Mechatronic V8 Engine Start Capabilities of an Automotive Starter/Generator System at the Super Cold Weather

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The use of a combined starter/generator integrated into the drive train of an automobile offers several possibilities for improvement of fuel economy. The use of such a starter/generator system is made feasible by a switch from a 14 volts electrical system to a 42 volts system, however, the sizing of the components is not a trivial problem. This study combines a dynamic electromechanical model of the starter, battery and power electronics with the nonlinear mechanics of the piston/crankshaft system and a thermofluid model of the compression and expansion processes to investigate the cold start problem. The example involves the start of an eight cylinder engine at -25 degrees Celcius. This paper shows how the mechatronic V8 engine of an automotive starter/generator system for the startability works well.

Key Words : Starter/Generator, Electromechanical Model, Piston/Crankshaft System, Thermofluid Model, Mechatronic V8 Engine

1. Introduction

As the automotive industry develops the engine technology has also been developed. Lots of researches for automotive engine have been done, for instance, modeling (Kim and Sung, 2001), Idle speed modeling/control (Joo and Chun, 2000), analysis of engine cooling system (Jurng et. al., 2000), heat transfer (Wu and Chiu, 1988 ; Yang and Park, 2001), and so on. The goal of this paper is to introduce a new starter/generator system which would be possibly in production in 2007 by Mercedes Benz. This paper also presents a bond graph simulation model designed to study the starting capabilities of candidate starter/generator systems at the very cold weather.

Modern automobiles use a 14 volt electrical system (commonly called a 12 volt system) with an engine driven alternator and a separate starter motor. The starter is usually connected to the engine flywheel with a large gear ratio only during the starting phase. Some smaller vehicles such as motorcycles have used a single electrical machine permanently coupled to the engine for both starting and generating but the design of such a single electrical machine for larger engines has proved difficult. One major problem for a combined starter/generator is the large torque required to start a cold motor with a cold battery. A large gear ratio between the electrical machine and the engine cannot be used to multiply the starting torque because the electrical machine would overspeed and be damaged at high engine speeds.

The design problem of combining high torque for starting and efficient generator operation is eased by increasing the system voltage. Several automobile manufacturers are considering an increase of the system voltage to 42 volt. This makes the idea of using a single electrical machine integrated permanently in the drive train for both starting and generating more practical.

There are many possible configurations for drive train starter/generators, and the potential advantages for increasing fuel economy using such devices are significant. For example, the

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engine can be shut down whenever the vehicle is stationary during stop and go traffic and started automatically when the driver releases the brake. Also, energy can be recovered during deceleration and used to assist during acceleration if the battery is almost fully charged. Furthermore, all accessories such as air conditioning, power steering, power brakes, etc. can be electrically driven only when necessary removing all belts and pumps from the engine itself, and removing a number of the parasitic losses associated with conventional vehicles.

In the present paper a bond graph (Karnopp and Margolis, 2000) simulation model is presented to study the starting capabilities of candidate starter/generator systems. The model represents a generalized mechatronic system well suited to bond graph techniques. The battery is modeled as a dynamic electrochemical system, the starter/generator and its power electronic driver is electromechanical, the piston engine is a nonlinear mechanical system and the air compression in the cylinders is represented as a thermodynamic system. The model contains true bond graphs, pseudo bond graphs, and empirically derived input-output models. Causal considerations facilitate the coupling of the various subsystem. The example involves the starting phase of an eight cylinder engine at -25 degrees in Celcius.

2. Development of the System Model

Figure 1 shows an overview of the entire system with a single cylinder system while Fig. 2 shows how the model is extended for multi-cylinder engines. Table 1 shows the parameter definitions for Figs. 1, and 2.

