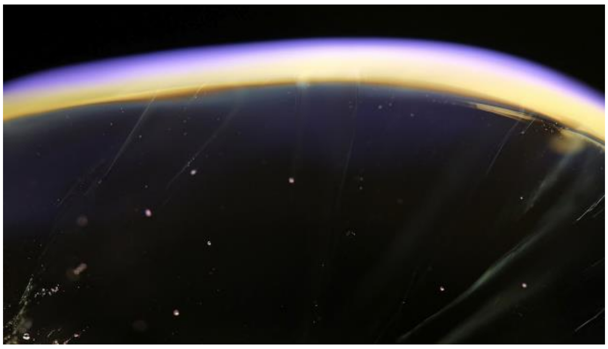
A Circuit Component Modeling Approach Based on Vehicle Control System Health Simulation



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***Abstract*—The simulation of vehicle control system based on transfer function or nonlinear differential equation, which implicates the health state information of every component in the model parameters, can't directly describe physical character of component. With the emergence of a large number of powerful professional circuit simulation software and the mechanism-electric design & simulation software, a system-level health simulation framework is presented based on the component-level response approximation of the circuit simulating data. In this framework, the circuit schematic model based on the component health behavior is created first; then a lot of data under the various health degradation or fault is obtained using the professional circuit design and simulation software such as Multisim or Proteus; thus the response identification model of the BP neural network which approximates the health behavior of the component, the component-level model, is applied into the system-level simulation. In this case, the simulated results of system-level can be obtained under the condition of every component health behavior. The example shows that the response approximation model is capable of well imitating the various health behaviors of the component.**

***Keywords*—circuit fault simulation; response approximation method; health behavior model; system-level health simulation**

I. Introduction

Recently, a lot of attention and positive responses from the international community are obtained on the research on Integrated Vehicle Health Management (IVHM) system [1-4]. With the help of this technology, a lot of physical mechanism becomes a white box, which leads to corresponding professional simulation software becoming mature, such as the Adams for mechanical power simulation, the Fluent for computational fluid dynamics simulation. Meanwhile, the corresponding fault simulation technology is also booming. Especially in the areas of circuit design and analysis, the simulation software was improved greatly. The corresponding circuit fault simulation is becoming mature. So it is possible to provide a lot of health or fault information of electronic components in vehicle control systems [5]. However, with the development of the electronic technology, the electromechanical systems are becoming more and more complex. The traditional modelling methods, such as the transfer function, the state space model, are not able to build the relationship between the parameter variables and the faults or health status of the system [6]. Hence, the integrated health monitoring system is becoming more and more important [7], particularly for the vehicle control system. In order to establish an ideal health monitoring system, the computer simulation becomes the main technology which can provide various performance degradation information of the component. In this case, the research on an advanced health monitor and management technology can be carried out deeply, which is a critical basis of IVHM.

In the traditional vehicle control system, the research is often based on the transfer function, the nonlinear differential equation, etc. The health information of every component is implicated in the parameters of the model above. Therefore, the simulation of IVHM system can be carried out but indirectly based on these parameters of model. Currently, the simulation of the vehicle control system is generally based on the parametric model [7]. The corresponding fault modeling approach is also based on the parametric model, which implies that the coverage of faults is relatively limited. In the real case, the vehicle control system is composed of electric circuit and mechanism-electric components, such as the inertia measure unit, the controller, the servo motor, etc. The circuit fault simulation can be carried out by a lot of mature commercial simulation software currently [5]. This is a direct way to do research on the component health, but the modeling consistency between the system-level and the component-level must be considered.

