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ORIGINAL SCIENTIFIC PAPER

Dynamic Modeling, Characteristic Analysis and Co-simulation of the Permanent-Magnet Spherical Actuator

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Abstract. As the traditional mathematical modeling may lead to difficulties in solving a complex problem, a novel co-modeling and simulation method for the three-degrees-of-freedom (3-DOF) permanent-magnet spherical actuator (PMSA) is presented. After describing the basic structure and operating principle of PMSA, a geometry model is set up based on the SolidWorks. The dynamic characteristics are then analysed by employing Automatic Dynamic Analysis of Mechanical Systems (ADAMS). Finally, a co-simulation platform based on ADAMS and MATLAB is implemented to validate the effectiveness of the dynamic model, control strategy and design methodology as well as to provide an innovative reference for the future research and experimental design of PMSA.

Keywords: dynamic modeling, characteristic analysis, co-simulation, permanent-magnet spherical actuator (PMSA).

Analiza dinamike, modeliranje in simulacija magnetnega sferičnega aktuatorja

Ker s tradicionalnimi matematičnimi orodji naletimo na težave pri reševanju kompleksnih problemov, je v članku predstavljen postopek za modeliranje in simulacijo magnetnega sferičnega aktuatorja s tremi prostostnimi stopnjami. Predstavljena je struktura in delovanje aktuatorja, ter njegov geometrijski model v programskem orodju SolidWorks. Sledi analiza dinamike ADAMS za ugotavljanje dinamičnih karakteristik magnetnega sferičnega aktuatorja ter opis simulacijskega orodja za potrditev pravilnosti in učinkovitosti predlaganega modela.

1 INTRODUCTION

Conventionally, a multi-degrees of freedom (M-DOF) high-precision motion mechanism, such as the robot, manipulator etc., is actualized by separate control of several single DOF actuators with a complex mechanical transmission mechanism. However, the increasing size, reducing stiffness, low efficiency, and slow responses are the dominant factors limiting its performance. Therefore, the spherical actuator which can provide up to a 3-DOF motion in a single joint has attracted great attention, and thus many types of the actuator have been studied [1-4]. In addition, this actuator can be applied in potential application fields like new energy [5] and satellite attitude control [6].

Among various actuator types, the three-degrees-of-freedom (3-DOF) permanent-magnet spherical actuator (PMSA) has been extensively studied due to its merits including small volume, low cost, simple structure, high flux density and reliability. Despite the many fruitfull results in the magnetic field and torque model [7], orientation measurement [8], etc., dynamic modeling and its control still present unique challenges becauses of the three strong coupling angle displacement components. The current trend is using the multi-rigid-body mathematical modeling methods, such as the Lagrange or Newton-Euler equation because of its M-DOF complexity [9-10]. But different PMSAs have a unique structure in a different three-dimensional (3D) coordinate system so that the complexities of the mathematical models vary greatly and even lead to considerable deviations from the actual system.

To reduce the development costs and shorten the development cycle, a novel method for designing, analysing and simulating of PMSA in a virtual platform that integrates SolidWorks and ADAMS with MATLAB is presented. Firstly, the basic mechanical structure and operating principle of PMSA are described. Secondly, dynamic modeling and characteristics analysis are given. Finally, a closed-loop co-simulation with a PD controller is implemented.

2 BASIC STRUCTURE AND OPERATING PRINCIPLE OF PMSA

The basic mechanical structure of PMSA is shown in Fig. 1. This actuator mainly consists of a dual-hemisphere-shell-like stator and a ball-shaped rotor. 24 cylindrical electromagnet coils (1200 turns) arranged in two layers are symmetrically set up into the stator shell

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along the equator. The outer and inner diameter of the stator are 182 mm and 232 mm, respectively. The four layer permanent-magnet (PM) poles are uniformly distributed in the rotor and every layer includes ten cylindrical magnet poles embedded along the equator as well. The N and S poles are distributed alternately. The diameter of the spherical rotor is 130 mm. Both the axes of the stator and rotor are concentric through the origin of the spherical coordinate (XYZ). To achieve 3-DOF movements, the air gap between the stator and rotor is maintained constant (1mm). The maximum tilting angle can be increased up to ±67 degrees due to the limited workspace [11].

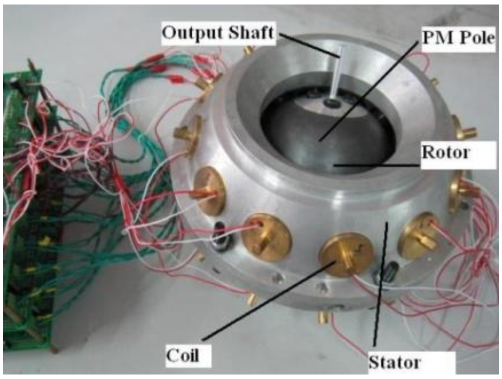
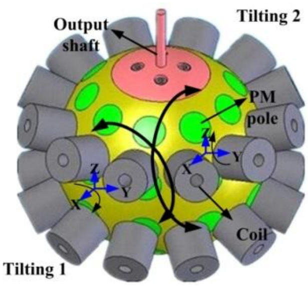


Figure 1. Basic mechanical structure of PMSA

The operating principle of PMSA is based on the repelling and attracting electromagnetic forces generated by some energized coils and the PM poles field.