Table 1 Parameter definitions for nonlinear mechanical part

a=crankshaft radius=1/2 stroke
b=connecting rod length
δ=length from piston pin to top of piston (assumed flat)
V=cylinder volume=$A_p(x_m-x)$
A_p=piston area
$b-a\leq x\leq b+a$,
$A_p(x_m-a-b)\leq V\leq A_p(x_m+a-b)$
$\kappa=\frac{V_{\max}}{V_{\min}}=\frac{x_m+a-b}{x_m-a-b}$=Compression Ratio

These figures contain standard true bond graph elements, word bond graph elements such as Transmission Starter Generator (TSG) and Battery (BATT) and pseudo bond graph elements such as the accumulator, C, and restrictor, R at the bottom of Fig. 1. The main purpose of these bond graphs is to define causal interactions between subsystems and to establish important physical variables useful in describing the subsystems.

Since all the subsystems were developed with the indicated causality shown in Figs. 1 and 2 and since all the subsystems were described in a common simulation language, ACSL, (ACSL Reference Manual, 1993) the system model could be readily assembled from the subsystem models. On the other hand, when subsystem models are developed independently in different simulation

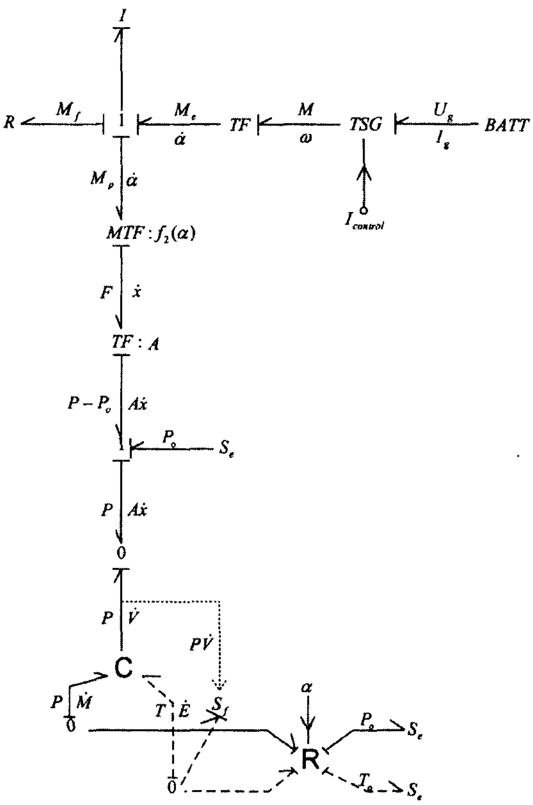


Fig. 1 Single cylinder system model

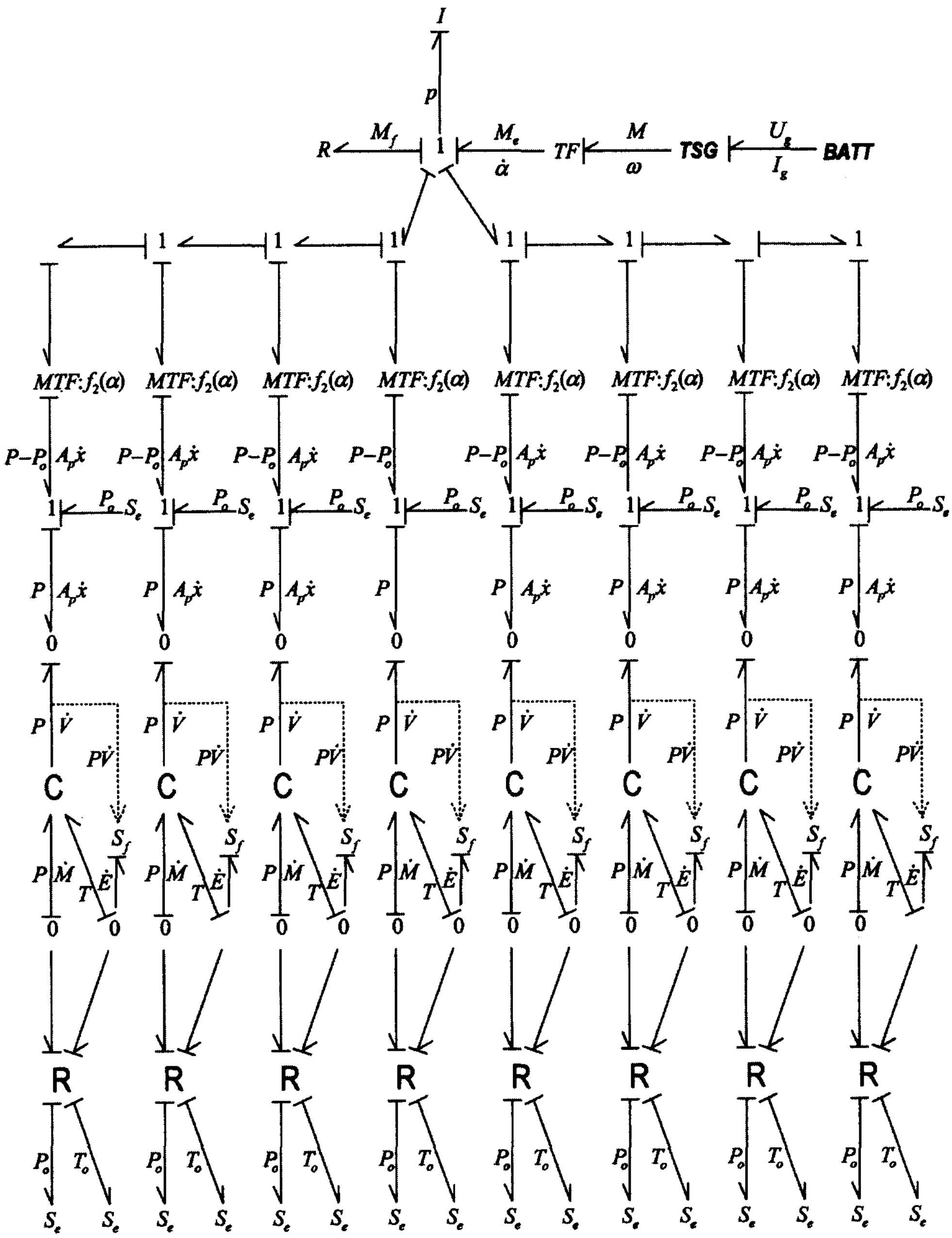


Fig. 2 Multiple cylinder system model, example of 8 cylinders system

environments and perhaps with little thought on how they will be interconnected, significant problems in coupling the subsystem models can occur. (see the example, [Kuebler and Schielen, 2000]).

Now the subsystems starting from the battery and proceeding toward the combustion chamber will be discussed. The battery models, represented by BATT are dynamic bond graph models of prototype batteries capable of more and deeper discharge cycles than normal starter batteries. These models have the current I_g as an input and deliver the voltage U_g as an output. The models were delivered by an independent contractor as

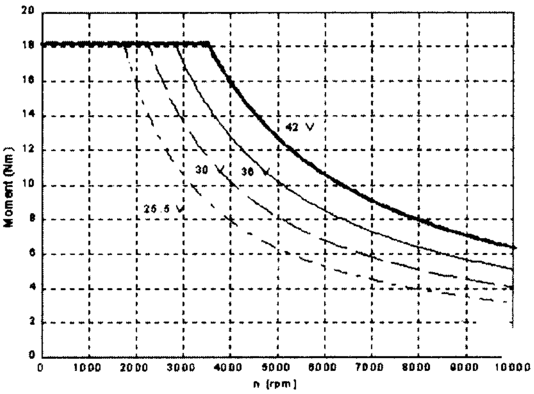


Fig. 3 Moment vs. (rpm) with four different voltages from experiments

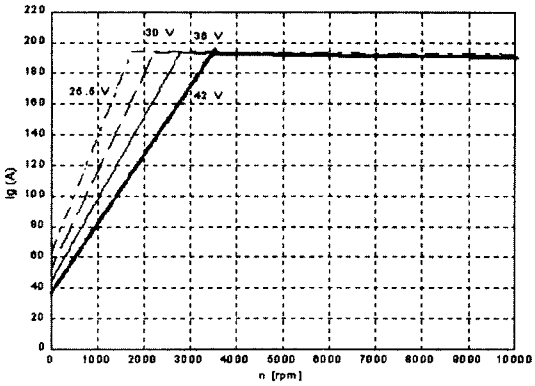


Fig. 4 Current vs. n (rpm) with four different voltages from experiments

ACSL files to be included in the system ACSL model. Because of the proprietary nature of these models, they will not be further discussed.

