Reduction of Engine Torque Ripple at Starting with Belt Driven Integrated Starter Generator

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***Abstract* - This paper describes a control method of belt driven Integrated Starter Generator (ISG) to reduce the engine torque ripple at starting, especially before combustion. It presents an analytical model of an engine and a belt without considering combustion, and proposes a control algorithm that manipulates the torque of ISG to reduce a vibration of the engine based on the estimated engine torque ripple and the belt dynamics between the engine and ISG. This method does not require any other information except crankshaft angle and ISG speed which are already available in the vehicle. Using proto type ISG and engine system, some simulations and experiments are carried out to verify the algorithm. The experimental results reveal more than 50% reduction of the ripple torque.**

I. Introduction

Since it has been known that the Integrated Starter and Generator(ISG) can generate more electrical power and improve fuel economy and reduce emission by stopping the engine at idle compared to conventional separate starting motor and Lundell alternator. ISG is an essential component of 42 Volt powernet, which is considered to replace the conventional 14 Volt system in the passenger vehicle. Even in traditional 14 Volt system, ISG is applied to improve fuel economy. In addition to the benefits above mentioned, the ISG can provide additional function such as reduction of the engine ripple torque inherent to combustion engine. There have been several research results to reduce engine ripple torque, but most of them are about crankshaft coupled ISG or hybrid one, which require relative large electric machine and modification of powertrain[1,2,3]. A possible alternative to this crankshaft coupled ISG is a belt driven ISG, which is easier to package, compatible to the conventional under-hood layout, and permits small electric machine with belt and pulley. But, in this case, it is more difficult to reduce the ripple torque because of the flexibility of belt and belt ratio[4].

This paper proposes a control method of 42V belt driven ISG system to reduce the engine torque ripple at starting. So, the vehicle can start smoothly after idle stop, that would be a great asset to passenger comfort. The method uses the information of crankshaft angle, which is already available in the vehicle, and no other information is needed. At starting mode before combustion, the torque of ISG is enough to suppress the ripple torque, and the flexibility of belt is able to be compensated by a properly designed compensator. The effectiveness of the proposed method is verified by both simulations and experimental results.

II. Estimation of Engine Torque

With the Fig. 1, the torque at the crankshaft can be expressed as a function of crankshaft angle, which is given in (1).

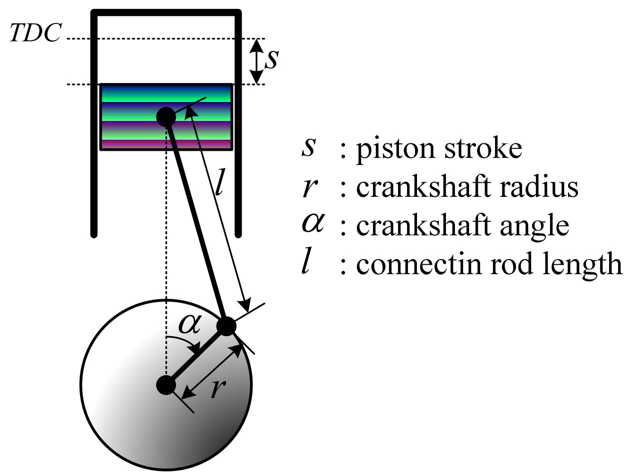

Fig. 1. Piston and crankshaft motion

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$$T_{engine}(\alpha)=\sum_{j=1}^{CYL}(p_j(\alpha)-p_0)A_p\frac{ds_j}{d\alpha} \quad . \qquad (1)$$

,where CYL is the number of cylinders, A_p is the piston crown surface area, α is the crankshaft angle as defined in Fig. 1, s_j is the piston stroke of j-th cylinder from Top Dead Center (TDC), p_j is the j-th cylinder pressure, and p_0 is the average pressure of intake manifold[5].