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Some fault simulation, whose model only contains the degeneration parameter, is easy to be carried out, because model structure need not to be changed. While most fault simulation, whose topology configuration of the model will change under different fault conditions, is difficult, since there are enormous challenges on how to build the complex fault model. Jean-Nicolas Paquino has built a multi-platform simulation system using SIMULINK and SimPower, which is a competent for parallel simulation of different circuit components for complex electronic equipment [8]. The parallel simulation platform can be extended as a scheduler to carry out simulation on different mechanistic models, such as electronic, mechanical and fluid systems. This method is expected to solve the problems of multi-mechanism and co-simulation. However, there is a lot of simulation software in this parallel simulation platform. The interface of different simulation software is very complicated. The work required by co-computation of different simulation software is numerous. Especially the simulation results may easily diverge sometimes. If a response approximation model can be used to replace the corresponding mechanism platform, various approximate health models of components can be transformed into the same environment for system-level simulation. Then a hierarchical and simplified health simulation system is constructed. The health behaviors model based on fault simulated database by professional simulation software can be concentrated into a unified environment for system-level simulation. The multi-interface requirements for different kinds of simulation software can be avoided.

II. Health Simulation Frame

Generally, a vehicle control system is composed of multiple components. For a specific circuit component, it is composed of many electrical elements, whose performance degradation will deteriorate the health behaviors of the component. As shown in Figure 1, the large amounts of health simulation data can be produced by component-level simulation. The simulation is related to various component health behaviors in the environment of professional circuit design and simulation software. Any complex component, with enough response test data, can be identified through in-depth study with various algorithms to get its mathematics model [9]. So research on the component health behavior modeling method is carried out in order to map the relationship between the health simulated data and the health behaviors. At last, the traditional simulation model of the vehicle control system is reconstructed whose component-level model is replaced by its corresponding component health behavior model (CHBM)[11]. The system-level simulation can be carried out under different health conditions of various components.

