večji je dobljeni vrtilni navor.

Preizkusni podatki so primerjani s teoretično oceno. Preneseni vrtilni navor s sklopko ERG je določen kot:

transferred torque is measured by a strain-gauge load cell.

3.3 Static performance of the ERG clutch

Figure 15 shows the static test results when the applied voltage to a one-sided electrode is raised in increments of 300 V from 0 to 900 V. A very clear distinction is observed between each voltage step. The higher the applied electric field, the higher the torque obtained.

The experimental data is compared with the theoretical estimate. The transferred torque using an ERG clutch is defined as:

$$T = \int_0^R \tau_y \times 2\pi r \times r \mathrm{d}r \quad (1),$$

kjer je τ_y dopustna napetost ERG in R polmer diska; $\tau_y \approx 6$ kPa pri jakosti električnega polja 1,5 kV/mm pri strižni stopnji 30 μm/s ob uporabi obojestranskih elektrod s polmerom R = 15 mm. V predhodni študiji je bilo razjasnjeno, da je napetost tečenja zaradi učinka ERG ustvarjena sorazmerno s priključenim električnim poljem [11]. Povprečno električno polje na površini ERG znaša 1,25 kV/mm pri priključeni napetosti 900 V na enostranske elektrode z režo 0,2 mm, kakor je prikazano na sliki 11. Tako je izračunana τ_y enaka 4,8 kPa teoretični vrtilni navor *T*, izračunan z enačbo (1), pa približno 0,032 Nm. Ta je manjši od preizkusno merjenega vrtilnega navora. Šteje se, da vrtilna hitrost glavnega diska vpliva na preneseni vrtilni navor. Slika 16 prikazuje zvezo med prenesenim vrtilnim navorom in vrtilno frekvenco glavnega diska ob priključitvi napetosti 900 V. Višja vrtilna frekvenca se kaže v višjih prenosih vrtilnega momenta. Spremenljivka t_y v enačbi (1) je odvisna od jakosti električnega polja na površini ERG in drsne hitrosti (vrtilna hitrost diska sklopke). Vrednost τ_y (= 6 kPa pri 1,5 kV/mm) vstavljena v enačbo (1) je bila veljavna pri zelo majhnih drsnih hitrostih (30 mm/s). Tako je pri zelo majhnih hitrostih (skoraj 0 min^{-1}) na sliki 16 dobljeni teoretični vrtilni moment blizu usklajenosti z izmerjenim.

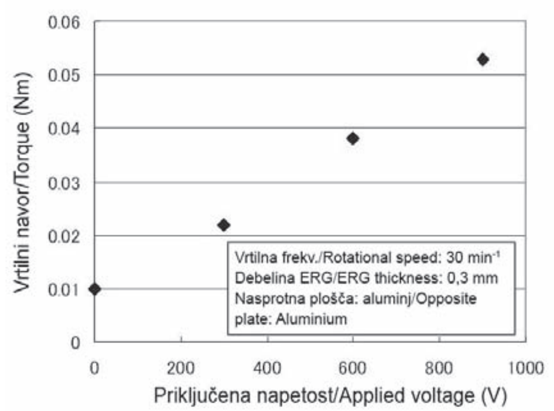
where τ_y and *R* are the ERG yield stress and the disk radius, respectively; $\tau_y \approx 6$ kPa at a 1.5kV/mm electric-field intensity under a 30μm/s shear rate when using the both-sided electrodes and R = 15 mm. In a past study, it was made clear that the yield stress due to ERG effect is generated in proportion to an applied electric field [11]. The average electric field at the surface of the ERG is obtained at 1.25kV/mm at an applied voltage of 900V to the one-sided electrodes with a 0.2-mm gap, as shown in Fig. 11. Therefore, τ_y is calculated as 4.8kPa and the theoretical torque *T* is also calculated using Equation (1) to be roughly 0.032 Nm. This is lower than the experimentally measured torque. It is thought that the rotational speed of the master disk influences the transferred torque. Figure 16 shows the relation between the transferred torque and the rotating speed of the master disk under an applied voltage of 900V. A higher rotating speed results in higher torque transfers. The variable τ_y in Eq. (1) depends on the electric-field intensity at the ERG's surface and sliding speed (the rotational speed of the clutch disc). The value of τ_y (= 6 kPa at 1.5 kV/mm) substituted into Eq. (1) was, however, valid at a very low sliding speed (30 μm/s). Therefore, at a very low speed (almost 0 min^{-1}) in Fig.16, close agreement is obtained between the theoretical torque and the measured one.