The cylinder pressure, p_j, is the sum of the motoring pressure and the combustion pressure. The former is due to the change of the cylinder volume as the crank rotates and the latter due to the combustion of fuel. On initial starting or restarting after the engine is stopped at idle, the engine speed is increased by ISG near the idle speed without combustion, thus only motoring pressure of engine should be considered. The motoring pressure can be expressed as following equations with assumption of isothermal process[2,5].

$$p_j(\alpha)=\frac{p_o}{\dfrac{V(\alpha)}{V_d+V_c}} \quad . \qquad (2)$$

$$V(\alpha)=V_c+A_p\left(l+r-s'\right)$$
$$s'=r\cdot\cos\alpha+\sqrt{l^2-r^2\cdot\sin^2\alpha} \quad . \qquad (3)$$

,where V_c and V_d are the clearance volume and the displacement volume of the cylinder respectively, and l, r are defined in Fig. 1.

Because it is a function of crankshaft position and average manifold pressure, the torque ripple can be easily modeled by equations from (1) to (3) when there is no combustion.

III. Model of Belt and Pulley System

As mentioned above, in the belt driven ISG, the maximum motor torque can be reduced, the layout change of underhood is minimized, and the design of ISG is free from temperature and vibration of engine. However, from the viewpoint of torque ripple control, the belt driven ISG is not a good candidate because of the flexibility of the belt. The

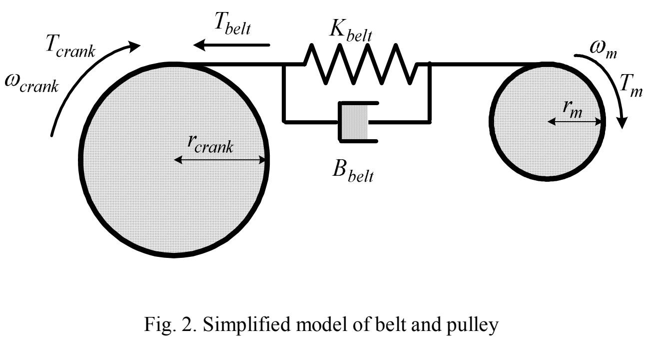

Fig. 2. Simplified model of belt and pulley

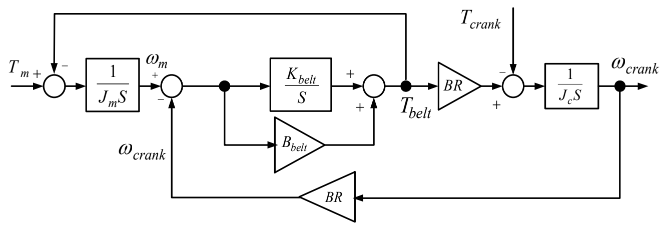

Fig. 3. Block diagram of the belt pulley system

torque of ISG is distorted by the belt, so the transfer characteristics from ISG torque to crank shaft torque through the belt and pulleys must be considered.

Shown in Fig. 2, the V ribbed belt, which is used in this study, could be modeled as a spring and a damper with assumption of no slip between the belt and pulleys[6]. In Fig. 2, K_{belt} stands for the spring constant of belt, B_{belt} stands for the damping of the belt and pulley system.

With this simple model, the state equation of the system can be derived as (4). And it can be expressed as a block diagram form as shown in Fig. 3, where BR means ratio of pulley diameters, and J_m, J_{crank} mean inertia of ISG and that of engine respectively.

$$\omega_m=\frac{1}{J_m\cdot s}\cdot\left(T_m-T_{belt}\right)$$
$$\omega_{crank}=\frac{1}{J_{crank}\cdot s}\cdot\left(BR\cdot T_{belt}-T_{crank}\right) \quad . \qquad (4)$$
$$T_{belt}=\left(\frac{K_{belt}}{s}+B_{belt}\right)\left(\omega_m-BR\cdot\omega_{crank}\right)$$

IV. Control Method

Fig. 4 shows the simplified control block diagram of the proposed method. The controller calculates the ISG reference torque using the information of the crankshaft angle, the ISG angle, and the DC link voltage of PWM inverter, which are already available in the commercial vehicle.

