Simulation of Battery SOC State of a Hybrid Electric Vehicle

(Applying a Proposed Method of Road Inclination Convert
to a Data Received by GPS)*

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Abstract

This report evaluates a position of SOC (State of Charge) along with a down hill drive on a real world to its simulation on an emission chassis dynamometer with a gradient road load. On a down hill drive, a vehicle kinetic energy regenerates the battery continuously and an amount of charge volume which shifts the battery SOC up. Excessive charge is a negative factor for the battery life which is designed both a long term of life and a long distance of drive. This regenerating driving mode could not be evaluated on a flat road. A gradient drive way or a gradient simulation system forced energy into a vehicle could evaluate the mode. To evaluate, on the one hand some necessary investigation is carried out to a realization of a down hill drive simulation on an emission chassis dynamometer and problems hitting upon the investigation has been clarified. On the other hand the real world data driving down hill is measured by HEV (Hybrid Electric Vehicle). The real world data collected by GPS (Global Positioning System) has fluctuated widely. This report proposes a method of spline interpolation to the data for a chassis simulation test and reviews the results of the test to the real world mode and evaluates the studies. And here we also report an applied chassis simulation for the study of this method.

Key words: Automobile, Motion Control, Simulation, Data Processing, Filter

1. Introduction

Environmental protection activity to the global warming program has been carried out in a various industrial fields. CO2 volume emitted from a transport industrial field reaches 20% of the other fields of Japan. Further more, the vehicle part of transports add up to 90% of the field ⁽¹⁾. To promote an environmental technology industry is developing for asking efficient vehicles. Hybrid electric vehicle (HEV) technology is one of the solutions which reached market near in 2000. Marked point of HEVs is to reserve a regenerate energy into a battery and to discharge at demand.

Adaptive energy management control under the design capacity is a suited solution in actual use. Major regenerating energy driving is a mode when coming to a stop and when driving down hill drive. The mode at a drive to stop is the pair mode of stop to drive which the management system is able to control energy balance. The mode at a down hill drive is the pair mode of hill climb drive which the management system is also able to control energy balance. Regenerating energy into the battery charges it which shifts the battery

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SOC up. Excessive charge is reduces battery life ⁽²⁾. The down hill driving mode could not be evaluated on a flat road. A gradient drive way or a system that forces energy into a vehicle could evaluate the downhill drive mode.

This paper evaluates SOC track line along with a down hill drive on a real world to its simulation drive on an emission chassis dynamometer with a function of gradient road load. At first, real world data driving down hill with HEV is measured. And also some necessary investigation is carried out to simulate the down hill drive on an emission chassis dynamometer. Problems hitting upon the investigation are clarified, and a spline interpolation method is proposed that the real world data transfigures to the chassis dynamometer setting. The chassis dynamometer simulation could evaluate the tracking line of SOC except for altering points of the vehicle directions in which both human brake working and vehicle brake control differ on the real world descent way. This paper reviews the results of the real world mode simulation on the chassis dyno and evaluates the studies. And further more study is carried out an applied chassis simulation.

2. Data measurement of real world modes

2.1 Outline for a data measurement system of HEV

Figure 1 shows the HEV on-board data measurement system for real world modes. The HEV consists of a hybrid engine of 179kW (240hp) output, 3L (liters) exhaust volume, and a hybrid motor of 11.9kW output.

Fig. 1 On-board measurement system of HEV

A Ni-MH (Nickel metal hydride) battery pack is located behind the rear sheet. The system voltage of the battery is 144V and the capacity is 6.0Ah. Measuring instruments are a GPS (Global Positioning System) sensor for the vehicle location data and a PC (Personal Computer) for the vehicle control data.

2.2 Results of the measurement

Real world modes are measured on a freeway with gradient road load in North America. Fig. 2 shows a vehicle tracking line measuring by GPS. The track starts at the point of elevation 944m, goes up to 1314m and then down to 116m. The total distance is about 100km and the driving time is about one hour. The freeway is a major trunk line located in a suburban area of a giant city. The test is performed during the middle of the day when traffic on the freeway is at a minimum.

Figure 3 shows both car speed and elevation measured by GPS. The car speed data fluctuates and some data processing before analyzing the data is necessary. Elevation seems much more stable than the car speed. It may be easy to calculate a gradient $\tan\theta$ from the elevation data. In the forefront of the applying, considerations have to be done because the data sources are the same like the car speed by GPS.

