ATTITUDE CONTROL OF FLYWHEEL WITH TWO-AXIS GIMBAL AND NONLINEAR INPUT SHAPING

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ABSTRACT

Flywheels are commonly used to save energy temporarily. Mechanical flywheels are even seen in many sport cars for storing the kinetic energy to boost the acceleration up. Some manufacturers are currently developing (and producing) UPS (Uninterruptable Power Supply) that utilizes flywheel for its electric power storage. Usually they are massive and frictions are negligible.

However, when it comes to "Flywheel Energy Storage for Electric Vehicle", these can be a problem because frictions and many other things can happen to intrude the storage system which leads to energy losses.

This paper introduces a method to reduce the vibrations introduced by external forces to the system, by eliminating the components which potentially stimulate the vibration.

RESEARCH OBJECTIVES

Flywheel energy storage system with active magnetic bearing (AMB) is one of the effective methods to save electric power. Usually magnetic bearings are used in systems with fixed (non-movable) environment. Here then, we developed a vehicle with flywheel using magnetic bearing and gimbal mechanism as an energy storage system.

Our ultimate goal is to develop a vehicle using flywheel (which is very clean environmentally) as the energy storage, as an alternative to the commonly used conventional batteries.

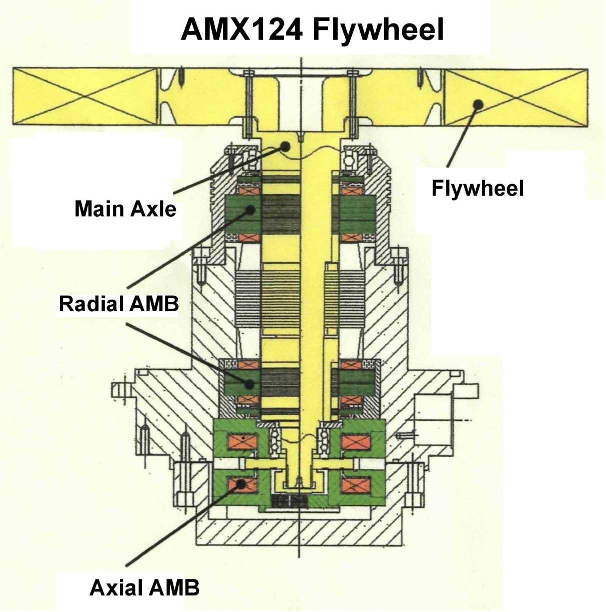

FIGURE 1: Flywheel Energy Storage with Active Magnetic Bearing

The real plant (control target) is a gimbal embedded flywheel (Fig. **1**) attached to an electric trolley (golf cart) as in Fig. **2**. Radial AMB means the AMB used for controlling the radial directions, and Axial AMB means the AMB controlling the axial direction. By this gimbal, the flywheel system has more two degree of freedoms, one is the angle about the longitudinal direction and the other is the angle perpendicular to the above angle.

The flywheel can rotate up to 18000 RPM (300 Hz). As

FIGURE 2: Flywheel attached to golf cart using gimbal mechanism

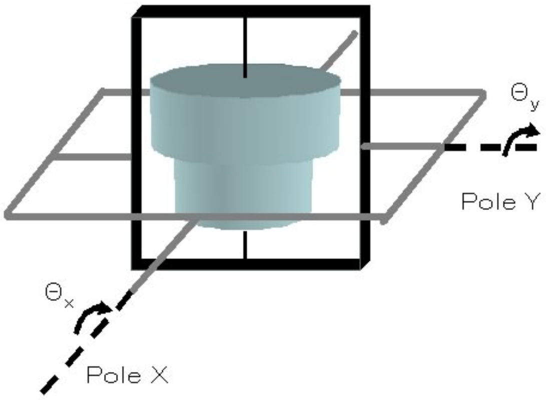

FIGURE 3: Overview of the gimbal mechanism

it is functioned as energy storage like a fuel tank, energy losses (because of friction, stabilization control inside the flywheel cage etc.) should be minimized. As we know a rotating rigid body has inertial moment and always keeps its attitude / position of rotation. However, vehicle can accelerate, brake and rotate. These phenomenons can make the flywheel unsteady, thus, a bad effect to the storage system which leads to energy loss.