With estimated ripple torque, mentioned in II, the reduction of ripple torque would be possible if the estimated torque could be applied against engine torque directly without belt and pulley. But, unfortunately it is impossible to apply the torque to engine directly. It is only possible to apply torque to engine via the belt and pulley, which transfers torque from ISG to the engine. Hence, the consideration of the dynamics of the belt and pulley is necessary. From Fig. 3, the transfer function from the ISG torque to the engine torque can be derived as (5) with the consideration of the dynamics of belt system.

$$\frac{T_{belt}}{T_m}=\frac{J_{crank}B_{belt}s+K_{belt}J_{crank}}{J_{crank}J_m s^2+B_{belt}(J_m BR^2+J_{crank})s+K_{belt}(J_m BR^2+J_{crank})} \quad . \qquad (5)$$

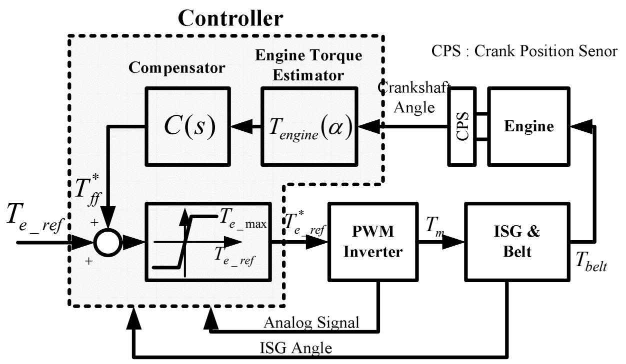

Fig. 4. Block diagram of proposed control method

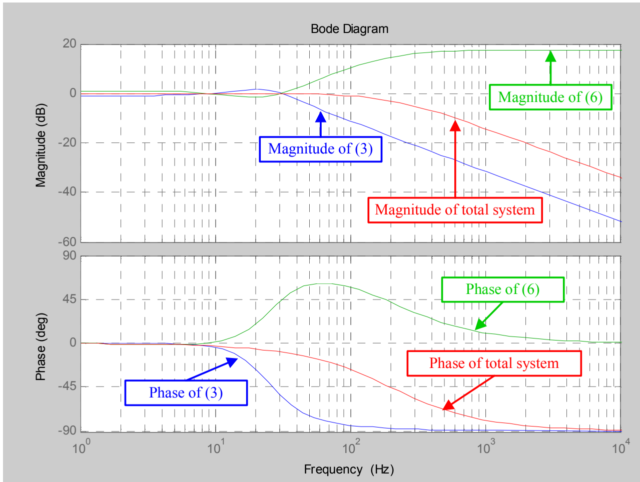

Fig. 7. Bode Diagram of (3), (6), and total system

After extensive tests with test set-up, the typical parameters of (5) were extracted. With the parameters a Bode plot of (5) is shown in Fig. 5. Based on the Fig. 5, a compensator can be designed to minimize the effects of the belt pulley system. At starting, the engine speed reaches about 6~10Hz, and in the case of 6 cylinder engine, the fundamental frequency of engine ripple torque rises up to 20~30Hz. From the Fig. 5, the gain is almost 0dB, and the phase is about 40° at this frequency range. Thus the compensator should compensate the phase delay of the belt system up to this frequency range. To meet the control purpose, the second order lead-lag network has been designed as (6). The proposed compensator has poles and zeros that cancel the zeros and poles of (5) and additional pole(ω_c) that is far away from these poles and zeros. Bode diagram of designed compensator is presented in Fig. 6, and that of total system is showed in Fig. 7. It is notable in Fig. 7 that the diagram of total system has the characteristics of the 1st order low pass filter of which cut-off frequency is ω_c.

$$C(s) = \omega_c \cdot \frac{J_{crank} J_m s^2 + B_{belt}(J_m BR^2 + J_{crank})s + K_{belt}(J_m BR^2 + J_{crank})}{(J_{crank} B_{belt} s + K_{belt} J_{crank})(s + \omega_c)} \quad (6)$$