The word bond graph element TSG represents the transmission starter generator itself which consists of the electrical machine and the power electronics necessary to control it. The model delivers the moment M and current I_g in response to input variables such as voltage U_g, angular speed ω and the current command signal $I_{control}$. This subsystem was described by equations fitted to test stand results from a prototype system. The equations apply only to motor operation and contain only a few basic parameters. M_o is a maximum moment, I_o a maximum current, k a slope and ω_o an offset angular speed. The parameters k and ω_o are found by fitting straight lines to measured results in the low speed region which can be seen in the model results shown in Fig. 3. The full load current I_{gm} is assumed to obey the equation.

$$I_{gm} = k(\omega + \omega_o)/U_g \tag{1}$$

Figure 3 shows the corresponding moment for the model.

In Fig. 1, the TSG element is connected through a transformer representing a possible gear box to the engine crank-shaft. The moment M is transformed to the electrical moment on the crankshaft M_e and $\dot{\alpha}$, the crankshaft angular velocity produces the electrical machine speed ω both through the gear ratio. (For a direct drive system, the gear ratio is unity.)

I element represents the total effective inertia referred to the crankshaft. This includes the inertia of the electrical machine as well as the average inertia of all the reciprocating engine parts. (Particularly for a multi-cylinder engine, it was judged not necessary for this project to model the internal engine dynamics precisely.) The friction moment M_f was derived from experiments on a real engine in a cold chamber with the spark plugs removed. This moment had a nearly constant component but was also a function of speed as would be expected due to the cold oil. At cranking speeds, there was negligible compression effect due to the open spark plug holes.

The modulated transformer (MTF) in Fig. 1 represents the kinematics of a piston. The angular speed is related to the linear piston speed $\dot{x}$ and the piston force F is related to the moment M_p with the function $f_2(\alpha)$ (see Chapter 9 of Ref. [Karnopp and Margolis, 2000]). Figure 5 shows dimensions associated with the crankshaft, connecting rod and piston. Note the distance δ cancels out of all calculations. From Fig. 5, it can be seen that the stroke is $2a$, the volume V is related to and the piston area, A_p.

$$V = A_p(x_m - x) \tag{2}$$

and the compression ratio κ is

$$\kappa = \frac{V_{max}}{V_{min}} = \frac{x_m + a - b}{x_m - a - b} \tag{3}$$

From analysis of Fig. 5, it could be determined

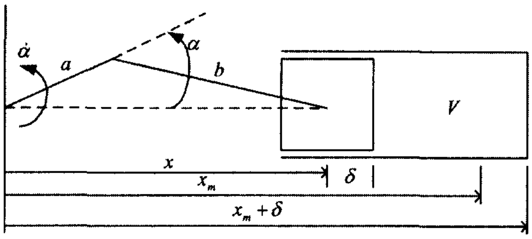


Fig. 5 Nonlinear mechanical motion of piston/crankshaft system

how x and $\dot{x}$ are related to α and $\dot{\alpha}$.

$$x=a\cos\alpha+[b^2-(a\sin\alpha)^2]^{1/2}=f_1(\alpha) \quad (4)$$

$$\dot{x}=-(a\sin\alpha)\left(1+\frac{a\cos\alpha}{[b^2-(a\sin\alpha)^2]^{1/2}}\right)\dot{\alpha}\equiv f_2(\alpha)\,\dot{\alpha} \quad (5)$$

Using $f_1(\alpha)$ and Eqs. (2) and (3), the volume can be related directly to α. The function $f_2(\alpha)$ is the modulus of the MTF. Note that for the multi-cylinder engine of Fig. 2, the $\dot{\alpha}$ is the same for all cylinders but the α's are related to the reference cylinder by the crankshaft throw angles. The functions f_1 and f_2 are identical in form for all cylinders, of course.

