11th International Symposium on Magnetic Bearings
August 26-29, Nara, Japan

AMB Flywheel-Powered Electric Vehicle

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ABSTRACT

This paper describes the new cocept and the configuration of AMB Flywheel-powered Electric Vehicle (AMB-FPEV) as the overview paper. In particular,flywheel (FW) energy storage system of AMB system, gimbal system, electric power steering system, circuit system of energy charge and discharge system, and partially autonomous driving control system are described. The real experimental data at outdoor running on the street is also shown with low speed.

INTRODUCTION

Flywheel energy storage system(FESS) works by accelerating a flywheel to a very high speed and maintaining the energy in the system as rotational energy. The energy is converted back by slowing down the flywheel. A typical system consists of a rotor suspended by bearings inside a vacuum chamber to reduce friction, connected to a combination electric motor/electric generator. Active magnetic bearings(AMBs) are necessary to improve a total energy efficiency. In conventional mechanical bearings, friction is directly proportional to speed, and at such speed, too much energy would be lost to friction. From this background, we have been focusing the good application in the use of active magnetic bearings in flywheel energy storage systems due to the significant advantages such as contactless and frictionless very high speed rotation. Besides such great advantages, in reality, the competitiveness of the magnetic bearings to other mechanical bearings in flywheel applications depends strongly on the reduction in bearing losses.

Flywheel-powered automotive car has been developing since long time ago and is ongoing research to make flywheel systems that are smaller, lighter, cheaper and have a greater capacity. It is hoped that flywheel systems can replace conventional chemical batteries for mobile applications, such as electric vehicles. Proposed flywheel systems would eliminate a problem of the disadvantages existing battery power systems, such as low capacity, long charge times, heavy weight, and short usable lifetimes. Also, it is not good for earth environment as lead pollusion.

When used in vehicles, flywheels also act as gyroscopic effect, since their angular momentum is typically of a similar order of a magnitude as the forces acting on the moving vehicle. This property may be detrimental to the vehicle's handling characteristics while turning. On the other hand, this property could be utilised to improve stability in curves. Conversely, the effect can be almost completely removed by mounting the flywheel within an appropriately applied set of gimbals, where the angular momentum is conserved without affecting the vehicles.

We have already achieved the good performance of the flywheel supported by zero-bias active magnetic bearings by means of the simplified controllers like schedulled adaptive PID controllers which completely compensate gyroscopic effects. The rotational speed of the flywheel can increase up to 300Hz without any gyroscopic effect. We have already mounted this FESS on an electric vehicle(EV) and designed the electric power conversion system as charge and discharge mode of energy. Also, we have already developed and implemented new algorithm to compensate gyroscopic effect while EV turning. Now we are going to verify the stearing performance of motion control and its total enegy efficiency comparing with conventional technologies. This paper will be explained the recent experimental results including the real EV maneuverability and drivability and the whole energy efficency comparing with conventional technologies.

WHOLE SYSTEM CONFIGURATION

Figure 1 shows the platform of AMB-FPEV. This AMB-FPEV is a very popular golf cart. And it is very easy to modify to flywheel-powered EV because of very simplified electric car. The specification of this EV is as follows;The whole length: 3,5m, The width: 1,2m,
The hight: 1,8m, The dry weight: 360kg, The maximum running speed: 20km/h, The maximum pasenger: 5 person,The battery voltage:48V,The motor power;2.8kW.

Figure 1: Flywheel-powered EV

Figure 2: Flywheel suspended by AMB

Figure 2 shows the Flywheel suspended by AMB with two axes gimbals. These gimbals will be used for vibration isolation in the case of acceleration and deceleration. Also, it will be useful for the turning of EV.

Figure 3 shows the side view of cross sectional schematic drawing.. The number 1 and 2 show the flywheel rotor and gimbals under the rear sheet. The weight of the flywheel rotor and gimbals is approximately 150kg. The behavior of the flywheel rotor and gimbals system is limited up to 20 degree like Fig.3 by using mechanical stoppers. Because the space is very limitted. The natural frequency of the flywheel rotor and gimbals system is located in the lower frequecy area comparing with the flywheel rotor without gimbals. According to stability analysis, the flywheel rotor and gimbals system can increase the stability zone. These analytical and experimental results will be explained in the related paper. This EV has four battery sets under the front sheet. Each battery is about 31kg and the whole weight is about 124kg. The number 3 means the battery location in Fig.3. The mode of charge and discharge can be controlled by means of the centralized main computer system and FW charger and discharger which will be automatically switched by using some signal of accel or brake pedal.