Fig. 2 Drive way of the field test

Fig.3 Car speed and elevation of the field test by GPS

3. A function of chassis dynamometer with gradient road load

This chapter estimates a realization of a simulation for real world modes with inclination road load on an emission chassis dynamometer with gradient road load.

$$F_c(t) = \mu_r \cdot W_c + \mu_a \cdot A_c \cdot V_c^2 + W_c \cdot \sin \theta + \frac{W_c + \Delta W_c}{g} \cdot \frac{dV_c}{dt} \quad (1)$$

herewith,

t : time [sec.]

V_c : car speed [m/s]

μ_r : rolling resistance coefficient

μ_a : coefficient ratio of aerodynamic efficiency

A_c : vehicle former shadow projection area [m²]

W_c : vehicle weight [N]

ΔW_c : inertia weight of rotation part of engine power plant [N]

θ : gradient [rad.]

g : gravitational acceleration [m/s²]

Equation (1) shows a vehicle driving force⁽³⁾. The first part of the right side of Eq. (1) represents a rolling resistance. The second one represents an aerodynamic resistance. The third one represents a gradient resistance. The fourth one represents an acceleration resistance. It is generally said that road load consists of the first three parts. Fuel economy is measured on an emission chassis dynamometer. Gradient road load is not factored for

official fuel economy tests. In the case of this, the emission chassis dynamometer absorbs the parts from the first to the second of resistances as a road load. The gradient resistance shown in the third part of the right side of Eq. (1) has no coefficient unlike both the first and the second parts. This means the vehicle weight directly impacts the gradient resistance. The emission chassis dynamometer absorbs much more loads by the addition of gradient resistance beyond loads of the regulation modes.

Fig. 4 Road load at a down hill drive

Figure 4 shows a down hill drive condition. The third part of the right side of Eq. (1) changes negative resistance which represents a driving force of vehicle is able to reduce the load of the engine power plant. A chassis dynamometer simulates this condition by applying energy to drive a vehicle during the down hill drive.

Kinetic energy during the down hill drive regenerates the battery. To promote total energy efficiency of HEV, the regeneration energy supplies to a demand of the vehicle general electric load at first and then flows into the battery. Fig. 5 indicates that a narrow solid line is a tracking line of SOC at the down hill drive shown in Fig. 2. Fig. 3 shows that the down hill drive starts at 920 seconds and regenerates continuously. Fig. 5 shows that the SOC is shifted to a rich side by the regeneration energy. Fig. 5 indicates that the bold line is an SOC tracking line simulated by the down hill drive on the chassis dynamometer with the same speed profile of the real world without the gradient road load. In this case, the chassis dynamometer provides both the rolling resistance and the aerodynamic resistance. No energy of regeneration makes the SOC tracking line stay on during the time of the down hill drive.

Fig.5 SOC characteristics on chassis test to the field test

4. Chassis substitution to the real world mode

4.1 Difficulties in substitution

Gradient $\tan\theta$ should be estimated both a car speed and an elevation level measured by a unit of GPS. A setting data for the chassis substitution consists of a mode profile of car speed and of gradient $\tan\theta$. The car speed measured by the GPS is not stable and is shown in Fig. 3. Therefore, this method of collecting vehicle speed is not appropriate for the data. The elevation level measured by the GPS is stable. But the first differentiation of the elevation, this is the same dimension of the car speed which is differentiated the distance, could be recognized unstable. The elevation level measured by GPS could not apply for itself to the data settings. It is necessary some data processing to the measured data by GPS for the chassis substitution. The data processing is as follows;

(a) Car speed

(b) Car acceleration

(c) Road inclination, $\tan\theta$ (GPS elevation by car control distance)

Fig. 6 GPS vs. car control

Like the vehicle data collection system shown in Fig. 1, the vehicle control data is also measured in the real world test. The car speed is one of the vehicle control data which has been collected at the test. Fig. 6(a) shows both car speed measured by GPS and measured by the vehicle control. It could be found that the car speed measured by GPS is not consistent with the car speed measured by the vehicle control. To investigate in more detail, the car speeds are differentiated to obtain their acceleration profiles which are shown in Fig. 6(b). The car speed measured by the vehicle control is also stable in its acceleration profile. Judging from the above analysis, it is better to apply the car speed measured by the vehicle control for the setting data of the chassis substitution. Fig. 6(c) shows gradient $\tan\theta$

which is estimated from both the car speed measured by the vehicle control and the elevation level measured by GPS. There is no employing the elevation data for the vehicle control. The elevation level is only measured by GPS. Fig. 6(c) shows the gradient $\tan\theta$ exceeds 40% at the time around 1250 seconds. The level of the gradient $\tan\theta$ is not appropriate to apply the chassis substitution for the setting.