We aim to control the movement of the trolley in such as, the influence to the inertial moment is minimized. Thus, the position of the flywheel will be very steady and energy loss will also be minimized. The reference track is given to the vehicle system, however, the actual track is more depending on the internal states of the flywheel and vehicle system. Thus, the result may differ from conventional (crane) systems below we use as reference models.

SYSTEM IDENTIFICATION

Modeling

By embedding the flywheel to a gimbal mechanism, the highly rotating flywheel acts like a gyroscope, and the gimbal mechanically compensate the inertial gyroscopic moment of the flywheel system. In other words, the gimbal helps the flywheel to keep its attitude. The gimbal will perfectly compensate if:

1. The mass of the gimbal frames are zero,
2. There is no friction between gimbal frames or between the frame and flywheel, and
3. The CoG (center of gravity) of the gimbal is the same as the CoG of the flywheel.

However, such gimbal is very difficult to create. A movement of gimbal can cause the attitude of the flywheel to be very unsteady. This is what we want to compensate on this research using input shaping algorithms and other control methods.

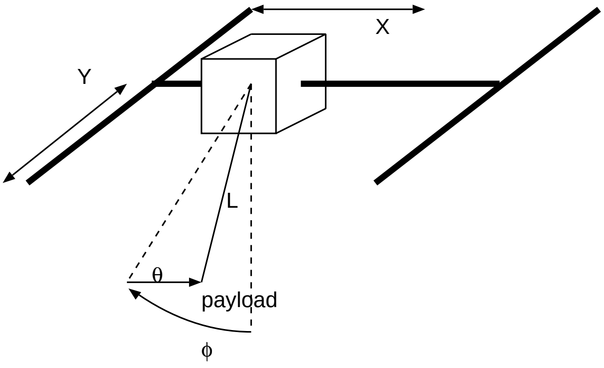

FIGURE 4: Bridge crane

Bridge Crane

In the actual system, the CoG of the flywheel is slightly lower than that of the gimbal. This makes this system, as in [1], with some exceptions, can be described as a Bridge Crane model having the following non-linear acceleration characteristics

$$
\begin{aligned}
L\ddot{\phi} + L\dot{\theta}^2 \cos\phi \sin\phi + g \sin\phi \cos\theta & \qquad (1) \\
= \ddot{x}\cos\phi + \ddot{y}\sin\phi\sin\theta, & \\
L\ddot{\theta}\cos\phi - 2L\dot{\phi}\dot{\theta}\sin\phi + g\sin\theta = -\ddot{y}\cos\theta & \qquad (2)
\end{aligned}
$$

which can be linearized to

$$
\begin{aligned}
\ddot{\phi} &= -\phi\frac{g}{L}+\frac{\ddot{x}}{L} && (3)\\
\ddot{\theta} &= -\theta\frac{g}{L}+\frac{\ddot{y}}{L} && (4)
\end{aligned}
$$

Tower Crane

Another model that can be used to resemble the actual system is a Tower Crane. This model is considerably better (but more complex) than Bridge Tower model. This is closer to the actual *Flywheel Electric Vehicle* system.

A tower crane with *non-rotating* payload has the following non-linear acceleration formula