Figure 4 shows the overview of the whole control system. The main computer system is compact PCI (cPCI) Platform which consists of five parts including flywheel control module, steering control module, power control module, autonomous driving control module and pathfinder & vision control module shown in Fig.4. The EV will be able to be switched fully autonomous driving and partially autonomous driving systems. Curretly, the partially autonomous driving system has been installed.

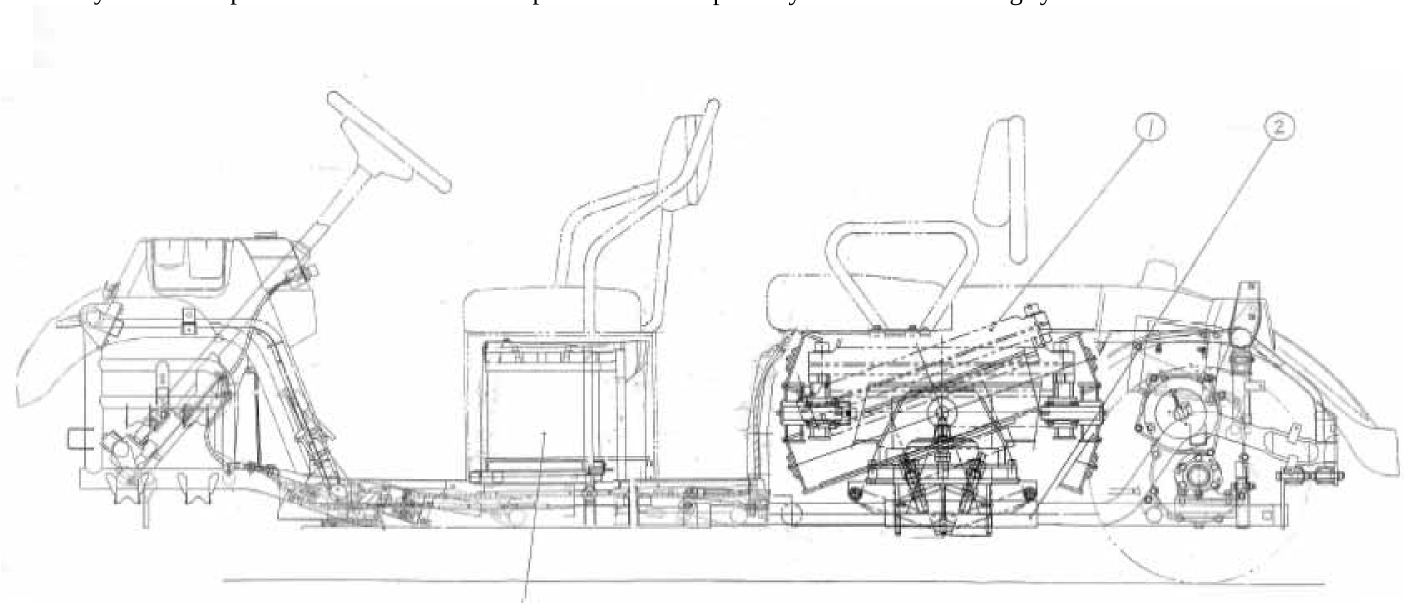

Figure 3: Top view of Flyweel rotor and gimbal arrangement

CIRCUIT DIAGRAM

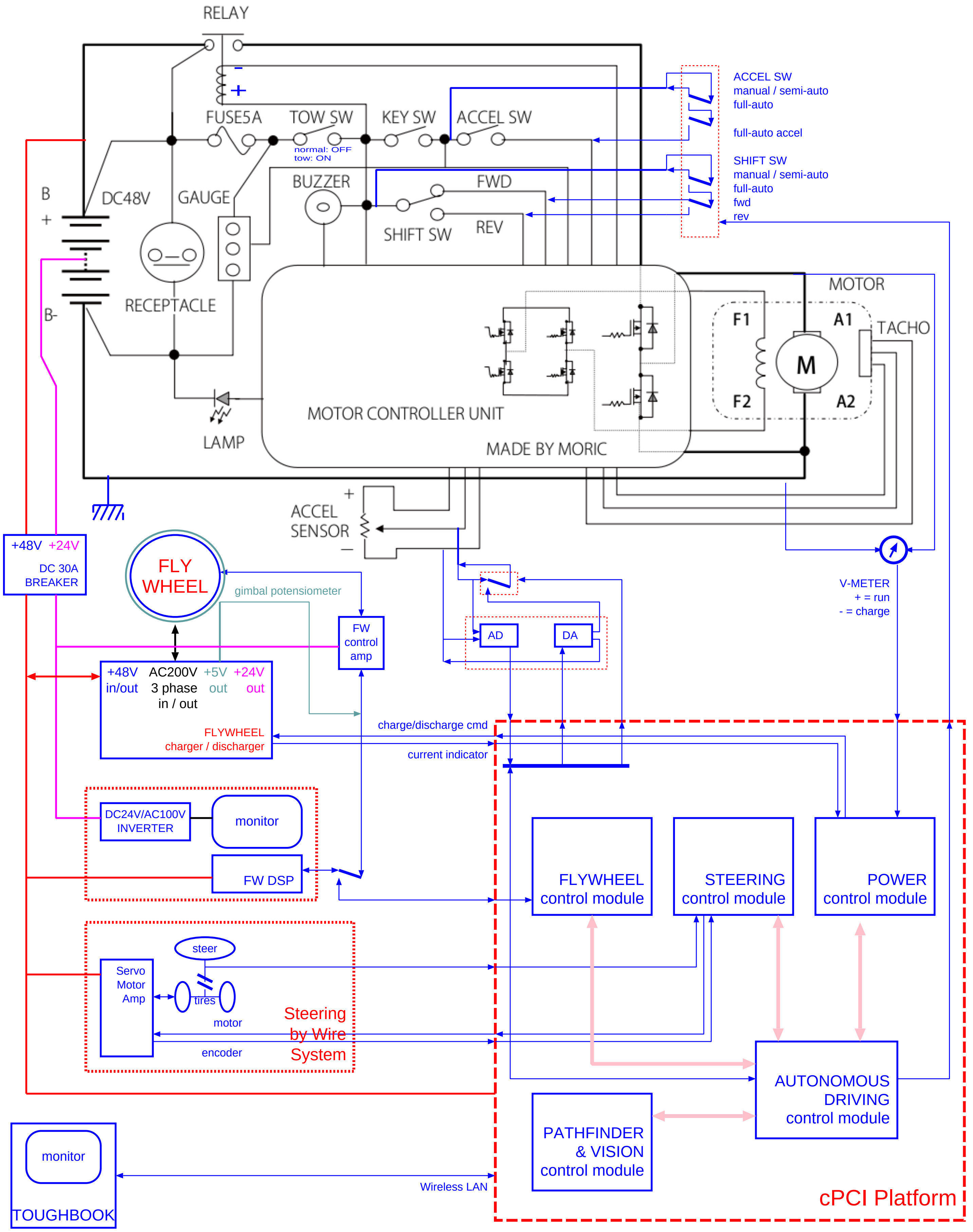

Figure 4: Confuguration of AMB-FPEV

This concept is very important to keep a good drivability and a maneuverability. This means that a reference trajectory as turning trajectory or acceleration and deceleration rate will be decided by human driver, and then the autonomous driving control module system in cPCI Platform computes the new trajectory in order to reduce the transient vibration and a gyroscopic moment. Also, the computed trajectory will be transmitted to steering control module. Finally, the new trajectory will be achieved by a servo computer controller step by step.

STEER BY WIRE DRIVING SYSTEM

Figure 5 shows the steering by wire schematic diagram. The steering handle encoder signal is going to the autonomous driving control module, and then the new trajectory will be computed and this new trajectory as a real reference signal is