Design and Analysis of a Permanent Magnet Synchronous Motor Considering Axial Asymmetric Position of Rotor to Stator

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ABSTRACT: *This paper presents the design and analysis of a permanent magnet synchronous motor (PMSM)consideringtheaxialasymmetricPMoverhangforasmartactuator(SA)applicationsuchas an isokinetic exercise machine. This structure helps take advantage of the motor space effectively and makes the system small in size and light in weight. However, two drawbacks related to the performance of motoroccur when the axial asym metricPMoverhangisused:(1)anaxialattractive force (AAF) is created, which can produce motor noise and vibration; (2) the torque of motor is reduced compared with the symmetric PM overhang model. We used five steps to solve these problems. Firstly, the AAF according to the variation in axial position of the rotor to the stator was calculated and analyzed. Secondly, the torque was calculated under the same conditions to confirm thatthesystemrequirementsweresatisfied.Thethree-dimensionalfiniteelementanalysiswasused to determine the AAF and torque. Thirdly, the appropriate axial position of the rotor to the stator was suggested considering the analysis results and space inside the housing. Next, the commercial bearingty pewaschosenso that the totalforceactingonthebearingwasbelowthebearingloadlimit to ensure motor stability. Finally, a prototype model was made and tested to confirm the accuracy of the analytical results. Through this study, by using the axial asymmetric PM overhang, the total length of SA was reduced by 5mm and the performance of motor wasguaranteed.*
Keywords: *axial asymmetric permanent magnet overhang; axial attractive force; groove ball bearing selection; isokinetic exercise machine; permanent magnet synchronous machine; smart actuator*

I. INTRODUCTION

Smart actuators (SAs) composed of modules integrating an electric motor, gear reducer, andcontroller,whicharewidelydevelopedasdrivingmodulesforrobots,areusedinmanyapplications to make the compact system. In this study, we examined when SAs are used as an electrical load on anisokineticexercisemachine(IEM),anddescribedthedesignandanalysisoftheelectricmotorthat constitutes theSA. IEM is a machine that controls the speed of contraction within the range of motion. It is widely used in rehabilitative activities or sports rehabilitation [1]. The main components of an IEM system areshowninFigure1a.Theelectricloadmainlyconsistsofacontroller,electricmotor,andreduction gear. Conventionally,thethreemaincomponentsoftheelectricloadareplacedseparately,creatingthe conventional electric load, as shown in Figure1b. However, since the space for the system islimited, using a SA type electric load is useful, as shown in Figure2. The SA module may help simplify the systemstructure,improvereliability,andcreateacompactsystem[2].Researchersareinterestedinthe permanentmagnetsynchronousmotor(PMSM)designforSAmoduletoachievehighefficiencyand high power density, which can be designed using optimal design techniques or the PM overhang to generate more magnetic flux in the air-gap [3–16]. Most PMSMs use a PM overhang structure in the rotortooperatetheHalleffectsensorforcost-savingandasimplifiedmotorstructure[4].