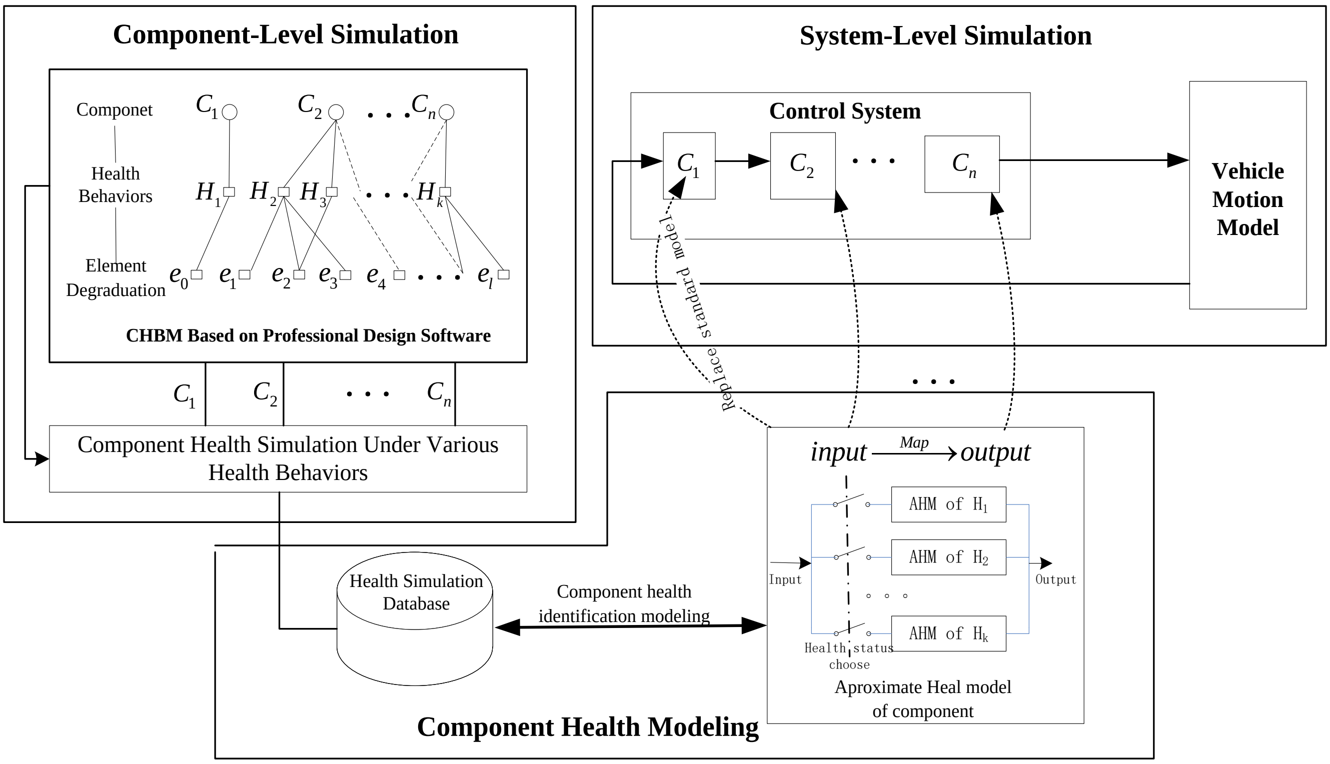

Figure 1 Health Simulation Frame

III. Component Health Behavior Modeling Method

In the health simulation frame, the exact circuit model of a component can be built by professional circuit design software. But the method to produce and utilize the component-level simulation database is the key to identifying CHBM. In theory, the essence of CHBM is the design of the component input signal in simulation test design and the design of identification algorithm.

Component input signal should be carefully designed to effectively stimulate the interior mode of the system, in order to get the information related to every health status of the component as much as possible [10]. Assuming the input of a component is $r(t)$ and its output is $y(t)$, a set of step functions can be applied to reconstruct $r(t)$. The time margin $[0,t]$ is divided into several pieces, the left end of each interval is the beginning of a step function, denoted as $S_i(t)$, $(i = 0,1,...,k,k+1,...,n)$, see Figure 2.

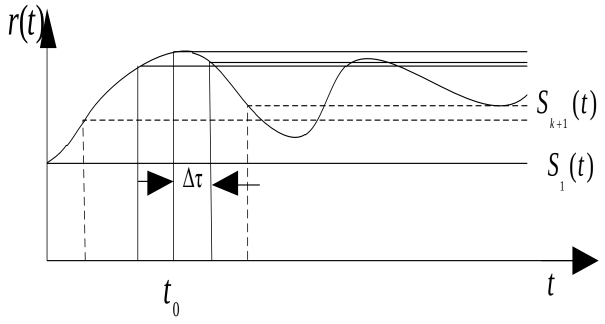

Figure 2 Input Signal Equivalent Principle

Assume the unit step function as $u(t-i\cdot\Delta\tau)=\begin{cases}1, & t\ge i\cdot\Delta\tau\\ 0, & t<i\cdot\Delta\tau\end{cases}$, then the range of the step function can be expressed as $S_i(t) = r(i\cdot\Delta\tau)\cdot u(t-i\cdot\Delta\tau)$. So,

$$r(t) \approx S_0(t) + \sum_{i=0}^{n}(S_{i+1}(t) - S_i(t)) \tag{1}$$

$$r(t) \approx r(0) + \sum_{i=0}^{n}\frac{r(i\cdot\Delta\tau+\Delta\tau)-r(i\cdot\Delta\tau)}{\Delta\tau}u(t-i\cdot\Delta\tau-\Delta\tau)\cdot\Delta\tau \tag{2}$$

For $\Delta\tau \to 0$, $r(t) = r(0) + \int_0^t r'(\tau)\cdot u(t-\tau)d\tau$, thus $r(t)$ can be reconstructed by the unit step function.

Assume $h(t-\tau)$ as the system response function of the unit step function $u(t-\tau)$.