3.4 Dinamična značilka sklopke ERG

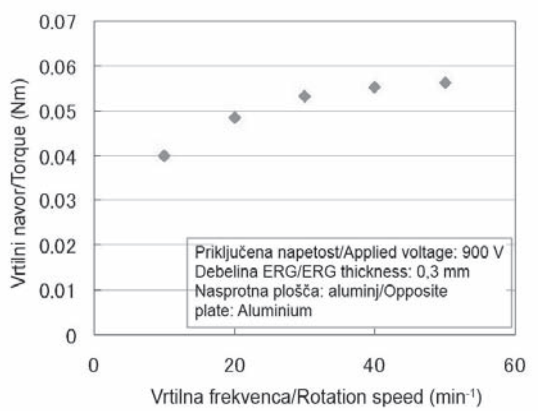
Vrednoten je tudi dinamični odziv prenesenega vrtilnega navora na priključeno napetost. Slika 17 prikazuje rezultate postopnega

3.4 Dynamic performance of the ERG clutch

An evaluation is made for the dynamic response of the transferred torque to the applied voltage. Figure 17 shows the results of the step-



Sl. 15. *Zveza med prenesenim vrtilnim navorom in jakostjo električnega polja [s preizkusi]*
Fig. 15. *Relation between transferred torque and electric field intensity [experimental]*



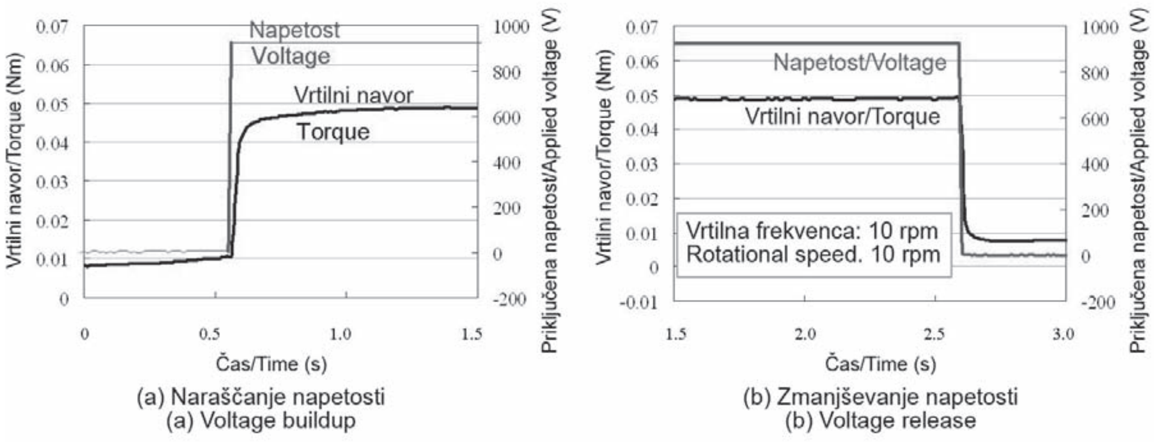
Sl.16. *Zveza med prenesenim vrtilnim navorom in vrtilno frekvenco [s preizkusi]*
Fig. 16. *Relation between transferred torque and rotating speed[experimental]*

odzivnega testa. Čas dviga in padca napetosti sta lahko izračunana z uporabo časovne stalnice. Slika 17(a) prikazuje zvezo med odzivom prenesenega vrtilnega navora in dvigom napetosti, iz katere lahko izračunamo odziv sistema. Celotni odmik časa pri dvigu napetosti znaša 20 ms. Slika 17(b) prikazuje izpis za padec napetosti. Celotni odmik časa pri padcu vrtilnega navora je 16 ms. Odziv učinka ER v ERG na priključeno električno polje je skoraj enak kakor v primeru ERT.