Figure 1. (**a**) Isokinetic exercise machine system and (**b**) conventional electric load.
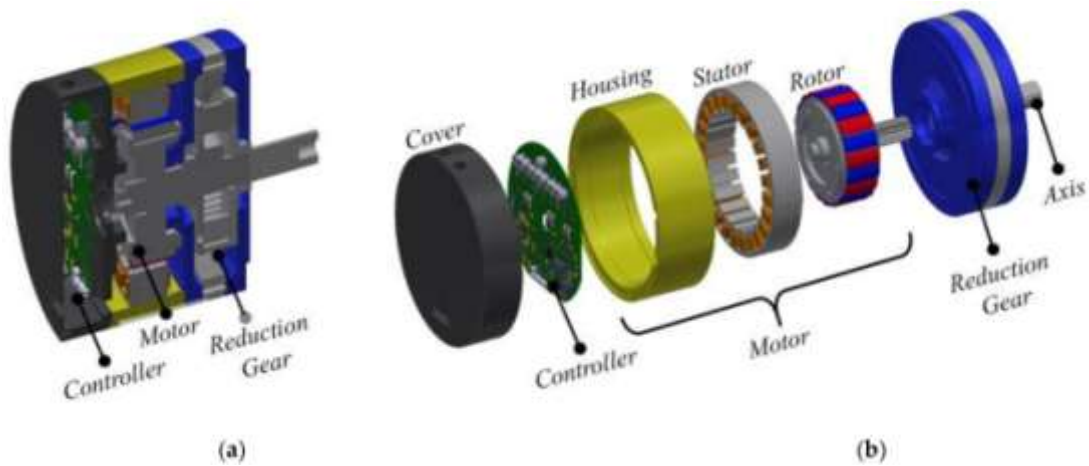
Figure 2. Smart actuator type electric load: (**a**) cross-section view and (**b**) close-up view.

Kang et al. [5] investigated the asymmetric PM overhang effect from the view point of Z-axis thrust, vibration, and noise. Chun et al. [6] analyzed the effect of symmetric and asymmetric PM overhang on the linkage fluxes of the stator and axial magnetic forces. In this study, we investigated the axial asymmetric position of the rotor with PM overhang to stator with the aim of providing more space inside the motor. Figure3a depicts the half cross-section view of symmetric brushless PMSM. As shown in Figure3b, the space (I) at the rear of the motor is only used for containing end-winding, coilconnections, and theHalleffectsensorboard,sothemechanicalandcontrollerparts must be placed in the other areas. If the axial asymmetry of the PM overhang is used, the area (II) is freed up and can be used for bearings and supporting parts. This study was developed from Luu et al.[17], providing a moredetailed and clearexplanationofthetheoryandanalyticalresultsalongwith additional experimentalresults.
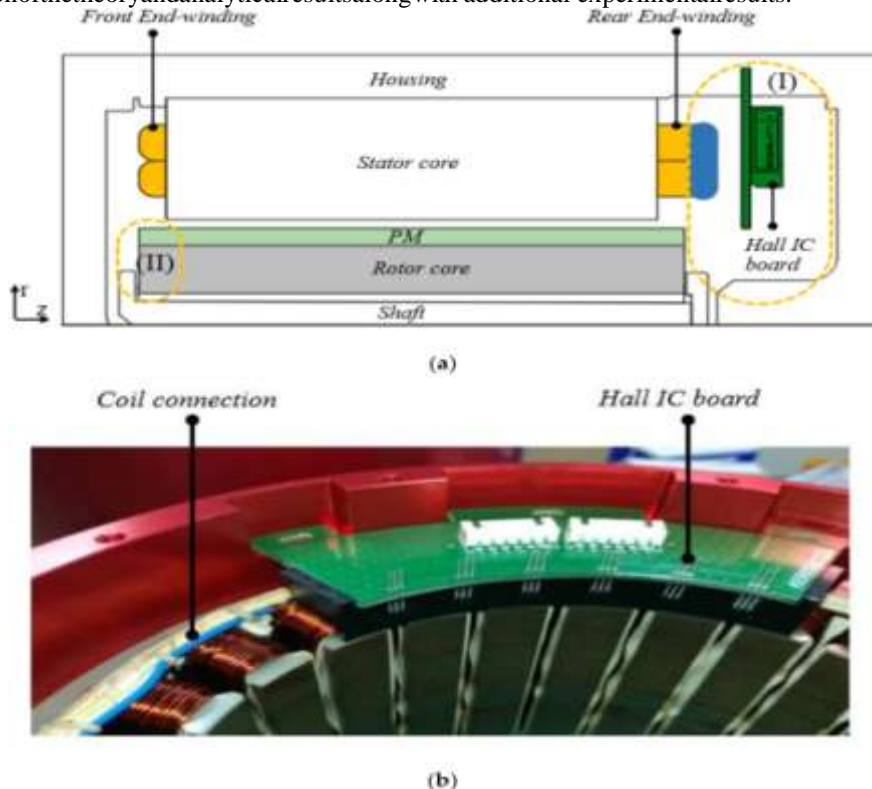

Figure 3. (**a**) Half cross-section view of brushless PMSM, (**b**) coil connection and Hall effect sensor board in brushless PMSM prototype.