Among them, the tilting motion around the X and Y-axis is analogous. After supplying the current for the coils in two longitudinal directions, the rotor can create the tilting motion in two orthogonal directions.



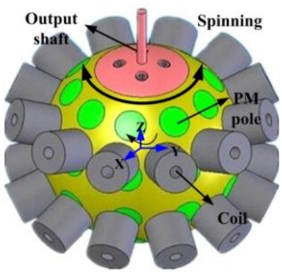


Figure 2. Tilting motion Figure 3: Spinning motion

When we supply the current for all the coils, the rotor will spin around its output shaft because of its symmetrical structure shown in Fig. 3.

Therefore, by varying the input currents of the stator coils, the rotor can produce the desired 3-DOF motion within its workspace.

3 Dynamic Modeling and Characteristics Analysis

A simple co-modeling method using SolidWorks and ADAMS is used to set up a PMSA rotor dynamic model and determine the operating characteristics.

3.1 Dynamic modeling

As well know, although the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) has the powerful ability for obtaining the kinematic and dynamic analysis of a complex mechanical system, it is difficult to build with its complex 3D model. Thus, a PMSA dynamic model is made by employing a professional model-building software-SolidWorks. According to the real design parameters, the PMSA rotor model can be divided into four entities including the hollow spherical shell, PM pole, output shaft and four screws. The basic modeling steps are: 1) Drawing the geometric sketch; 2) Creating rotor assemblies accompanied by mirroring and circumferential array operations; 3) Adding the screws into the threaded holes so as to achieve smart fastener operation. Then, a 3D model is completed as shown in Fig. 4.

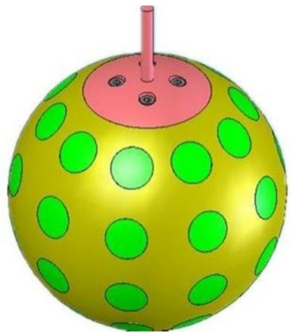


Figure 4. Assembled 3D model in SolidWorks

Then by using a parasolid format, the model can be easily imported into ADAMS. Although ADAMS can automatically create the above entity with the assembly information retained, it is necessary to redefine the material of each part and the related information such as the mass properties, constraints, etc. The parts without a relative movement will be fixed together by 45 fixed joints. In order to simulate the spherical motion, a ball friction coupling is installed in the center of the model. The material of the rotor and screw is stainless steel and the output shaft cover is aluminum. After adding the mass properties, the principal inertia moments of the rotor are calculated by ADAMS, and the solutions are: $I_{xx} \approx I_{yy} = 1.485 \times 10^{-2} kg \cdot m^2$, $I_{zz} = 1.496 \times 10^{-2} kg \cdot m^2$, where $I_{xx} \approx I_{yy} \neq I_{zz}$ is closer to practice due to the geometric symmetry. Thus, the dynamic model is accomplished.

3.2 Characteristic analysis

In this section, the PMSA dynamic characteristic analysis under no-load state is described. According to our experience and several trials, the following two schemes can be adopted to realize the desired 3-DOF motion, i.e. 1) first tilting and then spinning, and 2) tilting and spinning simultaneously. Then, the powerful ADMAS/Processor module is used to show the operating characteristics.

3.2.1 First tilting and then spinning

In order to achieve the desired motion, the driving force and torque are determined by the motion process function called the STEP function.

Among the STEP functions, the X-axis drive-force function is: STEP (time, 0, 0, 1, 0.01) + STEP (time, 1, 0, 2, -0.01) + STEP (time, 2, 0, 3, -0.01) + STEP (time, 3, 0, 4, 0.01), the Y-axis drive-force function is the same as the X-axis, and the Z-axis drive torque function is: STEP (time, 4, 0, 5, 150) + STEP (time, 5, 0, 6, -150).

The simulation time is set to 10 seconds and the simulation step is 500. After the simulation， measurement markers are added to allow for observation.

Fig. 5 shows the driving-function curve. During 0-4 seconds, according to the driving force of the step function to PMSA in the X-axis and Y-axis direction, the rotor firstly completes the tilting motion. During 4-6 seconds, according to the driving torque in the Z-axis direction, the rotor stops the tilting motion and then completes the spinning motion along the Z-axis.