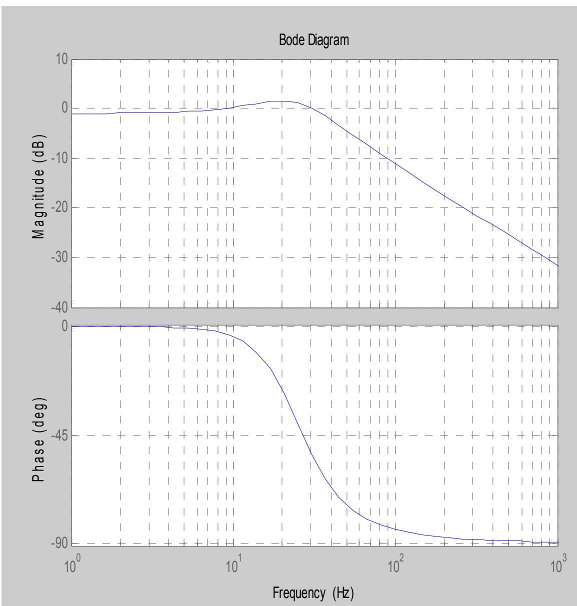

Fig. 5. Bode diagram of (3)

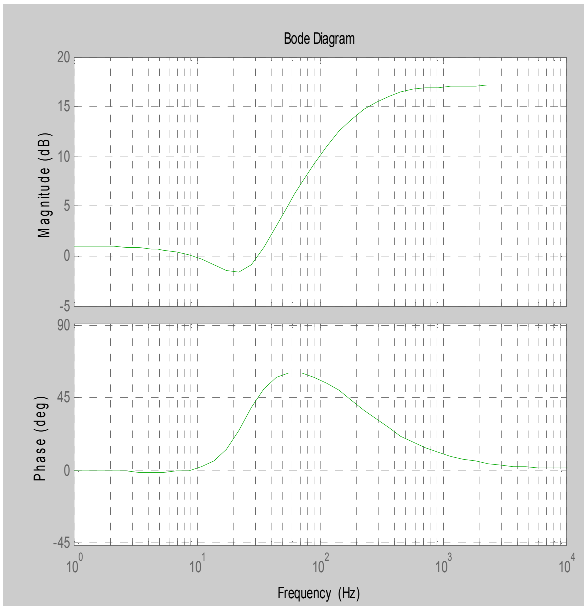

Fig. 6. Bode diagram of compensator

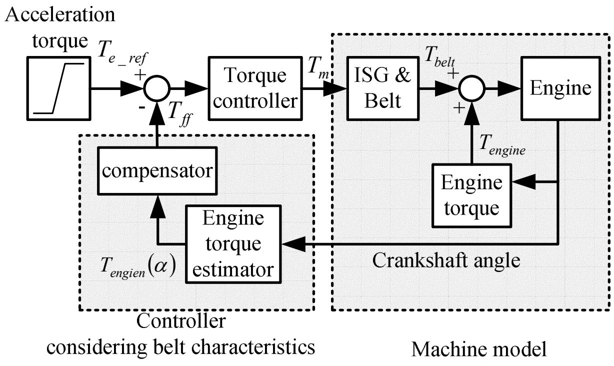

Fig. 8. Simulation block diagram

V. SIMULATIONS

Fig. 8 presents computer simulation block diagram of proposed control method in section IV. Through the simulation, it is assumed that there is no combustion in engine and no slip in belt and pulleys. The inertia of crankshaft is considered as a constant. On starting, the engine rotates not by engine combustion torque but by ISG torque, and the inertia of crankshaft is a function of crankshaft angle, but the variance is very small compared to the total value. Thus the assumptions can be justified. The torque controller in Fig. 8 limits the ISG torque according to ISG speed. The parameters used the simulation are shown in table 1.