The use of PM overhang has a positive effect on the performance of the motor; however, theasymmetricPMoverhangbreakstheaxialmagneticsymmetryofmotorandreducesthemagnetic torque. This generates an axial attractive force (AAF). AAF can damage the bearing and create noise and vibration [5].

Therefore, we investigated the value of AAF according to the axial position of the rotortothestator.ThetorquevalueisalsoaffectedbytheasymmetricPMoverhang,sowecalculatedthetorquetoensuretha tthesystemrequirementwassatisfied.BothAAFandtorqueweredetermined using three-dimensional finite element analysis (3-D FEA). Afterward, the commercial bearing was selected to ensure the stability of the motor. Considering the analysis results together with the actual dimension of the motor, the appropriateaxialposition oftherotortothestatorwasdetermined.Finally, the analysis results were validated by theexperiment.

II. PROPOSED MODEL DESCRIPTION

Severalperiodically3-DanalysismodelsofthePMmotorwithdifferentrotorcoretostatorcore positions are shown in Figure4, in which Dx is the distance between the mechanical centers of the rotorandstator.ThemotorissymmetricalwhenDx=0mm,i.e.thesymmetricalmodelhasa5mmof PMoverhangonbothsides.Theconcentratedwindingwiththe20-poleand24-slotmodelisdesigned tohavelowerend-windinglengthandlowercopperloss.Theaxiallengthoftherotoris10mmlonger thanthestator'saxiallength,i.e.,5mmofPMoverhangforeachsideintheaxialsymmetricalmodel. Thedesigntargetistomeettheratedtorquerequirementandobtainhighefficiency. Table1showsthe output performance requirements and dimensions of themotor.
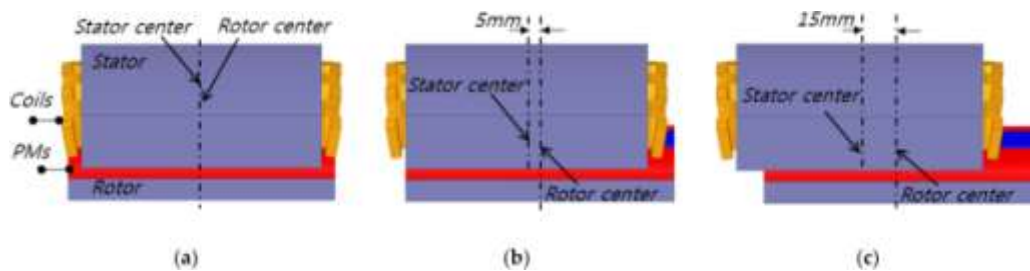

Figure4. Periodicthree-dimensional(3-D)analysismodel,whenDx,whichisthedistancebetweenthe stator center and rotor center, is (**a**) 0, (**b**) 5, and (**c**) 15mm.

Table 1. Specifications of the analysis model.