transmitted to the steering control module which sends the command to the driving motor via D/A converter. Also, the robust and adaptive servo controller will be following to achieve a reference signal. This mechanism is a quite important and main issue of this project which is already described.

Figure 6 and 7 show the original steering and the modified steering with the steering by wire system. According to Fig.5, the equation of motion of the motor is written as follows;

$$I_m\ddot{\theta}_m + C_m\dot{\theta}_m = T_m - \frac{1}{N_t N_m}T_c$$

I_m ; the motor inertia, C_m ; the motor damping, T_m; the motor torque, T_c ; the reaction torque, $N_t N_m$; the product of the steering gear ratio and the motor gear ratio. The equation of motion of the steering system is written as

$$I_t\ddot{\delta} + C_t\dot{\delta} = T_{SAT} + T_c \qquad \delta = \frac{1}{N_t N_m}\theta_m$$

Where, I_t ; the tire inertia, C_t ;the tire damping, T_{SAT} ; the self-aligning torque. Finally, the equation of motion is written as follows;

$$\left\{(N_t N_m)^2 I_m + I_t\right\}\ddot{\delta} + \left\{(N_t N_m)^2 C_m + C_t\right\}\dot{\delta} = T_{SAT} + (N_t N_m) * T_m$$

As the result, the contolled object is as follows;

$$I\ddot{\delta} + C\dot{\delta} = T_{SAT} + T$$

The servo control system is designed as the steering by wire sytem by means of the above equation of motion. The dynamical system parameters are estimated by system identification technique with experimental frequency responses.