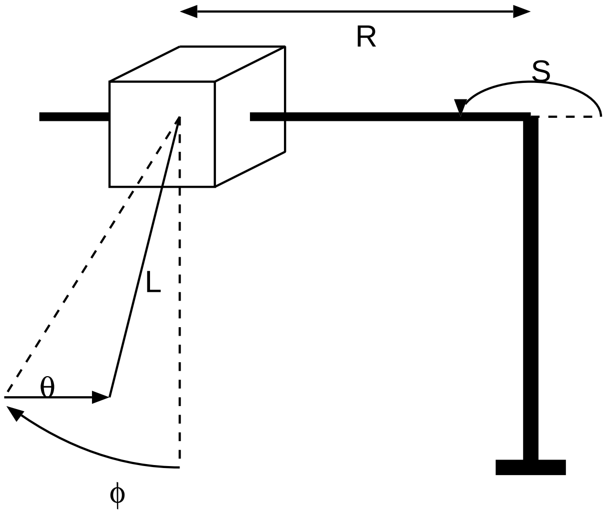

FIGURE 5: Tower crane

$$
\begin{aligned}
&L\ddot{\phi}+L\dot{\theta}^2\cos\phi\sin\phi+g\sin\phi\cos\theta && (5)\\
&=-\ddot{R}\cos\phi+R\dot{s}^2\cos\phi-R\ddot{s}\sin\phi\sin\theta\\
&-2\dot{R}\dot{s}\sin\phi\sin\theta-2L\dot{s}\dot{\theta}\cos^2\phi\cos\theta\\
&-L\ddot{s}\sin\theta+L\dot{s}^2\sin\theta\cos^2\theta\cos\phi,\\
&L\ddot{\theta}\cos\phi-2L\dot{\phi}\dot{\theta}\sin\phi+g\sin\theta && (6)\\
&=R\ddot{s}\cos\theta+2\dot{R}\dot{s}\cos\theta+2L\dot{s}\dot{\phi}\cos\phi\cos\theta\\
&+L\ddot{s}\sin\phi\cos\theta+L\dot{s}2\sin\theta\cos\phi\cos\theta
\end{aligned}
$$

which can be partially linearized to

$$
\begin{aligned}
\ddot{\phi} &= -\phi\frac{g}{L}-\frac{\ddot{R}}{L} && (7)\\
\ddot{\theta} &= -\theta\frac{g}{L}+\ddot{s}\frac{R}{L} && (8)
\end{aligned}
$$

Describing in state space domain, the variables the non-linear formula becomes

$$
\begin{aligned}
\vec{x} &= [\phi\ \dot{\phi}\ \theta\ \dot{\theta}\ R\ \dot{R}\ s\ \dot{s}]^T\\
\vec{u} &= [\ddot{R}\ \ddot{s}]^T
\end{aligned}
$$

with state space equations

$$
\begin{aligned}
\dot{x}_1 &= x_2\\
\dot{x}_2 &= -x_4^2\cos x_1\sin x_1-2x_8x_4\cos^2 x_1\cos x_3\\
&\quad -u_2\sin x_3+x_8^2\sin x_1\cos^2 x_3\cos x_1\\
&\quad +\frac{1}{L}(-g\sin x_1\cos x_3-u_1\cos x_1+x_5x_8^2\cos x_1\\
&\quad -x_5u_2\sin x_1\sin x_3-2x_6x_8\sin x_1\sin x_3)\\
\dot{x}_3 &= x_4\\
\dot{x}_4 &= 2x_2x_4\tan x_1+\cos x_3(2x_8x_2+u_2\tan x_1+x_8^2\sin x_3)\\
&\quad +\frac{1}{L\cos x_1}(-g\sin x_3+x_5u_2\cos x_3+2x_6x_8\cos x_3)\\
\dot{x}_5 &= x_6\\
\dot{x}_6 &= u_1\\
\dot{x}_7 &= x_8\\
\dot{x}_8 &= u_2 && (9)
\end{aligned}
$$

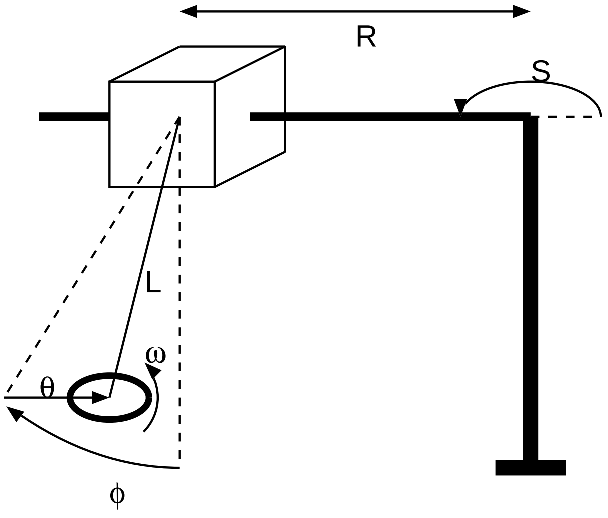

FIGURE 6: Tower crane with spinning payload

Tower Crane with Spinning Payload

The actual *Flywheel Electric Vehicle* system has a spinning payload (that is, the flywheel).Thus, we should also take the inertial moment of the rotating gyroscope (flywheel) into account. The attached payload is not a point mass. It is a rigid body and rotates about its axis.