Table 1. Parameters of engine, ISG, belt, and pulleys

Inertia of engine	J_{crank}	0.006 [kg.m^2]
Inertia of ISG	J_m	0.2 [kg.m^2]
Pulley ratio	BR	2.5
Spring constant of belt	K_{belt}	130 [Nm/rad]
Damping constant of belt and pulleys	B_{belt}	1 [Nm/(rad/sec)]

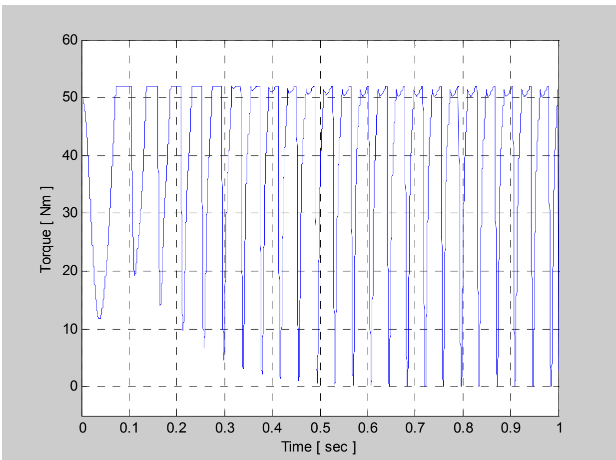

Fig. 9. ISG torque reference

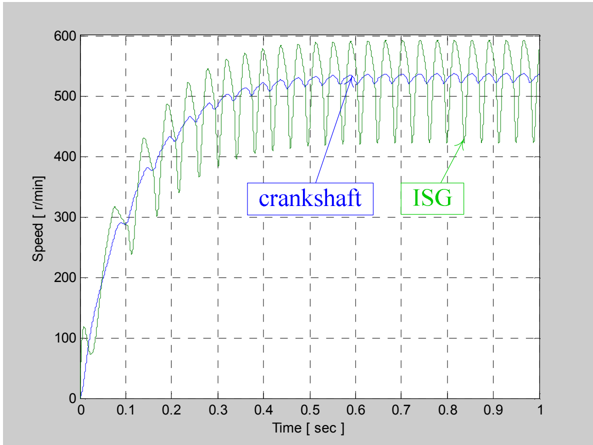

Fig. 10. Speed of ISG and crankshaft

Fig. 9, 10 show the waveforms of the torque, the speed of ISG, and the speed of engine versus time, when the proposed algorithm is applied. Fig. 11 is the waveforms of engine speed versus crankshaft angle for comparison, when a constant torque (50 [Nm]) is applied and the torque in Fig. 9 is applied to the ISG. In Fig. 9, the maximum torque is limited to 53 Nm, so the average torque is reduced. This causes the difference of the steady state speed of crankshaft between the cases when the controller is active and inactive. Fig. 11 illustrates this phenomenon. However, this is not a critical problem because, for the most application, the combustion of the engine starts above 400~500 r/min. In the case of application that requires high idle speed without combustion, especially in the electric vehicle creep mode, the ratio of speed ripple of crankshaft to steady state crankshaft speed can be a trade-off by introducing a constant gain, from 0 to 1, to T_{ff}, which is the term for compensation of ripple torque, in Fig. 8.