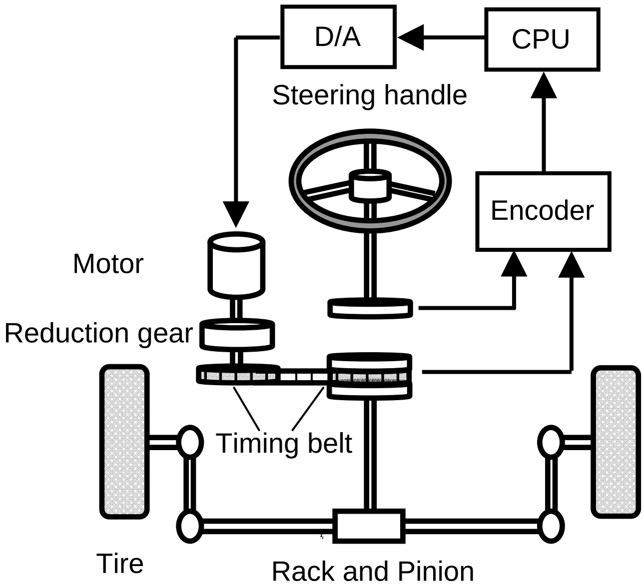

Figure 5: Configuration of steering by wire

Figure 6: Original front steering without steering by wire

Figure 7: Modified front steering with steering by wire

AMB FLYWHEEL ROTOR SYSTEM

Figure 8 shows the cross sectional view of the AMB flywheel system. Table 1 shows the specification of AMB flywheel rotor system. The zero bias control to save the whole energy is applied in this paper. It means that the bias current is not used in this system. The overview of AMB flywheel rotor system is shown in Fig.9. The total weight of Fig.9 is about 100kg. Figure 10 shows the schematic view of AMB flywheel rotor system supported by the inner and the outer gimbals. Figure 2 shows the setup view on EV. The gimbals weight is about 100kg including all components. We focused and

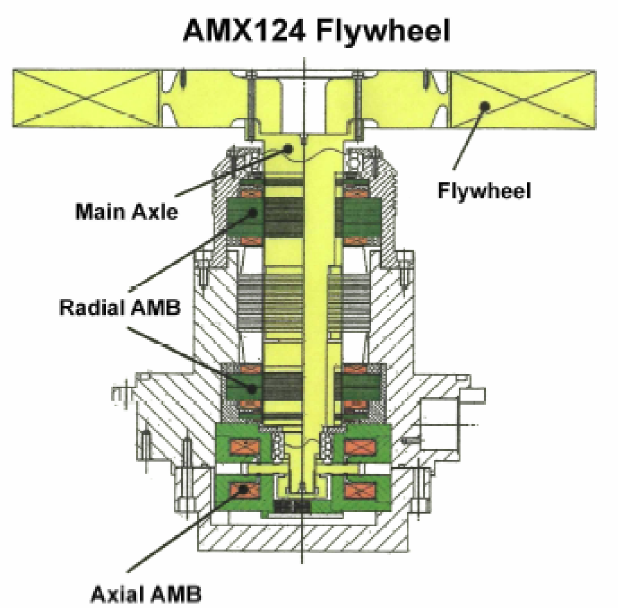

Figure 8: Flywheel energy storage system with active magnetic bearing

Figure 9: Overview of AMB flywheel rotor system

took into account the safety design so much against estimated several accident. The AMB flywheel rotor system has big gyroscopic effect because of overhang rotor. The several control scheme is applied as nonlinear control, passivity based control and adaptive control. In particular, the simple multi-input and multi-output adaptive control method is shown in Fig.11.

The simple adaptive control system uses a reference model in general. But, in the field of AMB, a reference model is not neccesary, and is to make tuning feedback gain by using output feedback signals like Fig.11.

EXPERIMENTS

Figure 12 shows the orbit of AMB flywheel rotor on EV without running at rotor speed. The left side means the upper orbit and the right side is the lower orbit. The maximum amplitude is approximately 3 μ m and the orbit seems very stable.