Precession. The hanging flywheel behaves like a top (whirligig) as illustrated on Fig. **7**

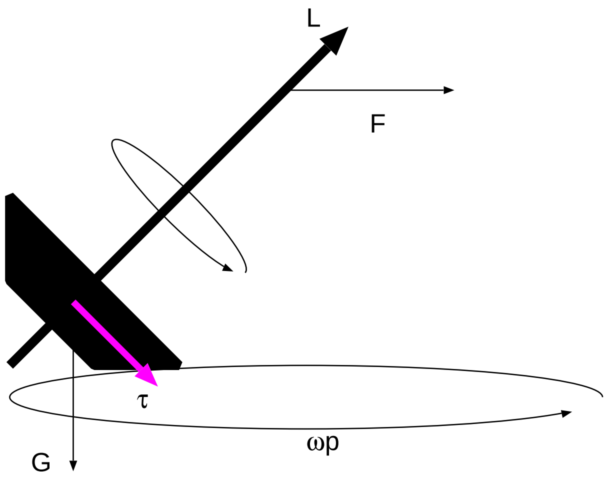

FIGURE 7: Precession of a top (whirligig)

When the vehicle (trolley) moves, it produces forces and also torques to the spinning payload. We may consider the torque as consisting of two components:

1. A component that has the same direction as the object's rotation axis, and
2. A component that is at a perpendicular angle to the rotation axis.

The component of the torque that lines up with the object's rotation axis will change its angular speed, just the way that a linear force acting along the direction that an object is sliding will change its linear speed - it will speed up if they act in the same direction, or slow down if they are in opposite directions.

The part of the torque that acts at a right angle to the spin direction will not make the object's rotation speed up or slow down, however. It will change the spin direction - a phenomenon known as *precession*.

Precession is the result of the angular velocity of rotation and the angular velocity produced by the torque. It is an angular velocity about a line which makes an angle with the permanent rotation axis, and this angle lies in a plane at right angles to the plane of the couple producing the torque. The permanent axis must turn towards this line, since the body cannot continue to rotate about any line which is not a principal axis of maximum moment of inertia; that is, the permanent axis turns in a direction at right angles to that in which the torque might be expected to turn it. If the rotating body is symmetrical and its motion unconstrained, and if the torque on the spin axis is at right angles to that axis, the axis of precession will be perpendicular to both the spin axis and torque axis.

Under these circumstances, the top's angular velocity of precession is given by:

$$\omega_p = \frac{\tau}{I_s \omega_s} \tag{10}$$

where

Is : the moment of inertia of the top
ω_s : the angular velocity of spin about the spin axis,
τ : the (external) torque.

As we know that $\omega = \frac{2\pi}{T}$, the period of precession can be calculated as:

$$T_p = \frac{4\pi^2 I_s}{\tau T_s} \tag{11}$$

In which Is is the moment of inertia, Ts is the period of spin about the spin axis, and τ is the torque.

Nonlinear model for tower crane with spinning payload disc.

For the above reasons, for a tower crane that has a spinning disc as the payload, Eq. 9 is slightly modified to describe the gyro effect of the flywheel disc.

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -x_4^2 \cos x_1 \sin x_1 - 2x_8 x_4 \cos^2 x_1 \cos x_3 \\
&\quad -u_2 \sin x_3 + x_8^2 \sin x_1 \cos^2 x_3 \cos x_1 \\
&\quad +\frac{1}{L}(-g \sin x_1 \cos x_3 - u_1 \cos x_1 + x_5 x_8^2 \cos x_1 \\
&\quad -x_5 u_2 \sin x_1 \sin x_3 - 2x_6 x_8 \sin x_1 \sin x_3) \\
&\quad +R_p \sin(\gamma_p) \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= 2x_2 x_4 \tan x_1 + \cos x_3 (2x_8 x_2 + u_2 \tan x_1 + x_8^2 \sin x_3) \\
&\quad +\frac{1}{L \cos x_1}(-g \sin x_3 + x_5 u_2 \cos x_3 + 2x_6 x_8 \cos x_3) \\
&\quad R_p \cos(\gamma_p) \\
\dot{x}_5 &= x_6 \\
\dot{x}_6 &= u_1 \\
\dot{x}_7 &= x_8 \\
\dot{x}_8 &= u_2
\end{aligned} \tag{12}$$