In the interval of $[0,t]$, with the application of the principle of superposition , the system response $y(t)$ of arbitrary excitations $r(t)$ can be written as the summation of all the step responses of the system.

$$y(t) = r(0)\cdot h(t) + \sum_{0}^{n}[r(i\cdot\Delta\tau+\Delta\tau)-r(i\cdot\Delta\tau)]\cdot h[t-(i+1)\cdot\Delta\tau] \tag{3}$$

Consider $\Delta\tau \to 0$,

$$y(t) = \int_0^t r(\tau)\cdot h(t-\tau)d\tau \tag{4}$$

Assume that the step response $h(t-(i-1)\cdot\Delta\tau)$ will not cause too much impact on the step response $h(t-i\cdot\Delta\tau)$.

That is, when $t > t_0$, $\int_0^{t_0} r(\tau)h(t-\tau)d\tau = C$, C is a constant.

$$y(t) = \int_0^{t_0} r(\tau)\cdot h(t-\tau)d\tau + \int_{t_0}^{t} r(\tau)h(t-\tau)d\tau \tag{5}$$

So,

$$y(t) = \int_{t_0}^{t} r(\tau)h(t-\tau)d\tau + \mathrm{C} \tag{6}$$

In this case, the system dynamics is determined only by the step excitation at the time of t_0 .

On the other hand, if there are some methods to establish the map relationship between the step signals and their responses of a system, then the response of any input can be obtained by these given system step response data.

In fact, the system dynamics is a set of solutions of the ordinary differential equations which can usually be expressed as follows,

$$\frac{d^n y}{dt^n} + q_{n-1}\frac{d^{n-1}y}{dt^{n-1}} + ... + q_0 y = p_{n-1}\frac{d^{n-1}r}{dt^{n-1}} + p_{n-2}\frac{d^{n-2}r}{dt^{n-2}} + ... + p_0 r \tag{7}$$

Its discrete form can be expressed as,

$$y(k-n) + q_{n-1}y(k-n+1) + ...q_0 y(k) = p_{n-1}r(k-n+1) + p_{n-2}r(k-n+2) + ... + p_0 r(k) \tag{8}$$

It can be further expressed as,

$$y(k) = p_{n-1}r(k-n+1)/q_0 + ... + p_0 r(k)/q_0 - y(k-n)/q_0 - ... - q_1 y(k-1)/q_0 \tag{9}$$

That is, the output of the system at time k is determined by the current input and the historical input and output. Research on the mapping method can be carried out to get an equivalent model, which can be used to prognosticate the solution of the differential equations in a certain initial conditions, namely,