Table 1 Parameters of flywheel rotor-AMB

Nomenclature	Value
Mass of main rotor axle (M_r)	$4.85[kg]$
Mass of flywheel (M_f)	$8.82[kg]$
Moment of inertia about z axis (I_z)	$1.86 \times 10^{-1}[kgm^2]$
Moment of inertia about x and y axis (I_r)	$1.73 \times 10^{-1}[kgm^2]$
Constant of upper magnetic attractive force (K_u)	$3.10 \times 10^{-6}[Nm^2/A^2]$
Constant of lower magnetic attractive force (K_l)	$4.47 \times 10^{-6}[Nm^2/A^2]$
Distance from the center of the gravity (upper:L_u)	$4.99 \times 10^{-2}[m]$
Distance from the center of the gravity (lower:L_l)	$1.67 \times 10^{-1}[m]$
Nominal air gap (X_0),(Y_0)	$0.25 \times 10^{-3}[m]$
Bias Current (I_0)	$0.3[A]$

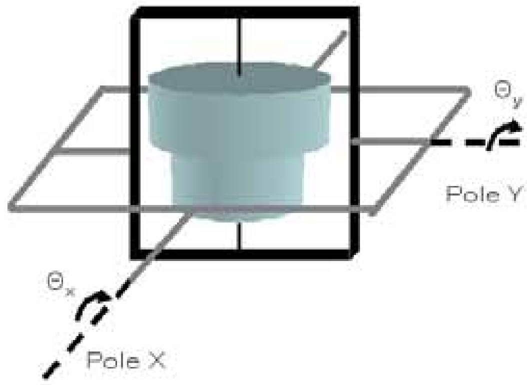

Figure 10: Schematic view of AMB flywheel rotor system suppoted by inner and outer gimbals

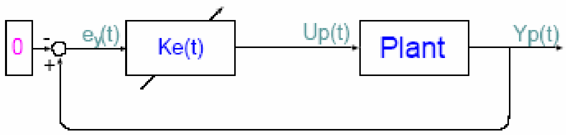

Figure 11: Zero Bias MIMO Simple adaptive control

Figure 13 shows the orbit of AMB flywheel rotor on EV with running at acceleration. Therefore, the orbit looks like unstable, but it is very stable orbit. Figure 14 shows the control display panel including important information. There are Flywheel rotor speed, Orbit plot with upper and lower side, FW status (charge or discharge), EV status (Accel, Decel, Steady), Input shaping (To reduce transient vibration and gyroscopic moment), Steering angle and EV speed, and so on.