where

$$\begin{aligned}
R_p &= L(\sin^2 \phi + \sin^2 \theta \cos^2 \phi \\
&\quad +4 \sin \theta \sin \phi \cos \phi \cos s \sin s) \\
\gamma_p &= \omega_r t \\
\omega_r &= \frac{\tau}{I_s \omega_s} \\
\tau &= R_p M g
\end{aligned} \tag{13}$$

PASSIVE CONTROL USING FEED FORWARD INPUT SHAPER

Provided that the system is perfectly identified, input shaping is an effective method for reducing motion-induced vibration. In our research, this method is used to control the attitude of the flywheel while the vehicle is moving forward/backward or changing its direction.

In current research we apply Zero Vibration (ZV) and other input shapers as ZVD (Zero Vibration + Derivative) and UMZV (Unity-Magnitude Zero Vibration) to find the best solution for our system.

System Settings and Parameters

Table **1** shows the parameters and settings of the flywheel-AMB system used in the vehicle.

TABLE 1: Parameters of the flywheel-AMB system

Symbol	Description	Value	Unit
M	Rotor axle + flywheel mass	12.453	kg
I_s	Moment of inertia	0.08299	kgm^2
ω_s	Flywheel rotation speed	300	Hz

The vehicle is rotating left in a circle with radius of 10 meters. The actual gimbal mechanism (including the cage of the flywheel and rotor axle) weighs about 200 kilograms.

RESULTS

By using Input Shaping method (to control the external input force which may influence the energy storage flywheel system), we achieved reasonably likeable results, even with standard methods as ZV (Zero Vibration) and without compensated slewing shaper as proposed in [1].

Compared to normal unshaped input, ZV gives us a reduction rate of induced vibration at about 50 per cent. ZVD gives even better, approximately 60 % ··· 65 % of vibration reduction rate. UMZV, meanwhile, did not give us significant improvement in our system, compared to ZV.

Results on Non-Rotating Flywheel

Fig. **8** and Fig. **9** show the desired path of the vehicle and the actual path (of the flywheel system), when the flywheel is static towards its axis (i.e., not spinning).

Moreover, from Fig. **10** and Fig. **11** we can see the discrepancies of the payload (i.e. flywheel) relative to the car.

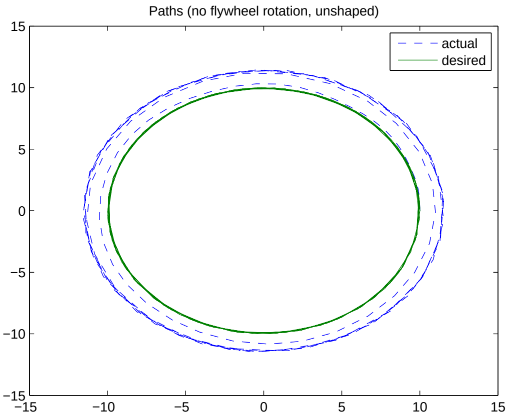

FIGURE 8: Desired & Actual Paths (no rotation, unshaped)

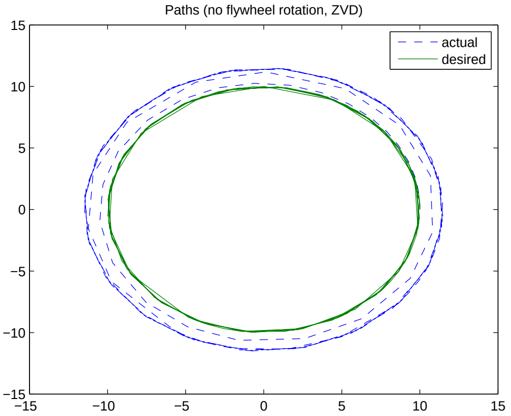

FIGURE 9: Desired & Actual Paths (no rotation, ZVD)

