Spherical Electrical Machines

Bhagat Singh Tomar
Assistant Professor ,
Electrical Engineering Department
Laxmi Devi Institute of Engineering & Technology.
Alwar ,Rajasthan (India)

Ms. Nisha
M.Tech(PS) ,Research Scholar
Laxmi Devi Institute of Engineering & Technology
Alwar ,Rajasthan (India)

Abstract- **This paper contains a summary of the work with spherical electrical machines found in the specialized literature. Spherical actuators allow several degrees of freedom (DOF), which is particularly interesting in robotics. The research into multidegree-of-freedom actuators has been ongoing for decades, the first designs dating from the 1950's. However, competitive performance has not been achieved until power electronics and digital signal processors were incorporated in the controls.**

Index Terms- Spherical Electrical Machines, Degrees Of Freedom (DOF), Asynchronous Motors, Induction Motors.

I .INTRODUCTION

The latest contributions on spherical machines are pointing towards asynchronous motors rather than permanent magnets. However, these concepts are already at a very early design stage, mainly focusing on simulations and how to achieve the movement of the rotor, while practical implementation and accurate controls are not yet reported.

The purpose of this report is to provide an insight view of the different topologies found in the specialized literature regarding two and three degrees of freedom actuators suitable for robot applications.

Advances in robotics, office automation and intelligent flexible manufacturing and assembly systems have necessitated the development of precision actuation systems with multiple degrees of freedom (DOF). In general, however, motion with several DOF is currently realized almost exclusively by using a separate motor/actuator for each axis, which results in complicated transmission systems and relatively heavy structures. This inevitably compromises the dynamic performance, owing to the effects of inertia, backslash, nonlinear friction and elastic deformation of gears.

Actuators which are capable of controlled motion in two or more degrees of freedom can alleviate these problems, while being lighter and more efficient. A particular interesting configuration to perform these tasks is the spherical machine.

II.PERMANENT MAGNET MACHINES

The principle of the spherical machine is shown in Figure1. The diameter of the inner sphere is 275 mm and the height of the pole shoes is 50 mm. The specified torque is 40 Nm in all positions. The rated speed is 12 rad/s. The gap between stator and rotor is approximately 40 micrometers. A high manufacturing accuracy is needed to build the elements of the inner and outer sphere. Oil inside the stator housing is used for the hydrostatic bearing and also for cooling purposes. The stator yoke is made of a soft magnetic powder composite with a relative permeability of 500, and it serves to reduce eddy current losses. In parked position or in case of a failure of the bearing system an additional mechanical brake is activated.

The rotor consists of a sphere with 112 NdFeB permanent magnets, arranged in seven rows each having 16 magnets with alternating north and south orientation. The outer stator core 5 casing has 96 stator poles and windings. The rotor is supported by hydrostatic bearings built into the outer stator case. The working area is only limited by the opening angle of the case (+/- 60º). The control hardware consists of three digital signal processor (DSP) boards, which offer 480 MFLOP computing power, memory for storing force characteristics, and a high number of input/output channels.
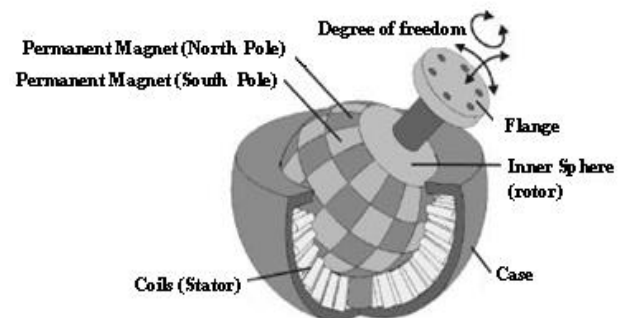

Figure 1 Principle of design

The main applications of Halbach magnetised machines are:
a) High-speed motors/generators. For example in flywheel energy storage systems.This is due to their low iron loss.
b) Servomotors. For example computer disks and electric power assisted steering. This is due to the low cogging torque and torque ripple.
c) Linear machines. Such as material handling and semiconductor wafer stepping. Due to the low inertia and high air gap field and force capabilities, linear Halbach motors can achieve very high acceleration.
d) Passive magnetic bearings/magnetic coupling. Actually Halbach machines are extensively been used for these applications.
e) Spherical motors. In particular it is interesting the fact that no rotor back-iron is needed, which would alleviate the actual weight problems in spherical machines. Their lower torque ripple would also be an advantage for position control. With adequate magnetization techniques they could be more easily manufactured than conventional surface permanent magnet spherical machines.
In general, all the actuators analyzed so far have an aperture in the stator to allow access to the rotor so as to attach the external payload, and the effect of this aperture has been

analyzed in [5]. The aperture modifies the magnetic field distribution, which in turn may degrade the performance of the actuator in three respects, since it may result in the following:

a) an asymmetrical flux density distribution, which would affect the excitation torque versus rotor angular displacement characteristics.

b) a reluctance torque component, due to the interaction of the permanent-magnet field and the asymmetrical stator iron geometry.

c) asymmetry in the radial force distribution, and hence an "unbalanced magnetic pull", which could impose a significant additional load on the bearing system.