4.2 Substitution approach

Starting from the mode profile of gradient $\tan\theta$ shown in Fig. 6(c), and discuss the method to reach an appropriate mode profile. At first verification, we took a filtering method of moving average to smooth varying data. The method eliminates data on both sides of data chains. As the result, data amount are different between the profile of car speed of control applying without filtering and the profile of gradient $\tan\theta$ applying with filtering. Furthermore, the method does not derive appropriate results both in transient variation and in steady condition, especially of a long time drive applying with the same order of filtering dimension. The elevation data measured by GPS does not make certain to apply filtering because the elevation data does not have struck some prominent noise and has been stable. Substitution approach applies a spline interpolation method ⁽⁴⁾. The spline interpolation is the method of joining with a smoothing curve function between points. The smoothing curve is determined by constants of the function considering with their around points which also could be joined smoothly. The method is like to trace a French curve for joining. A computer does the joining practice by way of solving a simultaneous equations of spline interpolation formulated in matrix. The measuring data point is x_i ($i:1 \sim N+1$). The spline interpolation function $S_j(x)$ ($j:1 \sim N$) is shown in Eq. (2). Eq. (2) is the third degree function of x .

$$S_j(x) = a_j + b_j \cdot (x - x_i) + c_j \cdot (x - x_i)^2 + d_j \cdot (x - x_i)^3 \quad (2)$$

Eq. (2) is defined by four sets of constants from a_j to d_j . Each of constants is fixed following conditions.

a) Eq. (2) with $S_j(x)$ should pass through both points of x_i and of x_{i+1}

$$S_j(x_i) = a_j, \quad S_j(x_{i+1}) = a_{j+1} = \{S_{j+1}(x_{i+1})\}$$

b) Both the first differentiation coefficient of Eqs. $S_j(x_{i+1})$ and $S_{j+1}(x_{i+1})$ should be equal

$$S_j'(x_{i+1}) = S_{j+1}'(x_{i+1})$$

c) Both the second differentiation coefficient of Eqs. $S_j(x_{i+1})$ and $S_{j+1}(x_{i+1})$ should be equal

$$S_j''(x_{i+1}) = S_{j+1}''(x_{i+1})$$

d) Both the end point of x_1 and of x_{N+1} have their boundary conditions respectively then define

$$S_j''(x_{j=1}) = 0, \quad S_j''(x_{j=N+1}) = 0$$

herewith

$$g_j = 1/(x_{i+1} - x_i)$$

The simultaneous equations of spline interpolation formulated in matrix are shown in Eq. (3). Eq. (2) with $S_j(x)$ ($j=1, j=N$) located in both ends are applied their boundary conditions respectively.

$$\begin{vmatrix} g_1 & 2 \cdot (g_1 + g_2) & g_2 & & \\ & \ddots & \ddots & \ddots & \\ & g_{j-1} & 2 \cdot (g_{j-1} + g_j) & g_j & \\ & & \ddots & \ddots & \\ & & g_{N-2} & 2 \cdot (g_{N-2} + g_{N-1}) & g_{N-1} \end{vmatrix} \begin{vmatrix} S'_1(x_1) \\ \vdots \\ S'_{j-1}(x_{i-1}) \\ \vdots \\ S'_N(x_N) \end{vmatrix} \\
 = 3 \cdot \begin{vmatrix} S_2(x_2) - S_1(x_1) & S_3(x_3) - S_2(x_2) & & \\ & \ddots & \ddots & \\ & S_j(x_i) - S_{j-1}(x_{i-1}) & S_{j+1}(x_{i+1}) - S_j(x_i) & \\ & & \ddots & \\ & & S_{N-1}(x_{N-1}) - S_{N-2}(x_{N-2}) & S_N(x_N) - S_{N-1}(x_{N-1}) \end{vmatrix} \begin{vmatrix} g_1^2 \\ \vdots \\ g_{j-1}^2 \\ \vdots \\ g_{N-1}^2 \end{vmatrix} \quad (3)$$

Where number of data points are $N+1$, number of equations of spline interpolation are N which connect between the data points. Constants are four as shown in Eq. (2). Total constants are $4N$. A computer has to solve $4N$ sets of simultaneous equations of spline interpolation.