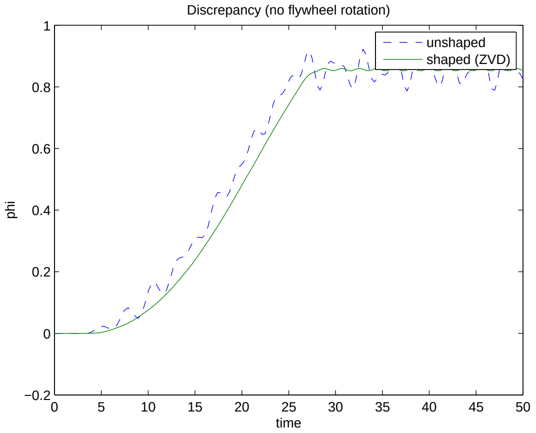

FIGURE 10: Discrepancy ϕ (no flywheel rotation)

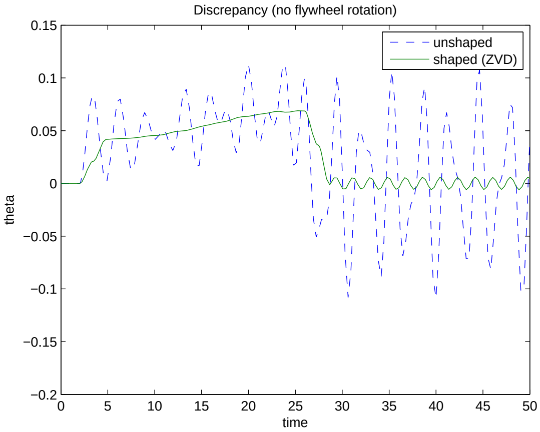

FIGURE 11: Discrepancy θ (no flywheel rotation)

The results shown here shows the ones with no input shaping applied, and the ones with ZVD input shaping method.

Results on Rotating Flywheel

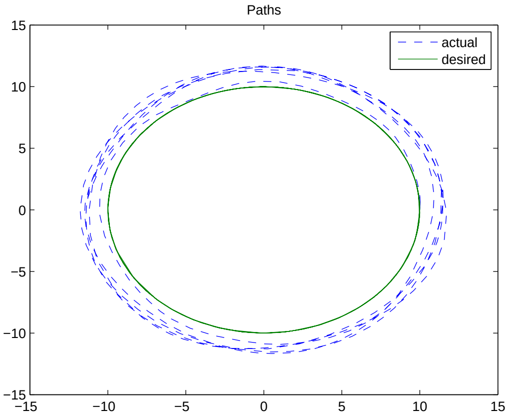

FIGURE 12: Desired & Actual Paths

Fig. **12** shows the desired path of the vehicle and the actual path (of the flywheel system), when the flywheel is rotating at 18000 RPM,

meanwhile Fig. **13** and Fig. **14** show the discrepancies of the flywheel relative to the vehicle.

From Fig. **15** and Fig. **16** we can see that, in our system, the result of ZVD (Zero Vibration + Derivative) method, is considerably better than the standard ZV (Zero Vibration) method.