$$y(k) = f_{neuro}\left(y(k-n),...,y(k-1), r(k-n),...,r(k)\right) \tag{10}$$

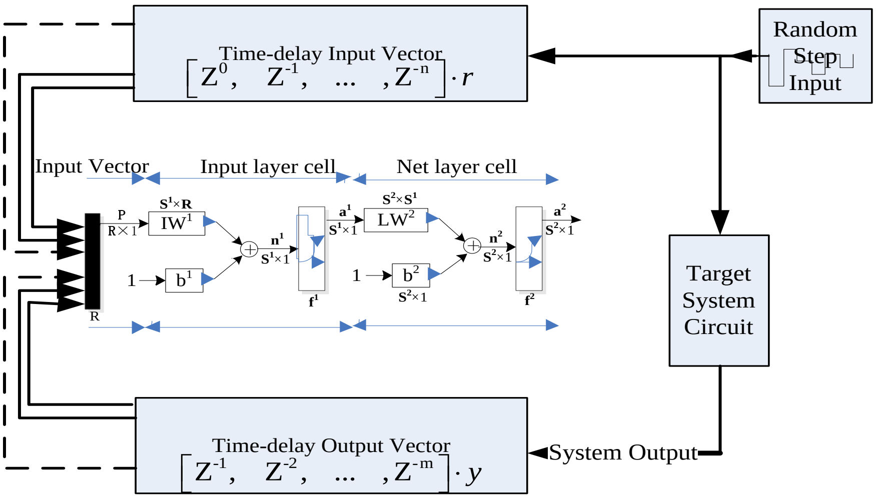

Figure 3 Response approximation modeling method

Because the step signal contains a set of full spectrum signals, the component can be fully motivated. A set of random step signals is used to motivate the circuit simulation model (the target component) to get sufficient amount of the system response data. The output is rich in health information of the circuits. Then, the input vector, its *n*-order time-delay, and the *m*-order output time-delay vectors of the circuit are used as training sample space. The BP neural network, which is chosen to learn the map relationship between the random step signals and their system responses, can be used as the response approximation core algorithm. The response approximation modeling method is shown in Figure 3.

IV. Example

A vehicle longitudinal control system, which is composed by a pitch angle sensor, a controller and an elevator, is shown as Figure 4. In order to simplify the problem, take the pitch angle sensor as an ideal model, the controller as a second-order model in transfer function form. However, a circuit model, which isdescribed by Proteus, is used as the controller. The function of controller is just to produce the PID control signal of elevator based on the difference signal between the command and actual values of pitch angle.

As shown in the Figure 5, the controller contains several elements such as the onboard computer 8051, the crystal, digital/analog, analog/digital converters, the power amplifier circuit, etc.

With orderly health simulation, the health mode and the effect analysis of every element are carried out to form the health behavior table of the controller [11].

Assuming four kind of health mode ($HM_i, i = 0, 4$) are considered, in which HM_0 represents the nominal health behavior of the controller. $HM_1 \sim HM_4$ represent the health behavior with some elements performance degradation. As shown in Table 1, two kinds of element health degradation are studied, one corresponds to three parameters of PID of the embedded software in 8051; the other is the variation of the crystal frequency. HM_0 's values are nominal values, while $HM_1 \sim HM_4$'s will change one of the nominal values. With the simulation of the controller circuit by changing these parameters value under different health behavior, a large number of health simulation data of this vehicle control system could be obtained based on the health information of the component. Then the circuit health behavior response approximation model (RAM) can be achieved based on the health simulation database by the method described in the Section 3.

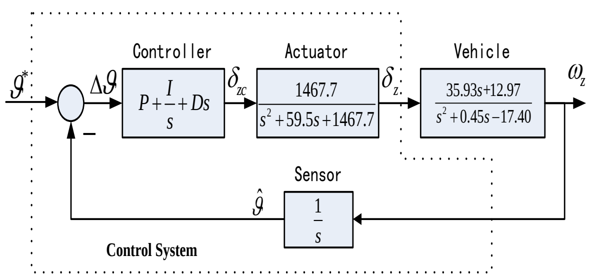

Figure 4 Block diagram of vehicle longitudinal system

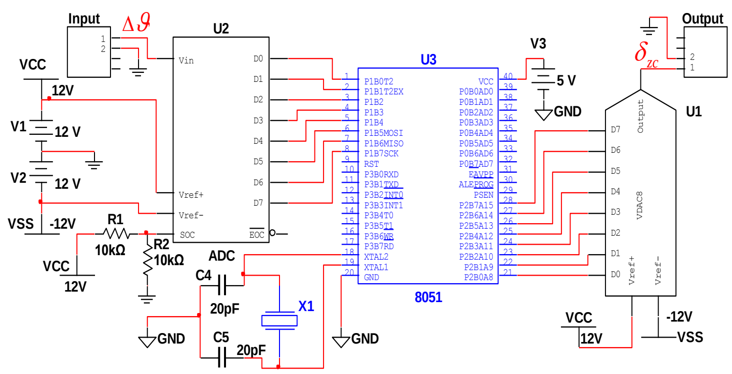

Figure 5 Controller circuit Proteus schematic diagram

Table 1 Controller health behavior table

Case (*i*)	Health Behavior	HM0	HMi	Corresponding Element
1	Proportion coefficient change	1	0.8	Software module of controller
2	Integral coefficient change	1	0.8	
3	Differentiation coefficient change	0.2	0.5	
4	Crystal frequency drift	12MHz	11.5MHz	Computer Crystal