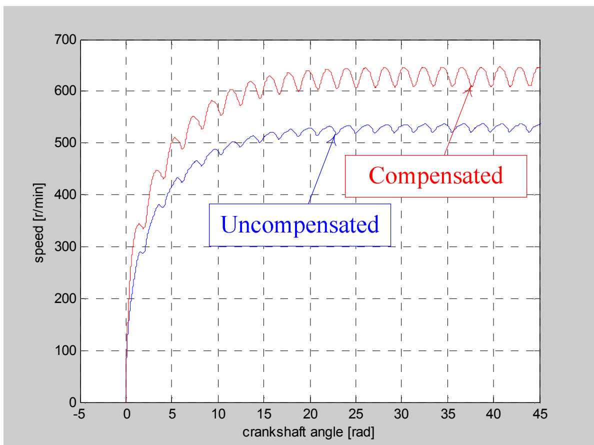

Fig. 11. Crankshaft speed with and without compensation

a) Exterior of the test vehicle b) ISG

c) 36V,12V batteries and DC/DC converter d) Inverter

Fig. 12. Test vehicle equipped 42V components

VI. EXPERIMENTAL RESULTS

The proposed control algorithm is applied to a vehicle with 2.5Liter 6 cylinder gasoline engine. The vehicle has been modified to accommodate to equip the 42V powernet components like 36V battery, ISG, inverter, and DC/DC converter. The inverter, which is connected to the 36V battery, delivers power from battery to ISG at motoring mode, or from ISG to battery at generating mode. Since most of electric loads are based on 14V ratings, the DC/DC converter and the 12V battery are needed. Fig. 12 shows the view of exterior and the view of inside of the hood of the test vehicle.

In Fig. 13 the crankshaft speed has been compared as a performance index of the vibration at starting. The compensated case indicates less speed ripple, which means less torque ripple. The ripples have been reduced to a half of the uncompensated case. In Fig. 14, at starting with compensation by proposed method, the torque command, the estimated ripple torque, the speed of ISG, and speed of crankshaft are shown. The torque command is limited due to the limited torque capability and the field weakening operation above a certain speed of ISG. This limited torque command causes the difference of the steady state speed between compensated and uncompensated case in Fig. 13, but it has not much meaning in the real applications as mentioned in section V. Regardless of the limitation of the magnitude, the phase of the torque is controlled to suppress the estimated ripple torque as expected.

To investigate the effect of proposed method on the ride, the vibration of the vehicle is measured at the driver's seat with an accelerometer. Fig. 15, 16 present the test method and the results. As shown in Fig. 16, when compensated, the vibration of y and z direction is considerably reduced up to 50% compared to the uncompensated case.

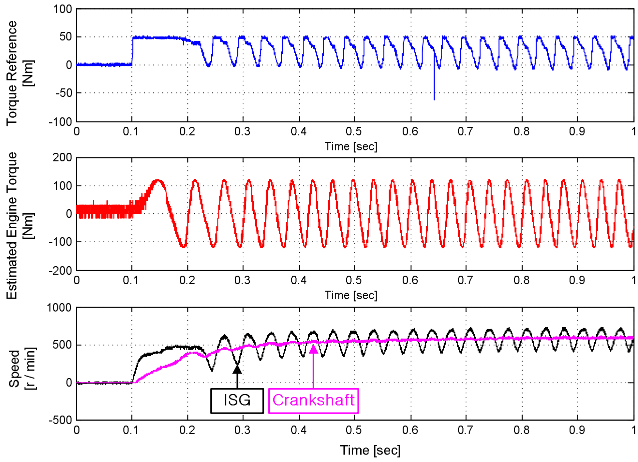

Fig. 14. Torque command, estimated ripple torque, speed of ISG, and speed of crankshaft