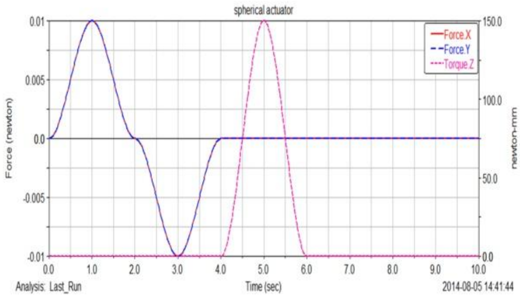


Figure 5. Driving-function curve

Fig. 6 shows the actual angle-displacements curve of the PMSA output shaft. The angle-velocities curve is decipted in Fig. 7. It can be clearly seen that the PMSA rotor moves evenly.

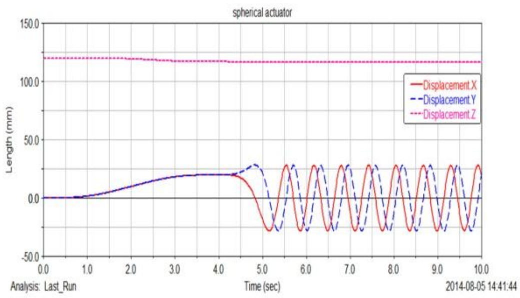


Figure 6. Output angle-displacements curve

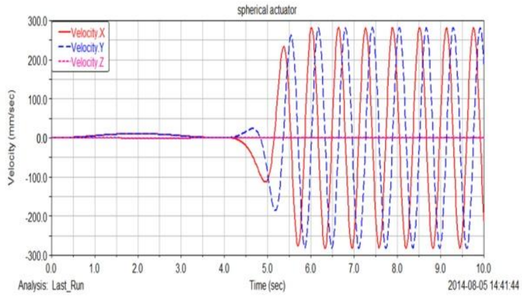


Figure 7. Output angle-velocities curve

To allow for visualization, the 3D trajectory in the top view is also shown in Fig. 8.

Figure 8. 3D trajectory

3.2.2 Tilting and spinning simultaneously

According to the second scheme, the STEP function is also used to achieve the desired motion.

By using the same simulation parameters as above, the X-axis drive-force function is amplified ten times: STEP (time, 0, 0, 1, 0.1) + STEP (time, 1, 0, 2, -0.1) + STEP (time, 2, 0, 3, -0.1) + STEP (time, 3, 0, 4, 0.1), the Y-axis drive-force function is the same as the X-axis, and the Z-axis drive-torque function is changed as: STEP (time, 0, 0, 2, 150) + STEP (time, 2, 0, 4, -150).

Fig. 9 shows the driving-function curve. During 0-4 seconds, according to the driving force of the step function to PMSA in the X-axis and Y-axis direction, the rotor completes the tilting motion. At the same time, according to the driving torque in the Z-axis direction, the rotor completes the spinning motion along the Z-axis simultaneously.

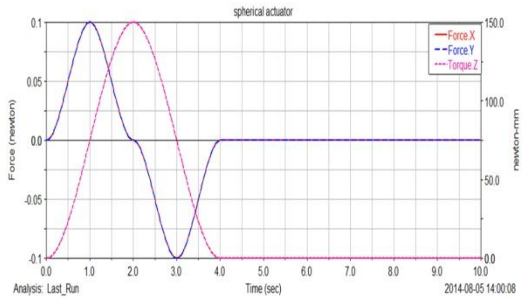


Figure 9. Driving-function curve

Fig. 10 shows the actual angle-displacements curve of the PMSA output shaft combing with tilting and spinning motion simultaneously. The rotor is rotated in a circular path with a reciprocating motion. Despite the large initial transient oscillation, the rotor moves stably after three seconds.

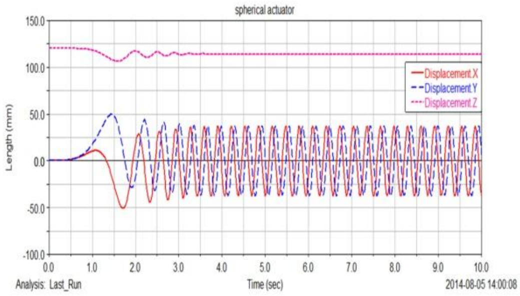


Figure 10. Output angle-displacements curve

The angle-velocities curve is decipted in Fig. 11. The 3D trajectory in the top view is also shown in Fig. 12.

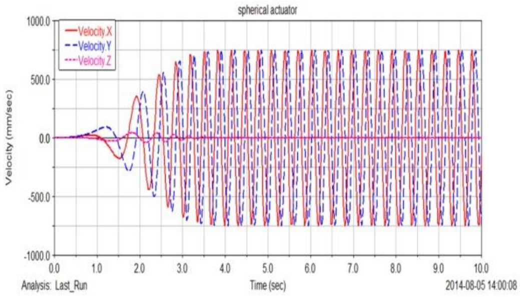


Figure 11. Output angle-velocities curve

Figure 12. 3D trajectory

To sum up, the dynamc simulation validates the model and provides grounds for the subsequent co-simulation control.