Specifications	Value		Unit
Output requirement	Ratedoutputpower (Continuous operation)	1.5	kW
	Maximumoutputpower (instantaneous operation, 30s)	4.5	kW
	Rated speed	540	rpm
	Rated torque	26.7	Nm
Dimensions	Stator outer diameter	180	mm
	Rotor inner diameter	90	mm
	Length of stator	90	mm
	Length of rotor	100	mm
	Air gap	2	mm
Cooling type	Natural cooling		

III. AAF ANALYSIS DUE TO ASYMMETRIC PMOVERHANG

Due to the asymmetric configuration, the 3-D FEA was used to calculate the AAF values. The magnetic field can be solved using commercial software (3D Maxwell, ANSYS, Inc., USA). The virtual workmethodisusedtodeterminetheaxialattractiveforceandmagnetictorque[18].

$$W_{mag} = \frac{1}{2} \oint B.HdV \tag{1}$$

$$AAF = \frac{\partial W_{mag}}{\partial z} \tag{2}$$

$$T = \frac{\partial W_{mag}}{\partial \theta} = F \times R_{rotor}^{\theta} \tag{3}$$

whereW$_{mag}$isthetotalstoredmagneticenergy,Bisthemagneticfluxdensity,Histhemagneticfield,zistheaxialdisplaceme
nt,F$_\theta$istheforceintheθ-direction,andR$_{rotor}$istheradiusoftheouterrotor.
Figure5showstheperiodical3-DanalysismodelsofthePMmotor.Sincethemodelhasafractional slot per pole
configuration, which is 20-pole and 24-slot, a 1/4 periodic of the machine was modeled in 3-D FEA. The
Neumann boundary condition was applied to reduce the analysis time. The model
withsymmetricalPMoverhanghasa5mmonbothsides.Theair-gapfluxdensitydistributionin
both symmetric and asymmetric models is shown in Figure6. In the case of the symmetric model, theair-
gapfluxdensityisdistributedsymmetricallyonbothsidesoftheoverhangregion.Incontrast, the asymmetric model
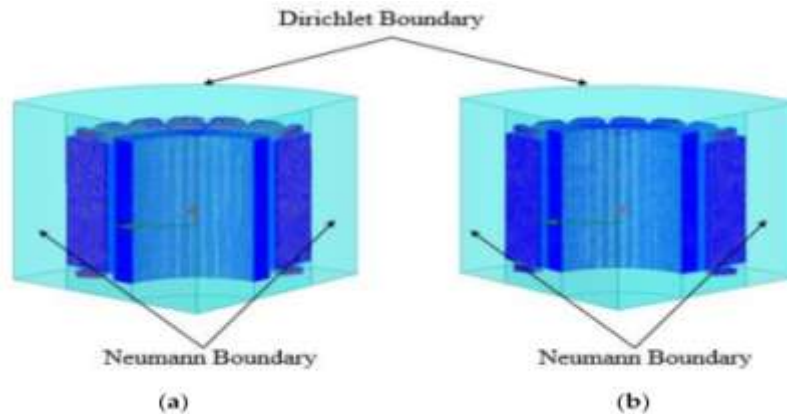generates asymmetrical flux, which produces AAF and motorvibration.

Figure 5. Periodically analysis model by using 3-D finite element analysis (FEA) (number of triangle elements is about 400,000): (**a**) symmetrical and (**b**) asymmetrical models.
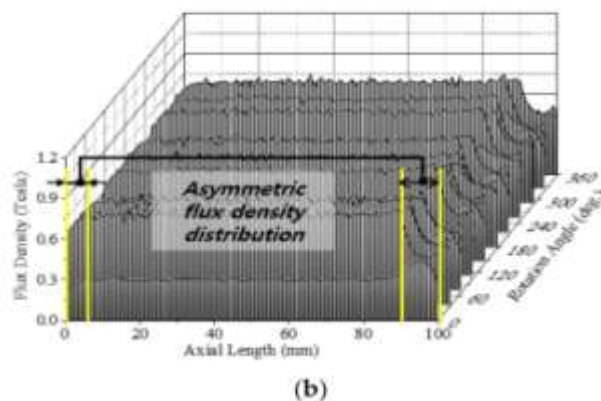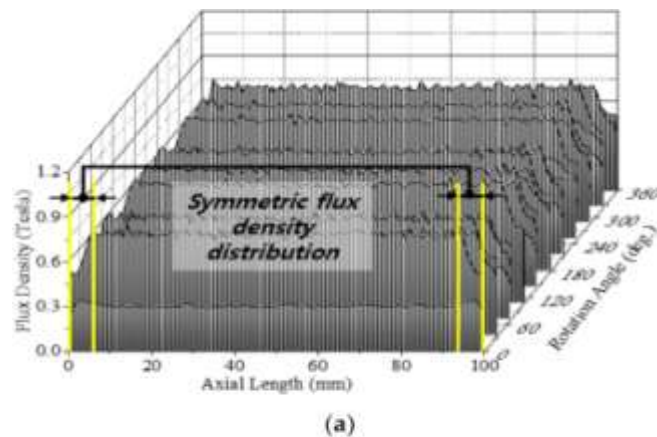