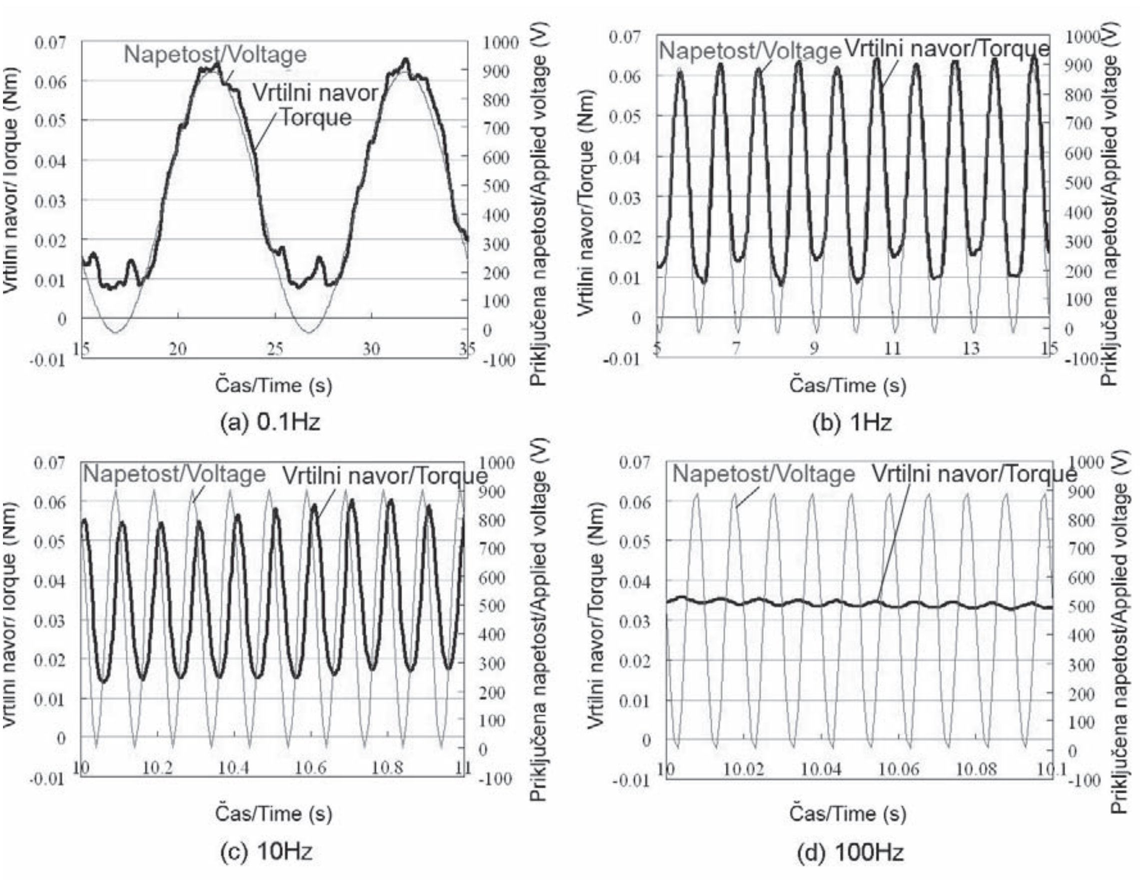
Povezava med jakostjo električnega polja in prenesenim vrtilnim navorom pri priključeni sinusoidni napetosti (V_{maks} = 900 V) in vrtilni frekvenci gnanega motorja 30 min^{-1} je raziskana z namenom določitve frekvenčnih značilnosti prenesenega vrtilnega navora. Slika 18 prikazuje rezultate testa frekvenčnega odziva pri frekvencah

response test. The voltage build-up time and the release time can be calculated using a time constant. Figure 17(a) shows the relationship between the response of the transferred torque and the voltage build-up, from which the system response could be calculated. The total delay in the build-up time is calculated as 20 ms. Figure 17(b) shows a plot of the voltage release. The total delay for the released torque is 16 ms. The response of the ER effect in the ERG to an applied electric field is almost the same as that of an ERF.

To characterize the frequency characteristics of the transferred torque, the relationship between the electric-field intensity and the transferred torque is investigated under an applied sinusoidal voltage (V_{max} = 900 V) at a driven motor rotation speed of 30 min^{-1}. Figure 18 shows the results of the component of electric vector in case of the



Sl. 17. *Rezultat postopnega odzivnega testa [s preizkusi]*
Fig. 17. *Result of step response test [experimental]*



Sl. 18. *Rezultat frekvenčnega odzivnega testa [s preizkusi]*
Fig. 18. *Result of frequency response test [experimental]*

napetosti 0,1; 1,0; 10 in 100 Hz. Razvidno je, da se preneseni vrtilni navor enakomerno spreminja s sinusoidno napetostjo do frekvence napetosti 10 Hz. Pri 100 Hz se preneseni vrtilni navor le malo spreminja. Slika 19 prikazuje razmerje amplitud priključenega električnega polja in prenesenega vrtilnega navora. Amplitudno razmerje pri 0,1 Hz je določeno kot 1, tj., 0 dB. Slika 20 prikazuje fazno razliko med priključenim električnim poljem in prenesenim vrtilnim navorom. Rezultati nakazujejo, da je odrezna frekvenca za sistem prenos vrtilnega navora 18 Hz.