Fig. 7 Compensated lines by spline method

Table 1 shows an actual method of solution above four steps from a) to d) on the basis of Fig. 7. In Fig. 7, data points are four ($=N+1$), equations of spline interpolation are

Table 1 Analytical method in the case of Fig.7

	Analytical conditions	Each x in Fig.7	Equations
a)	Equation S_j passes through both x_i and x_{i+1}	$S_1(x_1), S_1(x_2), S_2(x_2), S_2(x_3), S_3(x_3), S_3(x_4)$	6
b)	Both the first differentiation coefficient of equation S_j and of equation S_{j+1} are equal.	$S'_1(x_2) = S'_2(x_2)$ $S'_2(x_3) = S'_3(x_3)$	2
c)	Both the second differentiation coefficient of equation S_j and of equation S_{j+1} are equal.	$S''_1(x_2) = S''_2(x_2)$ $S''_2(x_3) = S''_3(x_3)$	2
d)	Both the end point of x_i and of x_{N+1} have their boundary conditions respectively.	$S''_1(x_1) = 0$ $S''_3(x_4) = 0$	2
		Total equations	12

three ($=N$). Total constants are 12 ($=4N$). A computer has to solve $4N$ sets of simultaneous equations of spline interpolation.

4.3 Data for chassis substitution

4.3.1 Sampling frequency and substitution data

Measuring data by GPS are featured the spline interpolation method in 4.2. The spline interpolation applied the measuring data picking up a sampling span.

From Figs. 8(a) to 8(c) show that the bold line is the measuring data by GPS and the solid line is the spline interpolation curve joining with the measuring data in each eight points. The interpolation shows that the data fluctuations are reduced whereas not changed the measuring data value.

(a) Car speed

(b) Car acceleration

(c) Road inclination, $\tan \theta$ (GPS elevation by car control distance)

Fig. 8 GPS vs. GPS with spline interpolation

4.3.2 Estimation for adaptiveness of substitution data

A level of interpolation is verified the car control speed to the car speed measuring by GPS applied spline interpolation. Fig. 9 shows that the bold line is the measuring data by car control speed at the real world test and the solid line is the spline interpolation curve joining with the measuring data by GPS in each 16 points. The interpolation shows that the data fluctuations are reduced. Whereas the car speed by GPS is applied the spline interpolation and is not applied a data filtering, this process could make the car speed by GPS trace near by the car control speed.

Fig. 9 Car speed (GPS with spline interpolation vs. car control)

Figure 10 shows the correlations between the car control speed figures at the real world test and a car speed figures by GPS changing with the sampling data points. It could be found that the curve of correlations has a peak near by 16 points of sampling.

This relation should apply the elevation data measuring by GPS. The measuring elevation data by GPS are joined the spline interpolation curve in each 16 points respectively which makes the elevation data of spline interpolation. The splined elevation and the car control speed could formulate the mode profile of the gradient $\tan\theta$ for the chassis substitution.

Fig. 10 Estimated adaptiveness for spline interpolation speed to the car control speed

5. Verification of the real world mode in chassis dynamometer

5.1 Test results on the descent way

Figure 11(a) shows the SOC tracking line on the descent way. The solid line is the real world test and the bold line is the chassis simulation. The setting data for the chassis simulation is as follows; The car control speed applies as the mode profile of car speed, and the 16 samplings splined elevation divided by the distances integrated the car control speed applies as the mode profile of gradient $\tan\theta$. It could be found that the SOC tracking line of chassis simulation is to behave similarly to the SOC in real world test.