4 CO-SIMULATION TEST

As stated in [12], the PMSA dynamic system is a multi-input, multi-output and strong coupling nonlinear system. The control objective is to design the control torque $\boldsymbol{Tol} = [Tol - X, Tol - Y, Tol - Z]^T$ which makes the angle-displacements $\boldsymbol{q} = [PX, PY, PZ]^T$ track with desired trajectory $\boldsymbol{q_d} = [X, Y, Z]^T$. Here, PID controller is adopted to control PMSA to gain 3-DOF angle displacements. The co-simulation control platform is shown in Fig. 13.

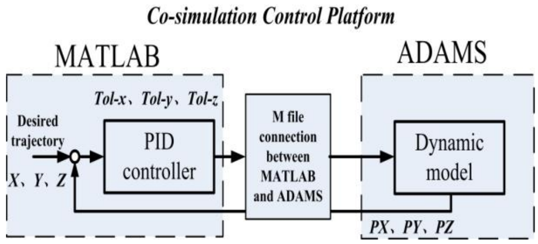


Figure 13. Structure of the co-simulation control platform

First, the input and output of the PMSA rotor model in the ADAMS were determined as state variables ($\boldsymbol{Tol}, \boldsymbol{q}$). The information exported as an M file was then exchanged with MATLAB through these variables in real time. Thus, the closed-loop PMSA control system was completed to achieve high-precision tracking control.

According to the above operation principle, we set up and tested the PMSA dynamic control system shown in Fig. 14 .

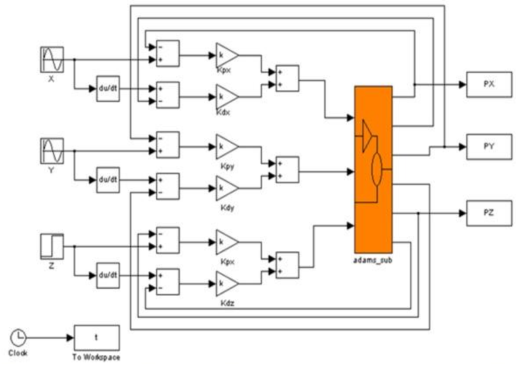


Figure 14. Structure of the co-simulation control system

The simulation time is set to 10 seconds and the sample time to 0.005 seconds. The desired trajectory is set to $\mathbf{q_d} = [0.02\sin(2\pi t), 0.02\cos(2\pi t), 0.119]^T$. The controller parameters are specified through some trials to achieve a favourable performance, such as proportionality factor $K_p = [35,35,18]^T$, differential factor $K_d = [8,8,2]^T$.

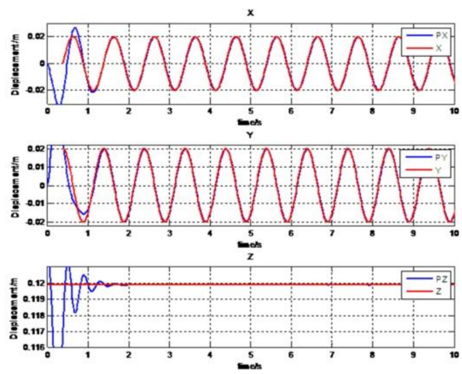


Figure 15. Angle-displacements tracking curve

Fig. 15 shows a practical angle-displacements response to the control torque. After about one second, three strong coupling angle-displacement components can track the desired trajectory smoothly accompanied with slight vibrations occurred. Compared to Fig.10, the PD co-simulation control system achieves more accurate and faster trajectory tracking.

Fig. 16 shows the input control-torque in real time. It can be seen that there are great vibrations during the 0-0.2 second, since in the initial time the PMSA rotor requires more energy.

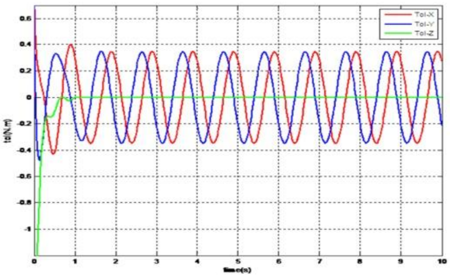


Figure 16. Control-torque curve

5 Conclusion

A novel method for designing, analysising and controling PMSA by using a co-simulation technique based on SolidWorks, ADAMS and MATLAB is presented. After dynamic modeling, characteristic analysis and PD co-simulation control are carried out to verify the method effectiveness. Compared with the traditional mathematical modeling, the method is easy to implement and is much more specific. It can also be applied to other complex mechatronic control systems.

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