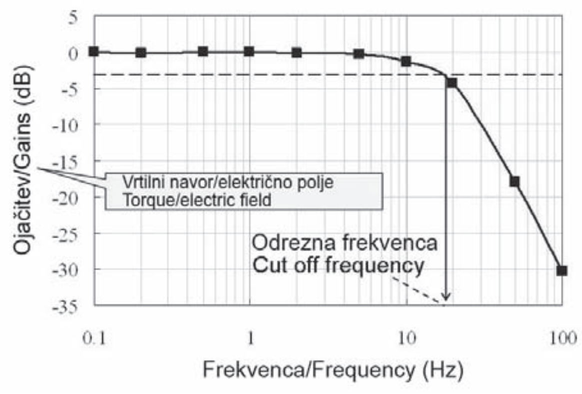
frequency-response test at voltage frequencies of 0.1, 1.0, 10 and 100 Hz. Clearly, the transferred torque varies smoothly with the sinusoidal voltage until a voltage frequency of 10 Hz. However, at 100 Hz, the transferred torque hardly changes. Figure 19 shows the ratio of the amplitude of the applied electric field to that of the transferred torque. The amplitude ratio at 0.1 Hz is defined as 1, i.e., 0 dB. Figure 20 shows the phase difference between the applied electric field and the transferred torque. The results indicate that the cut-off frequency for the torque-transfer system is 18 Hz.

4 SKLEP

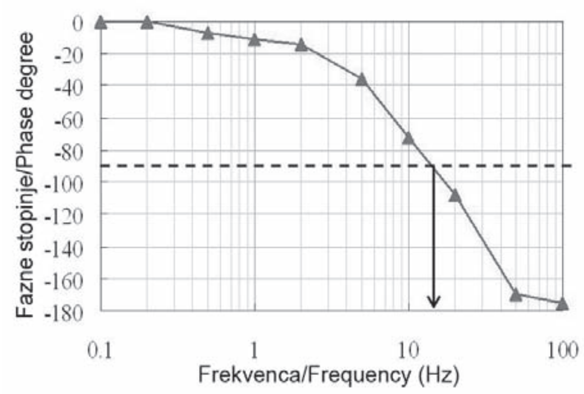
Prispevek predlaga, da se elektro-reološki gel (ERG), ki spreminja svojo površinsko lastnost v skladu s priključenim električnim poljem, lahko uporabi kot torna sklopka. Z namenom doseči učinkovit vpliv ER v sestavu enostranske elektrode je numerično in preizkusno raziskan vpliv vzorca

4 CONCLUSION

This paper proposes that electro-rheological gel (ERG), which changes its surface property according to an applied electric field, can be utilized for a friction clutch. In order to obtain an efficient ER effect in a one-sided electrode configuration, the relation between the electrode pattern and the ER effect is evaluated both



Sl. 19. *Zveza med ojačitvijo in frekvenco [s preizkusi]*
Fig. 19. *Relation between gain and frequency [experimental]*



Sl. 20. *Zveza med fazo in frekvenco [s preizkusi]*
Fig. 20. *Relation between phase and frequency [experimental]*

elektrode na učinek ERG. Na podlagi rezultatov vrednotenja vzorcev elektrode je razvita oblika enostranskih elektrod za sklopko ERG. Izdelan je prototip sklopke ERG. Razvita sklopka ERG kaže odlične lastnosti za prenos vrtilnega navora. Preneseni vrtilni navor se ob priklopu različnih napetosti na široko in enakomerno spreminja. Odziv prenesenega vrtilnega navora na priključeno električno polje je dovolj hitro za praktično uporabo, časovna stalnica je približno 20 ms.

Čeprav sklopka ERG ni primerna za ostre in težke razmere, kakor je avtomobilska torna sklopka, ker je ERG mehkejši od materialov splošno uporabljenih za lamele sklopk. Tako menimo, da je lahko sklopka ERG uporabljena za natančne stroje in v primeru majhnih vrtilnih frekvenc.

numerically and experimentally. On the basis of the result of the electrode-pattern evaluation, the shape of the one-sided electrodes for an ERG clutch is designed and the prototyping of the ERG clutch unit is carried out. The developed ERG clutch unit shows excellent performance for torque transfer. The transferred torque changes widely and smoothly under the application of various voltages. The response of the transferred torque to an applied electric field is fast enough for a practical application, and the time constant is approximately 20 ms.

Though the ERG clutch is not suitable for severe and hard conditions, such as the friction clutch of a vehicle, because the ERG is softer than the materials used for general clutch plates. Therefore, we consider that the ERG clutch can be used for a precision machine and under the conditions of a low rotational speed.

ZAHVALA

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