III. INDUCTION MACHINES

Traditionally, induction (asynchronous) spherical machines have not attracted commercial interests, probably due to the relatively complex stator core and winding arrangement and the inherently poor servo characteristics of induction motors. The first topology has been presented in [7], and it is shown in Figure 2. The external surface of the rotor can be slotted (left picture) or smooth (right picture). In case of a smooth rotor, the winding is a thin, conducting layer of copper or other diamagnetic material. Rods made of diamagnetic, conducting materials, create a winding in case of slotted rotor.

The rotor may be situated in the centre of the stator in such a way that distances between the rotor's surface and the stator are constant in the polar directions, or the rotor could even roll on the internal surface of the armature.The armature should have diametrally opposite pairs of coils. They are connected in series, so that when one of them acts as a North pole, the other acts as a South pole. To cause rotation of the rotor around one of its polar axis, an armature should have additional elements, which can produce migration and rotation of the field around the polar axis. These elements can be additional armatures or modular magnetic circuits with double slot-tooth structure. The presented three-phase spherical induction motor has four symmetric situated modular exciters, with six slots each. The air gap radius is 50 mm and the outer stator radius 80 mm. The air gap is 0.4 mm An interesting idea has been cited in [8] about filling the gap of spherical machines with ferrofluids.

A numerical model testing this idea is presented in [9]. The main purpose of ferrofluids in terms of electric effects is to fill air gaps in magnetic circuits in order to increase the permeability in the gap to reduce the magnetic resistance in the circuit. This leads to a decrease of the magnetizing current and an increase of the efficiency. First 10 results from theoretical studies show that the magnetic resistance using a ferrofluid is reduced by about 10%, if the solid magnetic materials are taken into account. However, no experimental results have been reported.

Analytical and finite element modeling proved that massive rotor's performances are much worse comparing to the rotor with an internal layer composed of iron and an external layer created of copper. However, for the rotor with teeth, not only the electromechanical conversion is better, but also the maximal torque produced is higher, around 20% more than option b) and 40% more than option).

The distribution of the teeth in the rotor has to be as regular as possible in order to ensure torque isotropy. The most uniform distribution on a sphere is defined by the vertices of a regular icosahedrons, i.e. formed of identical equilateral triangles, inscribed in this sphere. Additional vertices and face number were created by tessellation, which consists in adding new vertices in the center of each face of the considered solid.
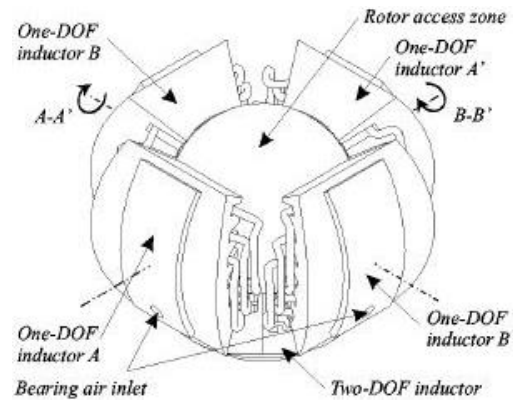

Figure 2 Spherical induction motor

IV. RELUCTANCE MACHINES

The 3-DOF spherical motor presented in [13] operates on the principle of variable - reluctance (VR). The machine consists of two spheres as shown in Figure 3. These two spheres are concentric and are supported one on the other by bearing rollers in the gap. The stator poles are wound by coils and each coil can be energized individually. The ferromagnetic poles are strategically distributed on the stator surface.

The rotor poles which have no coil are distributed on the rotor surface. Both the stator poles and the rotor poles are of circular shape. The measurement mechanism of the rotor orientation consists of two circular sliding guides one sliding block, and three encoders. For simplicity in motion control, it is desired that the poles are evenly spaced on the stator and on the rotor following the pattern of regular polyhedrons.