The transformer with modulus A_p in Fig. 1 relates $\dot{\alpha}$ to $A_p\dot{x}$, the rate of decrease of volume, and F to the gage pressure $P-P_o$ where P_o is atmospheric pressure assumed acting on the underside of the piston.

The final elements in the model have to do with air compression in the combustion chambers of the cylinders. This effect is modeled using the pseudo bond graph accumulator C and Restrictor R. (see [Karnopp and Margolis, 2000], Section 12.4 for a thorough discussion of these elements). The output variable of most interest is the pressure P in the cylinder. The restrictor represents the flow of air into and out of the combustion chamber either through the intake and exhaust valves or past the piston rings. The valves open and close as a function of α, so the restrictor is shown modulated by α. The restrictor is modeled as an isentropic nozzle with a single equivalent area which changes with crank angle. When either the intake or the exhaust valves for a cylinder are open, the equivalent nozzle area is large and the pressure in the cylinder is nearly atmospheric pressure. During the time both sets of valves are closed, only leakage paths past the piston rings or through the closed valves are active so that the equivalent nozzle area is small and the pressure in the cylinder is mainly a function of the changing cylinder volume.

At the beginning of the simulation, the pressure in all the cylinders is assumed to be atmospheric. As the crankshaft begins to turn, some cylinders will have open valves and hence will not change pressure appropriately. Those' cylinders which happen to have closed valves will experience increasing pressure if they happen to be on the compression stroke or a decrease in pressure if they happen to be on the power stroke. In critical situations, the startability may depend upon the electrical torque being large enough to overcome the combination of engine friction and the torque required to compress the air in some of the cylinders. In any case, cylinder compression results in a complex oscillating torque which varies with crank angle and angular velocity being hard to compute except by a physically based model such as the one presented here.

A minor peculiarity of this system is that from Figs. 1 and 2. One might expect that the volumes of each cylinder would be pseudo bond graph state variables, but the crank angle actually determines all the volumes using Eqs. (2) and (4). In fact α is also necessary to determine the valve timing. This is one of those cases in mechanics where a displacement state variable is necessary for modulated transformers and restrictors and it eliminates the need to integrate to find a number of other state variables.

3. Results and Discussion

The simulation results of 8 cylinder engine model are shown in Figs. 6 through 8. Figure 6 shows the capability of the battery. The battery voltage starts from 41 volt and drops down to 31 volt in the steady state region when the current has the maximum value of 290 A. Figure 7 shows the electrical moment on the crankshaft M_e and the crankshaft angular speed $\dot{\alpha}$ during the first 1 second of a start, but in this case, the gear ratio between the electrical machine and the crankshaft