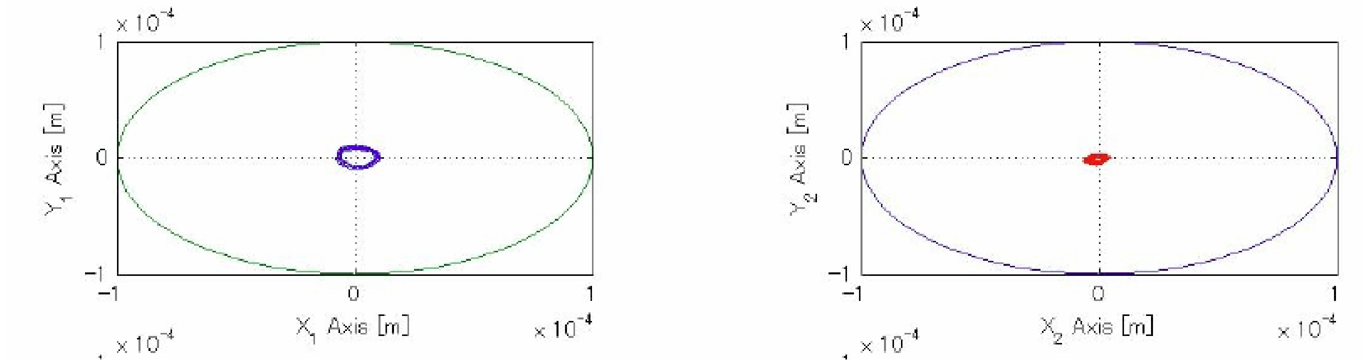

Figure 12: Orbit of AMB flywheel rotor on EV without running

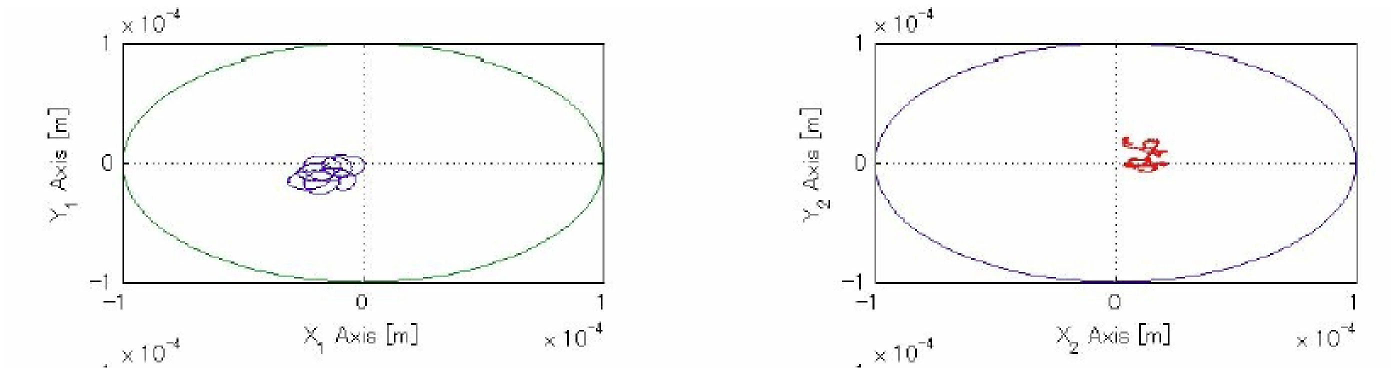

Figure 13: Orbit of AMB flywheel rotor on EV with running at acceleration

CONCLUSIONS

The new cocept and the configuration of AMB Flywheel-powered Electric Vehicle (AMB-FPEV) is explained. In particular, the whole system configuration of AMB-FPEV, the steering by wire driving system and the AMB flywheel rotor system have been described. The real experimental data at outdoor running on the street has been also shown with low speed.

According to the experimental results, it has been verified that AMB-FPEV is effective. The transient vibration and a gyroscopic effect have been well controlled by our proposal sheme in low running speed region. After this, the peroformance of AMB-FPEV will be verified at the more extreme situation like the larger acceleration rate and the emergency stop. The charger and discharger system of the energe conversion and the efficency of AMB-FPEV should be optimized .

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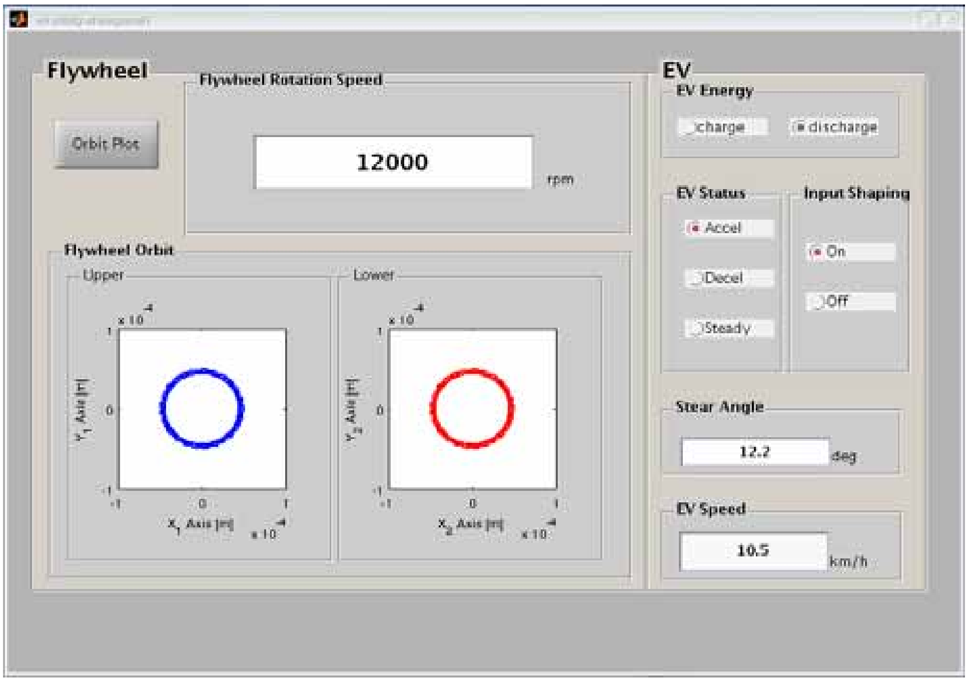

Figure 14: Control display panel