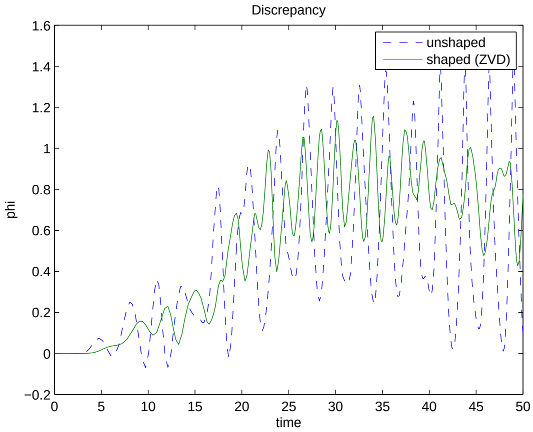

FIGURE 13: Discrepancy ϕ

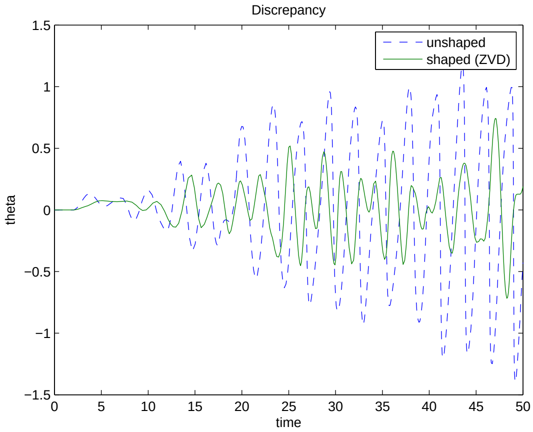

FIGURE 14: Discrepancy θ

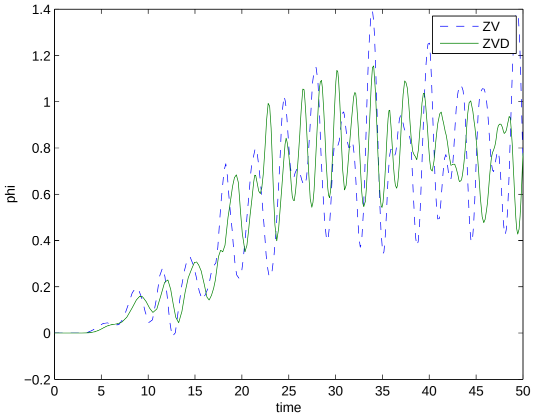

FIGURE 15: ZV vs. ZVD (ϕ)

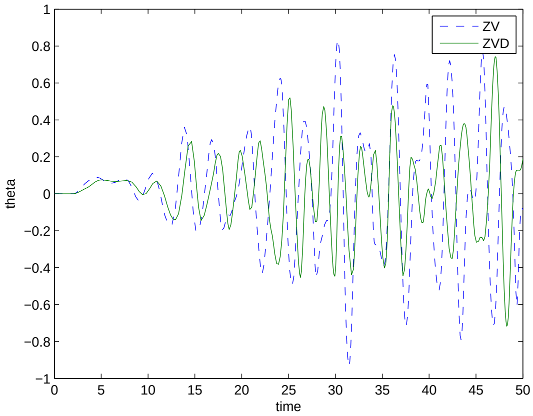

FIGURE 16: ZV vs. ZVD (θ)

SUMMARY & FUTURE WORKS

It is shown above that Input Shaping is effective in reducing vibrations that might be introduced by incoming external forces. In our system, even without using compensated slewing shaper, ZV (Zero Vibration) and particularly ZVD (Zero Vibration + Derivative) delivered reasonably likeable results.

In other hand, we are currently developing a testbed for evaluating AMB flywheel as an alternative energy storage system, in a project named " AMB Flywheel Powered Electric Vehicle ". In the near future, we plan to do the following researchs:

1. Combination of input shaping (feed forward control) and feedback control. Input shaping, from its name, is an effective way to manage the incoming external force, so as not to stimulate the vibration to the system. However, this method is not powerful enough to eliminate / reduce the vibrations that already existed before the external input comes in.

2. Using Charger/Discharger Unit, the developed vehicle is already able to *charge* and *discharge* the electric energy to and from the flywheel. The next step to do is measuring its *charging* and *discharging* efficiency as an energy storage.

3. Currently we have two types of flywheel that able to be implemented into the system; one is called *heteropolar flywheel* and the other one is *homopolar flywheel*. The flywheel currently attached to the car is heteropolar. Homopolar flywheel is expected to be having much higher efficiency than the heteropolar one. We plan to replace the currently attached heteropolar flywheel with the homopolar one, and examine how efficient it is.

4. Autonomous driving system. The flywheel car is now running on a *semi-automatic* mode. It can be driven by human being in a full *manual* mode or assisted by computer. In the future, while completing the development and research of *path finder / visioning system*, we aim to develop a full autonomous driving system.

References

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