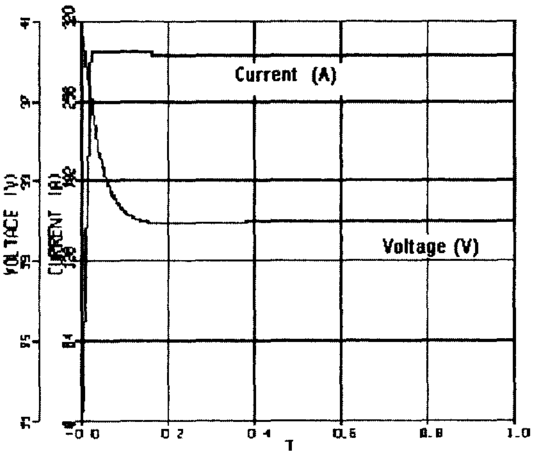


Fig. 6 Battery voltage and current

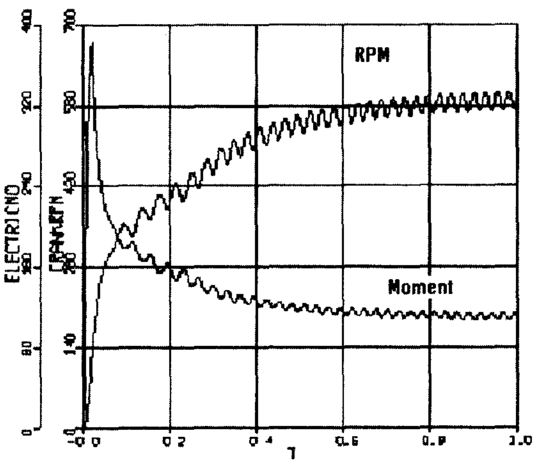
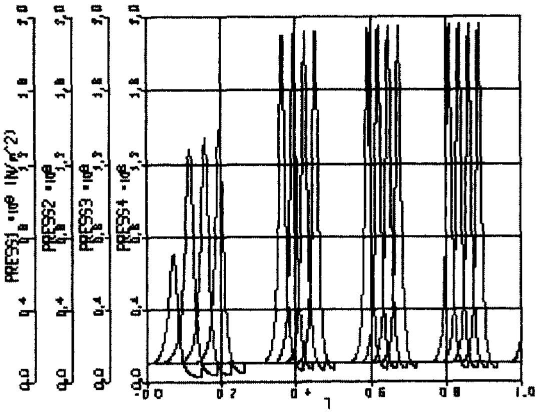


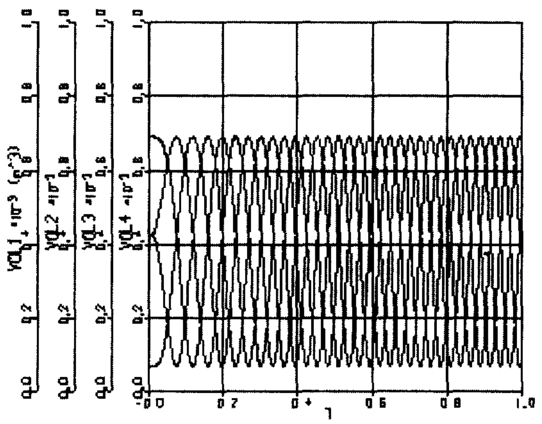
Fig. 7 Electric machine moment and crankshaft speed in RPM

was assumed to be fairly large. Note that the electrical machine has the maximum moment 18 N-m as shown in Fig. 3. For a directly coupled machine, the maximum moment would be adjusted by scaling the starter/generator system by simply changing the parameters. The crankshaft speed starts from zero and eventually oscillates over the range 540-560rpm.

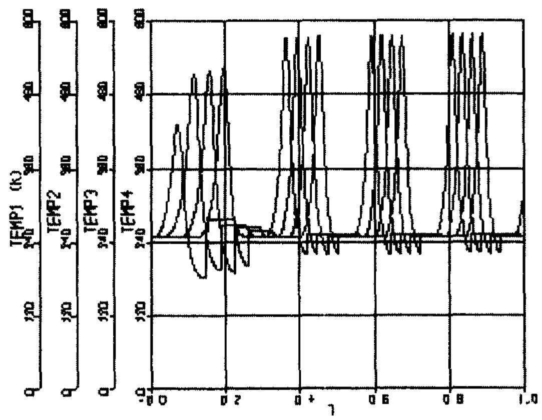
Figure 8 shows the overall dynamic responses of the 1st, 2nd, 3rd and 4th cylinders out of the 8 cylinders. The dynamic responses of 5th, 6th, 7th, and 8th are the same as the ones of the 1st, 2nd, 3rd and 4th cylinders. The 1st cylinder has a zero degree of initial crankshaft angle. Then the initial crankshaft angle for $(n-1)^{th}$ cylinder will be increased by $\pi/2$. The pressures, temperatures, and energies in Fig. 8 show a periodic response



(a) Pressure1, 2, 3, 4 ($10^6 N/m^2$)



(b) Volume 1, 2, 3, 4 ($10^{-3} m^3$)



(c) Temperature 1, 2, 3, 4 (K)

Fig. 8 1st, 2nd, 3rd, 4th cylinder responses of 8 cylinder engine model due to these different crankshaft angles. After one revolution, all responses show a repetitive nature. The pressure in the cylinder starts from the atmospheric pressure. As the crankshaft begins to turn, the pressure remains the same while the volume and mass increase since this cylinder starts on the intake stroke. In the compression stroke the pressure and temperature increase, and then decrease again during the expansion stroke.