**Figure 6.** Air-gap flux density distribution: (**a**) symmetrical model and (**b**) asymmetrical model.

With variation in Dx, the value of AAF is as shown in Figure7a. AAF is 0 N when Dx = 0, indicatingthatmotorissymmetrical.AAFincreasesdramaticallywhenDxislessthan9mm.Afterthat point, AAF tends to be constant. The torque gradually decreases by about 11.4% when Dx increases from 0 to 15 mm.

For a more visual perspective of the change in AAF and torque according to the variation in Dx, torque was normalized at Dx = 0mm and AAF was normalized on the basis of F_θ at Dx = 0 mm, which are defined as torque percent ratio and AAF percent ratio, respectively, as shown in Figure7b. ThetorquepercentratiodecreasesslightlyasDxincreasesfrom0to3mm,andincreasesdramatically as Dx is over 3 mm. On the contrary, the AAF percent ratio significantly increases by 20% as Dx changes from 0 to 3 mm and remains at almost 50% of F_θ when Dx is over 3 mm.

Tochoosetheproperpositionoftherotortothe stator, thebearingpositionandspaceinsidethe housingshouldbeconsidered.Combinedwiththeanalysisresults,wefindthat5mmisareasonable axial position of the rotor to the stator, as shown in Figure8. At Dx of 5 mm, the torque is 30.26 Nm, which satisfies the systemrequirements.
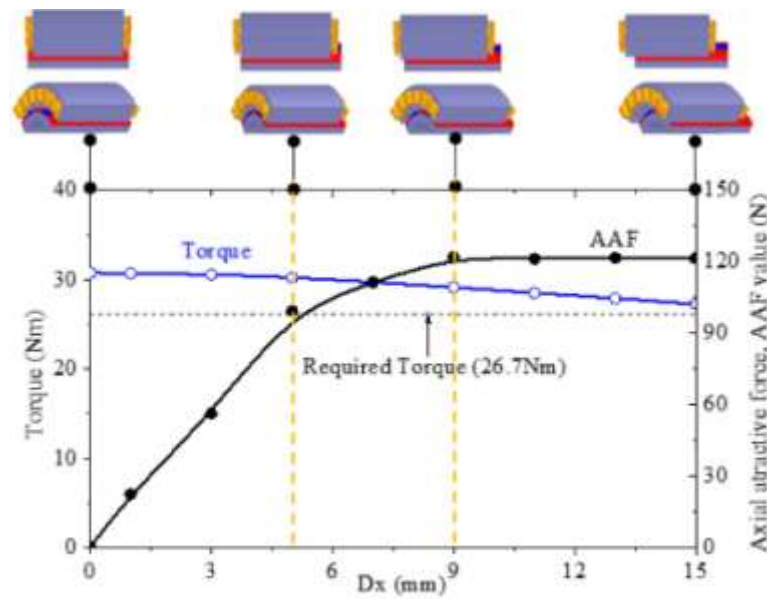
(a)
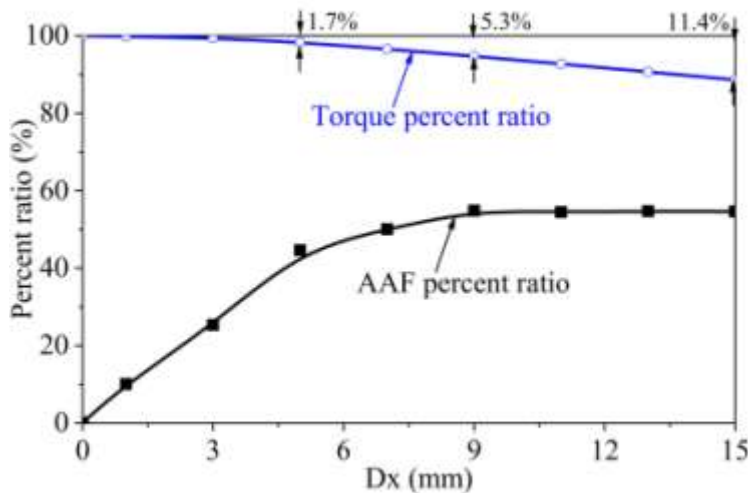
(b)