Figure 11(a) shows the SOC tracking line of the chassis simulation with the gradient road load is closer to the real world SOC than the SOC of the chassis simulation without the gradient load shown in Fig. 5. However, in Fig. 11(b), the battery temperature by

thermistor sensing on major points of average of the battery is hotter than the real world. To determine the cause of the temperature rise, both of the regeneration energy amounts are examined. Fig. 11(c) shows that the chassis test have an increase in regeneration energy both at 1200 seconds (point A) and at 1500 seconds (point B) compared the real world. The points of these around are altering points of the vehicle directions shown in Fig. 2. It is supposed that the difference of human brake working and the difference of car brake control make the difference of regeneration energy amount. Unless the differentiation of these, both the tracking line of the regeneration energy amounts comply with simultaneously.

(a) SOC characteristics

(b) Battery temperature

(c) Regeneration into battery

Fig.11 Chassis test vs. the field test (descent way)

5.2 Test results on the ascent way

Figure 12(a) shows the SOC tracking line of which drives the opposite way from the finish point as a start shown in Fig. 2. The solid line is the real world test and the bold line is the chassis simulation. The chassis simulation and the data setting is to take the same procedure of the descent way. It could be found that the SOC tracking line of chassis simulation is to behave similarly to the SOC in real world test. Fig. 12(c) shows that an

amount of regeneration energy into the battery is the same figures both the real world test and the chassis simulation. Fig. 12(b) shows that the battery temperatures are not differs like the descent way. It could be evaluated that the mode profile of the gradient $\tan\theta$ by the method of the spline interpolation to the elevation data measuring by GPS stands for the real world of SOC on the chassis substitution.

(a) SOC characteristics

(b) Battery temperature

(c) Regeneration into battery

Fig. 12 Chassis test vs. the field test (ascent way)

6. Application of the Chassis substitution method

Figure 12(c) shows each amount of regeneration energy into the battery both the real world test and the chassis simulation are the same on the ascent way. We simulate SOC tracking line on the chassis dynamometer with increased of regeneration energy on the ascent way. The simulation takes a method of cutting air conditioner load which makes regeneration energy increase and of applying the mode profile on the ascent way. Fig. 13 shows the test result. Fig. 13 shows battery regeneration increase in proportion to the SOC rising from the point of C in the chassis simulation. From the point of D, battery regeneration restricts which makes the same line track in the real world test. The increase of

Fig. 13 SOC characteristics increased regeneration on chassis test to the field test

the battery temperature without air conditioner makes control change to decrease the regeneration. Chassis simulation test with gradient road load has a potential to verification like this application test.

7. Conclusion

This paper evaluates SOC status of both chassis dynamometer simulation with gradient road load and of real world down hill driving. The measurement data from the GPS is hard to apply on the chassis dynamometer. The method is proposed for the chassis substitution to specify the mode profile of the gradient $\tan\theta$ by the method of the spline interpolation and the verification is done on the chassis dynamometer. It could be found that the SOC tracking line in chassis simulation is likely to behave similar to the SOC both on the descent way and on the ascent way in real world testing. And more investigation is taken for the differences of tracking lines of SOC. The differences of amount of regeneration energy are altering points of the vehicle directions in which human brake working differs on the descent way. Unless the differentiation of these, it could be evaluated that the mode profile of the gradient $\tan\theta$ by the method of the spline interpolation to the elevation data measuring by GPS stands for the real world of SOC on the chassis substitution. This chassis substitution method could be applied widely for simulation on a chassis dynamometer. For future steps, further studies should take application methods of the chassis dynamometer with gradient road load.

References

- (1) The Ministry of Land, Infrastructure and Transport, The Ministry of Land, Infrastructure and Transport white paper 2007, II .The trend of land, infrastructure and transport administration 2. Provision in the transportation section, (2007)
- (2) Sakamoto, T., Matsuda, T., Honda R&D Co., Ltd., Minami,T., Honda Motor Co., Ltd., Evaluation of Hybrid Electric Vehicle Battery Life in North American Market, The 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exposition, <http://www.evs22.org/>, (2006)
- (3) Nasukawa, H., Miyashita, Y., Shiokawa, M., Vehicle driving performance and test method (in Japanese), Third correction version, (1999/04), p.p.30-31, Sankaido
- (4) Yoshimura, K., Takayama, M., Spline function applied for PC (in Japanese), (1988/12), Publications Service of Tokyo Electrical Engineering College.