The simulation results show the reasonable magnitudes and explain that the engine can be turned on at the cold weather of −25 degree in Celcius. Note that the engine firing is not modeled in this research. However, after the transient responses until 0.3 sec, the engine would start fire at 0.38 sec, 0.40 sec, 0.42 sec, and 0.44 sec, respectively, as the pressure and energy increase. Without the help of TSG system, it may not reach a certain level of pressure or energy to start the engine firing at that cold weather. Even it would take more time to reach the energy/steady state responses.

4. Conclusion

Industrial mechatronic systems often involve more than just electromechanical elements and electronic control. Bond graph modeling techniques can be very helpful when many energy domains are involved in the system components as the example of this paper illustrates. Bond graph causality is useful in establishing submodel input and output variables even when some components are described by fitting mathematical models to test stand data. Often the test results have to be rearranged to fit easily into a system simulation and bond graph causal analysis on word bond graph elements can be useful in this process. Finally, using a single simulation language for all elements and subsystem avoids problems of coupling and coordinating simulation programs for parts of the system which may have been represented in several languages. In principle, mathematical models should be independent of the simulation languages used to study the system.

This paper presented a bond graph simulation model designed to study the V8 engine starting capabilities of TSG systems with 42 volt systems. The whole mechatronic V8 engine model combined with one of the four batteries modeled as a dynamic electrochemical system, the electromechanical starter/generator and its power electronic driver, the nonlinear mechanical piston engine system and the thermodynamic air compression system in the cylinders. The model also contained true bond graphs, pseudo bond graphs, and empirically derived input-output models. The example shown in this paper involved the starting phase of an eight cylinder engine at −25 degrees in Celcius. The V8 engine with the help of TSG system showed a good start capability at that weather.

References

ACSL Reference Manual, Version 10.1, MGA Software, Concord, MA 10742, USA, 1993.

E-maschine im Antriebss trang (Electrical Machines in the drive train) LUK Fachtagung, (Technical Conference of LUK Automotive Systems), Krauss, Markus, Daimler Chrysler Technical Note TN-FT2/L-1999.014

Joo S. H. and Chun K. M., 2000, "Idle Speed Modeling and Optimal Control of a Spark-Ignition Engine," *KSME International Journal*, Vol. 11, No. 1, pp. 88~95.

Jurng J. S., Hur N. K., Kim K. H. and Lee C. S., 2000,000"Flow Analysis of Engine Cooling System for a Passenger Vehicle," *KSME International Journal*, Vol. 11, No. 1, pp. 88~95.

Karnopp, D. C., Margolis, D. L. and Rosenberg, R. C., 2000, *System Dynamics: Modeling and Simulation of Mechatronics Systems*, John Wiley & Sons.

Kim H. S. and Sung N. W., 2001, "Multi-dimensional Engine Modeling: NO and Soot Emissions in a Diesel Engine with Exhaust Gas Recirculation," *KSME International Journal*, Vol. 15, No. 8, pp. 1196~1204.

Kuebler, R. and Schielen, W., 2000, "Two Methods of Simulator Coupling," *Mathematical and Computer Modeling of Dynamic Systems*, Vol. 6, No. 2, pp. 93~114.

Wu H. W. and Chiu H. W., 1988, "A Study on the Characteristics of Heat Transfer in an Engine Piston," *KSME International Journal*, Vol. 2, No. 1, pp. 19~27.

Yang H. C. and Park S. K., 2001, "A Study on the Behavior and Heat Transfer Characteristics of Impinging Sprays," *KSME International Journal*, Vol. 15, No. 3, pp. 374~383.