Figure7.(**a**)Thechangeinaxialattractiveforce(AAF)andtorquevaluesaccordingtothevariationin Dx, and (**b**) AAF and torque percentratio.
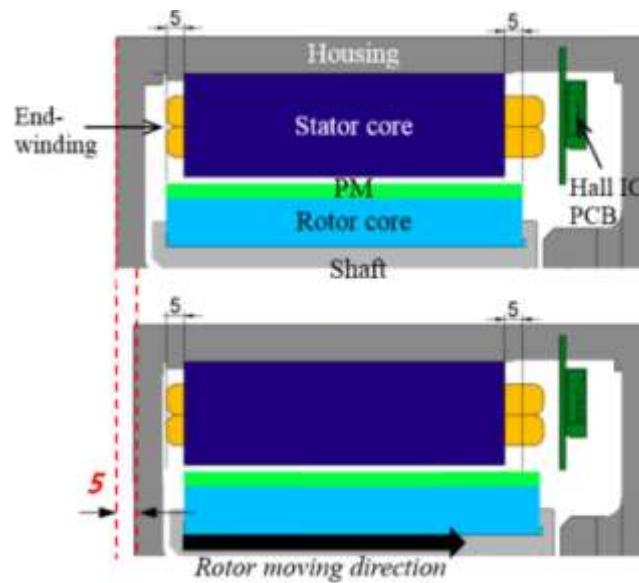
Figure 8. The axial cross-section of the motor in r-z plane when (top) Dx = 0 mm and (bottom) Dx = 5 mm) (unit:mm).

IV. BEARING SELECTION CONSIDERING AXIAL ATTRACTIVEFORCE

To select the correct bearing for each application, several factors need to be considered, such as allowable space, bearing load (magnitude, direction), and rotational speed. For this studied motor, both axial and radial forces act upon the bearing. In the previous section, the axial force caused by axial asymmetry of the motor was determined, which is 99.27 N. We assumed that the motor is ideally symmetrical in the radial direction; thus the radial magnetic forces eliminate each other on the bearing. Therefore, the weight of the rotor and the rotational force (tangential component of the force) that generates the motor torque are considered radial loads. Since the maximum torque is less than twice the rated torque and the main operating point is the rated torque range, the rotational force was calculated based on the rated torque. To consider the maximum load on both bearings, we used the case where the direction of gravity to the rotor coincides with the direction of rotational force.Theradialloadwascalculatedbymultiplyingthesumofthesetwoloadsbyaloadfactorof1.2 (the value for the environment with little external impact on the shaft [19]). The load acting on each bearing was calculated using the moment equilibrium equation [19,20]. We chose deep groove ball bearings in this study because they can carry both axial and radial loads and have outstanding noise and vibration characteristics.Sincetheinnerringrotates,thevalueoftherotationalcoefficientVis1in Equation(4),sotheequationofequivalentloadontheballbearingisasexpressedinEquation(5).
The dynamic equivalent radial load acting on the ball bearing is calculated by [20]

$Pr = X.V.Fr+Y.Fa$ (4)
$Pr = X.Fr + Y.Fa =0.496kN$ (5)
where

Pr is the dynamic equivalent radial load N,
Fr is the actual radial load N, Fa is the actual axial load N, X is the radial load factor,
Y is the axial load factor, and
V is the rotational factor.