Each vertex of the polyhedron corresponds to the location of one pole. The regular polyhedrons are tetrahedron (4), octahedron (6), cube (8), icosahedrons (12), and dodecahedron (20). The choice on the particular pattern influences the range of inclination. To provide 3-DOF motion, at least two independent torques which are not collinear acting on the rotor are required. Thus, it is necessary to have more stator poles than rotor poles. The mismatch is also necessary to avoid electro-magnetic singularities, when all the stator and rotor poles are fully overlapped.
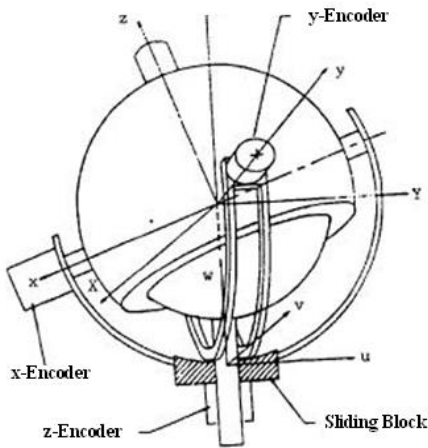
Figure 3 Basic structure of the VR spherical motor

The kinematic analysis of the spherical wrist actuator and an exact relationship of the overlapping area in three dimensional spaces is derived analytically. In general, a VR motor has a relatively large range of motion, possesses isotropic properties in motion, and is relatively simple and compact in design. The trade-off however, is that a sophisticated control scheme is required. An air bearing for this kind of machine was analyzed in [14]. The air bearing is essentially a regulator that tends to maintain the rotor at is equilibrium position.

It is clean and has a cooling effect on interacting components, and does not interfere with the actuator electromagnetic system. The air bearing is characterized by three distinct flow regions; namely the restrictor, air pocket, and the annulus. Air enters the bearing from a pressure source, passes through the restrictor, flows through the annulus and then exhausts to the atmosphere. To maintain the rotor in equilibrium at the stator center, the air bearings are designed to direct their forces at the vertices of polyhedrons towards the stator center. Thus, once the bearing locations are specified, the directions of the bearing forces are considered known. Theoretically, the minimum number of simple point bearings required to achieve bi-directional position control of the spherical rotor in a three-dimensional space is four.

Another attractive approach to the air bearing concept, is to design a compound unit so that pressurized air passes through the center of the electromagnetic pole enabling it to also serve as a bearing. The advantages of a compound unit are twofold:
a) The air-jet will provide cooling effect to the electromagnetic pole coil windings.
b) The design will optimize the stator surface by maximizing the size of each bearing, thereby enhancing load-bearing capacity. The results indicate that the magnetic disturbance is adequately compensated by the air-bearing system since the force has little impact on the air bearing. Another attractive approach to the air bearing concept, is to design a compound unit so that pressurized air passes through the center of the electromagnetic pole enabling it to also serve as a bearing.

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The detailed kinematics of air bearings are analytically described in the paper, and evaluated by simulation. The results indicate that the magnetic disturbance is adequately compensated by the air-bearing system since the force has little impact on the air bearing.

V. OTHER 2-DOF TOPOLOGIES

Some other topologies have been found for 2-DOF actuators that are worth including in the survey. The spherical direct drive actuator consists on a constant magnet rotor fastened in gimbals and located between two pairs of crossed solenoids. The windings of each pair of solenoids are located in alignment and are connected in phase for a mechanical moment magnification enclosed on a magnet rotor. Such disposition of the windings allows, in the first approximation, to neglect their mutual influence and mutual induction. Position is measured by means of four Hall sensors, and a control system is used to excite the adequate coils depending on the position error.
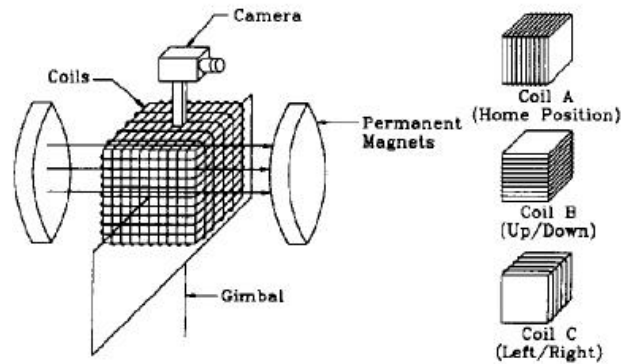

Figure 4 Picture of Bederson's pointing motor principle.

The motor consists of three orthogonal motor windings in a permanent magnetic field, configured to move a small camera mounted on a gimbals, see Figure 4. It is an absolute positioning device and is run open-loop. The basic principle is to orient a permanent magnet to the magnetic field induced by three orthogonal motor windings by applying the appropriate ratio of currents to the three coils. Coils A and B control the tilting, while coils A and C control the panning.