Limited by the pages, only case 1(HM_3) is shown in this paper. Assuming differentiation coefficient value is changed from the nominal value of 0.2 to degradation value of 0.5 in the controller circuit simulation system, the other parameters are fixed to the nominal value(HM_0). This is implemented by modifying the program of the onboard computer 8051. After the simulation database of HM_0 and HM_3 is obtained, the response approximation models (RAM) have learned the dynamic characteristics of the PID controller with the parameters of [1,1,0.2] and [1,1,0.5]. In order to check the validity of the response approximation model, the transfer function model of PID, which is called target system model (TS model), and RAM are used in the vehicle longitudinal system model respectively. Figure 6 gives the time response comparison between the parameters of [1,1,0.2], [1,1,0.5] and their corresponding TS models. Furthermore, the consistency within a specific frequency band between TS model and its RAM model with parameters [1,1,0.2] is studied, as shown in the Figure 7. The above results shows that the model errors are so small that RAM can be applied into the system-level simulation by replacing the traditional model.

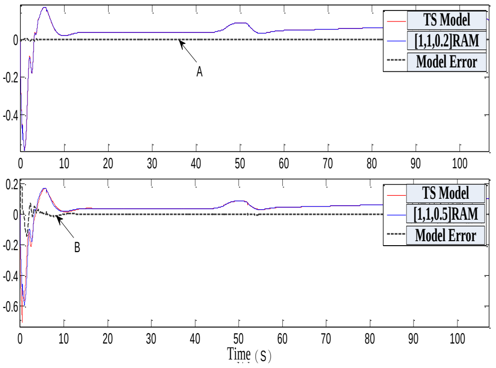

Figure 6 Comparison with RAM model and TS model

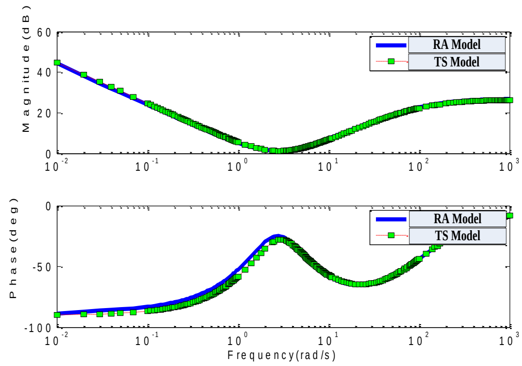

Figure 7 Comparison of the frequency domain characteristics

V. Conclusion

The different health behaviors of a certain system are shown by the different fault dynamic data. This method provides a way to extract health data from a circuit. With the aid of response approximation modeling method, the map relationship between fault data and the system input can be found. All the different health behaviors of components are capable to be consolidated into a system-level simulation in a consistent expression. The different health behaviors of systems with different mechanisms can be simulated on the same platform.

In order to obtain a better approximation model of the system, the time-delay order *m* and *n* and the sampling frequency of training data should be adjusted according to the order of the target system. The adequacy of the training information is impacted by the random step input. The width of each random step should be adapted to the adjusting time of the target system. Since the amplitude of the random step input is limited, the input and the output of the response approximation model are bounded. It means that the response approximation model can work effectively within a bounded input range. When the health behaviors are regarded as a set of different dynamic characteristics of a system, the dynamic response data (or health data) of the system becomes the bridge to connect the response approximation model and the system health behaviors. Therefore, with the circuit fault simulating data, this response approximation method is able to find its way to make a contribution to the IVHM system.

This paper discusses the core dynamic learning algorithm of BP neural network. The use of other non-linear learning algorithm may get better performance, but the basic principle is the same.

VI. Acknowledgments

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