The values for X and Y are listed in the bearing table provided by the manufacturer [20]. Consideringtheallowablespaceforthebearingandthebearingloadlimit,weusedthe6205-ZZ bearing (NTN Bearing Corporation, Japan) in thisstudy.

V. EXPERIMENTAL VALIDATION

1.1. Resistance and Back Electromotive ForceComparison
Tocheckwhethertheprototypewasmanufacturedexactlyasthedesignedmodel,theresistanceandbackelectromotiveforce(backEMF)weremeasuredusingadynamosystemasshowninFigure9. The data were acquired using the dynamo user interface and power analyzer. Table2presents the comparison of phase resistance and back EMF between the calculated values and experiment results for the symmetrical model. It was clearly observed that the error

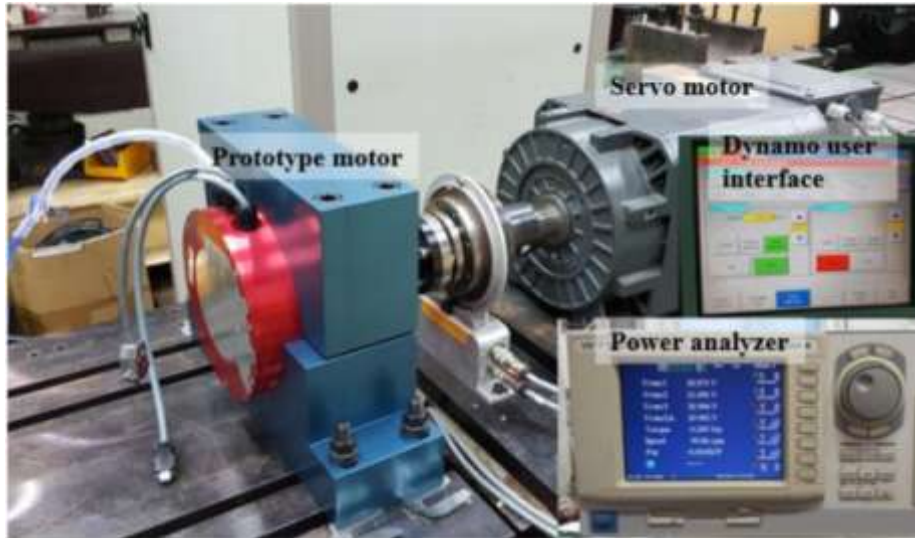betweenthecalculatedandmeasured values was acceptable, at under5%.

Figure 9. The experimental setup to measure the back electromotive force value.

Table 2. Comparison of resistance and back electromotive force (back EMF) between calculated and measured values.

Parameters	Unit	Calculated Value	Measured Value	Error (%)
Phase resistance	Ω	0.66	0.664	0.6
Phase back EMF constant	Vrms/rpm	0.13	0.12	4.6

1.2. Measurement of Axial AttractiveForce

Theforcemeasurementsystemwassetup,asillustratedinFigure10.Theloadcell(BDHS–1t)was used to measure the AAF value. A coupling is used to connect the motor shaft with the hand-wheel. Whenthehand-wheelturnsintheclockwisedirection,therotormovesalongthe+z-direction,andvice versa. Each $180°$ rotation of the hand-wheel, the rotor linearly moves 1.1 mm. Therefore, the AAF depending on the rotor position with respect to stator core wasmeasured.