The position of the rotor can be calculated given the currents applied to the three coils. However, due to manufacturing tolerances, the calculated currents give only an approximation to the actual position of the motor. Therefore the motor had to be calibrated to associate motor positions with the related set of currents that move the motor to these positions. An open-loop controller was implemented successfully, but for higher performance a velocity or position sensor could be added to run the motor with a closed-loop control strategy.

The prototype is 4x5x6 cm, weights 160 gram and is capable of actuating a 15 gram load. Its total workspace is approximately 60°. The position of the motor could be achieved in steps no smaller than 0.011°.

VI. CONCLUSION

Advances in robotics, office automation and intelligent flexible manufacturing and assembly systems have necessitated the development of precision actuation systems with multiple degrees of freedom (DOF). In general, however, motion with

several DOF is currently realized almost exclusively by using a separate motor/actuator for each axis, which results in complicated transmission systems and relatively heavy structures. This inevitably compromises the dynamic performance, owing to the effects of inertia, backslash, nonlinear friction and elastic deformation of gears, for example. Actuators which are capable of controlled motion in two or more degrees of freedom can alleviate these problems, while being lighter and more efficient. A particular interesting configuration to perform these tasks is the spherical machine.

REFERENCES

[1] K. Kahlen, I. Voss, C. Priebe and R.W. De Doncker, "Torque control of a spherical machine with variable pole pitch", IEEE Trans. Power Electron., Vol. 19, No. 6, pp. 1628-1634, 2004.

[2] K. Kahlen and R.W. De Doncker, "Current regulators for multi-phase permanent magnet spherical machines", IEEE Industry Applications Conf. Rec., 2000, Vol. 3, pp. 2011-2016.

[3] W. Wang, J. Wang, G.W. Jewell and D. Howe, "Design and control of a novel spherical permanent magnet actuator with three degrees of freedom", IEEE Trans. Mechatronics., Vol. 8, No. 4, pp. 457-468, 2003.

[4] J. Wang, G.W. Jewell and D. Howe, "Analysis, design and control of a novel spherical permanent -magnet actuator", IEE Proc.- lectr. Power Appl., Vol. 145, No. 1, pp. 61-71, 1998.

[5] J. K. Mitchell, G. W. Jewell, J. Wang, C.M. Bingham and D. Howe, "Influence of an aperture on the performance of a two-degree-of- freedom iron-cored spherical permanent-magnet actuator", IEEE Trans. Magnetics. Vol. 38, No. 6, pp. 3650- 3653, 2002.

[6] Z.Q. Zhu and D. Howe, "Halbach permanent magnet machines and applications: a review", IEE Proc. - Electr. Power Appl., Vol. 148, No. 4, pp. 299-308, 2001.

[7] G. Kaminski and A. Smak, "Induction motors with spherical rotor", ICEM'04 Conf.Proc., Sept. 2004, Cracow, Poland, 4 pp.

[8] D. Spalek and K. Waleczek, "Spherical induction motor with ferrofluids in gap",ICEM'04 Conf. Proc., Sept. 2004, Cracow, Poland, 6 pp.

[9] A. Nethe, T. Scholz, H.D. Stahlmann and M. Filtz, "Ferro fluids in electric motors –A numerical process model", IEEE Trans. Magnetics. Vol. 38, No. 2, pp. 1177-1180, 2002.

[10] G. Galary, B. Dehez and D. Grenier, "Finite element modeling of a two-degree of freedom spherical actuator", ICEM'04 Conf. Proc., Sept. 2004, Cracow, Poland, 6 pp.

[11] S.M. Sokolov, O.V. Trifonov and V.S. Yaroshevsky, "Research of spherical direct drive actuators control systems", IEEE Int. Conf. on Robotics & Automation, May 2001, Seoul, Korea, 6 pp.

[12] B.B. Bederson, R.S. Wallace and E.L. Schwartz, "A miniature pan-tilt actuator: the spherical pointing motor", IEEE Trans. Robotics & Automation, Vol. 10, No. 3, pp. 298-308, 1994.

[13] K.M. Lee and J. Pei, "Kinematic analysis of a three degree-of-freedom spherical wrist actuator", Fifth Int. Conf. On Advanced Robotics, Atlanta, USA pp. 72-77, 1991.

[14] D.E. Ezenekwe and K.M. Lee, "Design of air bearing system for fine motion application of multi-DOF spherical actuators", IEEE Int. Conf. on Advanced Intelligent Mechatronics, Sept. 1999, Atlanta, USA, 7 pp.

AUTHORS

Bhagat Singh Tomar, Assistant Professor, Electrical Engg. Department, Laxmi Devi Institute of Technology, Alwar, Rajasthan(India)

Ms. Nisha M,Tech (PS), Research Scholar Laxmi Devi Institute of Engineering & Technology, Electrical Engg. Deptt. Alwar ,Rajasthan (India),