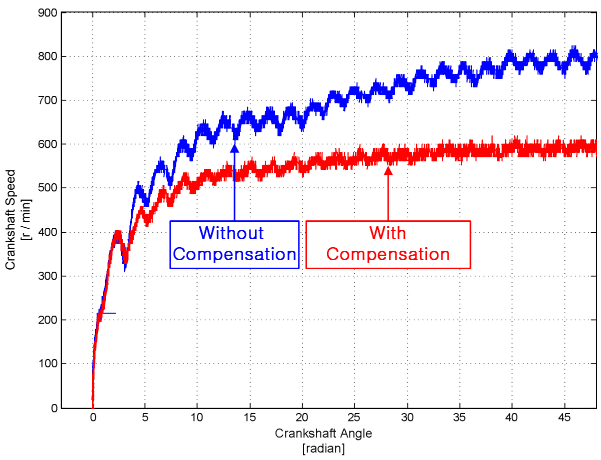

Fig. 13. Crankshaft speed with and without compensation

Fig. 15. Position of accelerometer

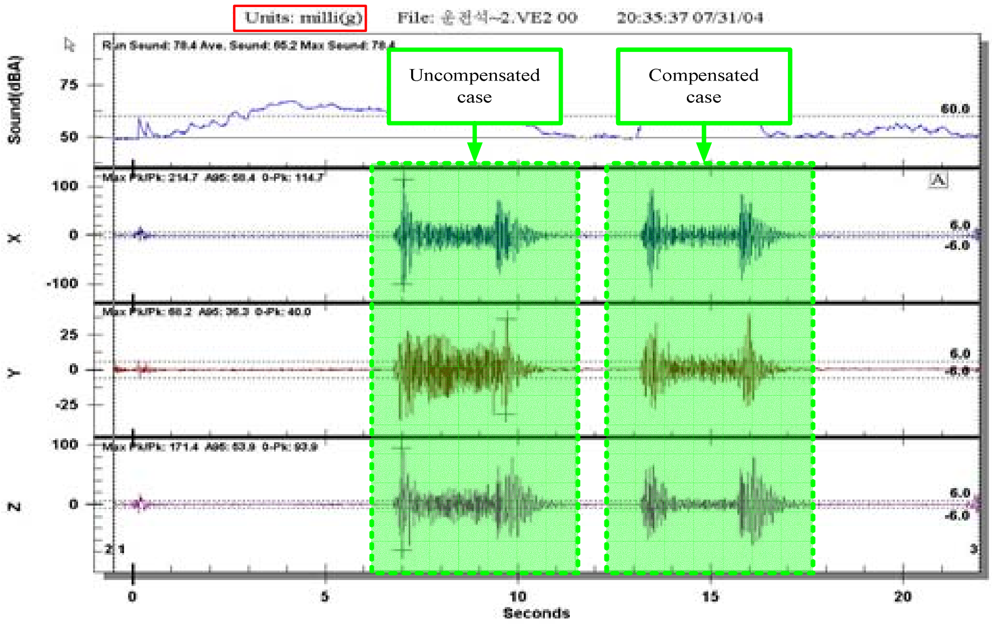

Fig. 16. Accelerometer measuring result

VII. Conclusions

In this paper, a control method of 42V belt driven ISG system to reduce the engine torque ripple at starting has been proposed, in order that the vehicle can start smoothly. The simple analytical model of an engine without considering combustion has been presented, and the dynamic model of belt and pulleys also has been described. Based on these models, the controller that can suppress the torque ripple intrinsic to an internal combustion engine has been designed. Some simulation and experimental results have been presented to verify the effectiveness of the method. The results show more than 50% reduction of the torque ripple. The method uses only the information of crankshaft angle, which is already available in vehicle. Therefore it can be easily applied to the vehicle with belt driven ISG.

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References

[1] Hyeoun-Dong Lee, Seung-Ki Sul , “Diesel Engine Ripple Torque Minimization for Parallel Type Hybrid Electric Vehicle” , Conf. Rec. IEEE-IAS Annual, Meeting , 1997.

[2] Roy I. Davis, Robert D. Lorenz, “Engine Torque Ripple Cancellation with an Integrated Starter Alternator in a Hybrid Electric Vehicle : Implementation and Control”, IEEE Trans. on Industry Applications Volume 39, No.6, 2003.

[3] A.T. Zaremba, R.I. Davis, “Control Design for Active Engine Damping using a Starter/Alternator”, Proceeding of the American Control Conference, 2000.

[4] Rassem R. Henry, Bruno Lequesne, Shaotang Chen, Jeffrey J. Ronning, Yanhong Xue, “Belt-Driven Starter-Generator for Future 42-Volt Systems”, SAE SP-1619.

[5] U. Kiencke, L.Nielsen, “Automotive Control Systems for Engine, Driveline, and Vehicle”, Springer.

[6] J.S. Snadhu, M.K. Wehrly, and W.F. Resh, B.A. Rose, “An Investigation of Rotational Response of Accessory Drive Serpentine Belt System”, SAE 01NVC-227