ThecomparisonbetweenthecalculatedandexperimentalvaluesisshowninFigure11.TheAAFvalueincreases astheaxialpositionoftherotorcoretothestatorcoreincreases.Similartotheanalysis results, the measured value tended to be constant when Dx exceeded 9 mm. The experiment results are consistent with the analysisresults.

1.3. Isokinetic Exercise MachineTest

After the motor had been tested separately, it was assembled together with a controller and reduction gear to create the smart actuator type electric load as shown in Figure2. Both isotonic exercise mode and isokinetic exercise mode tests were implemented to check the performance ofthe system, as shown in Figure12a. In the isotonic mode, the same force is applied in the pedal and the value of force depends on selecting a resistance between 0 to 100%, while in the isokinetic mode, the constant speed is maintained regardless of the force exerted in the pedal. Both help to increase muscle endurance and muscle strength. In addition, training in the isokinetic mode also reduces the risk of injury. The torque value was measured in the two training modes and results are showninFigure12b,c.Theexperimentsshowthattheisokineticexercisemachineworkswellinboth training modes.

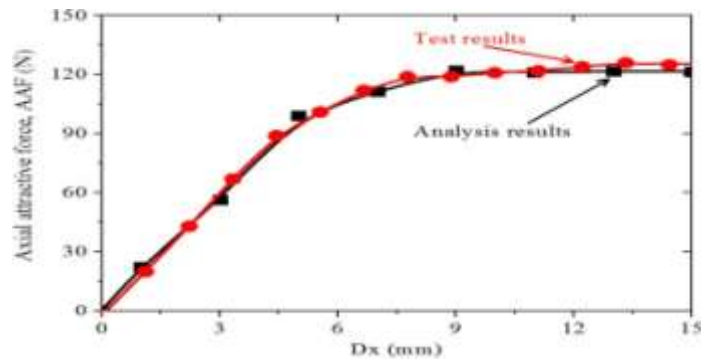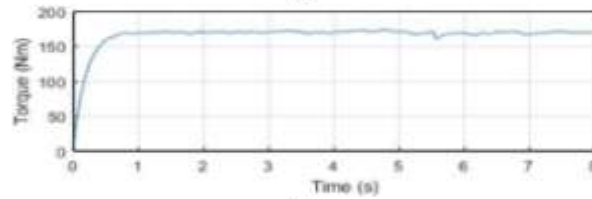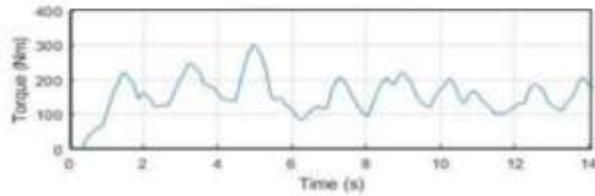**Figure 10.** The experimental setup for the measurement ofAAF.

Figure 11. Comparison between measured and analyzedresults.

Figure 12. (**a**) Isokinetic exercise machine operation test for elbow joint exercise, (**b**) torque waveform in the isotonic training mode, and (**c**) torque waveform in the isokinetic training mode.

VI. CONCLUSIONS

Inthispaper,thedesignandanalysisofaPMSMwereproposedconsideringtheaxialasymmetric position of the rotor to the stator for efficient use of space inside the motor. Due to the axially asymmetrical motor, the Z-thrust force appeared, which may cause motor noise and vibration, and torque was reduced. To maintain the performance of motor, we numerically and experimentally investigated the axial force and torque according to the axial position of the rotor to the stator. Considering the available spaceforthebearing,andthesimulationresults,wefoundthat5mmisthe axial offset position of rotor core center to the stator core center, which means that the axial length of the motor can be decreased by up to 5mm. At a 5 mm of the axial offset position of the rotor to the stator, torque was reduced by 1.7% in comparison to the symmetric overhang PM model, which still met the system requirement. The process of how to choose a bearing to maintain the stability of the motor was alsopresented.

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