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Research on the Optimal Sensor Placement of Vehicle Control System Based on Bode Sensitivity Function

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Abstract: In allusion to the optimal sensor placement problems for the condition monitoring and fault diagnosis of the vehicle control system in the weapon system, the optimal sensor placement theory based on Bode sensitivity function is adopted to place sensor. Simulation experiment is carried out through simulation model which has a two-circuit closed loop system, and the results indicate the rationality of choosing detection points according to sensitivity function amplitude. Finally, the basic scheme and instructive rules on sensor placement of the vehicle control system are proposed. The scheme can optimize the sensor placement and obtain the rich information of the system at a low cost. By this way, the effect of condition monitoring and fault diagnosing are improved obviously. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Condition monitoring and fault diagnosis, Sensor placement, Bode sensitivity function.

1. Introduction

As a large complex mechatronic system, the vehicle control system of the weapon system is in charge of the important operations such as leveling, erection and so on. In operation of the vehicle control system,, the control of the hydraulic system is realized through electromagnetic valve controlled by computer, and the corresponding function of mechanism system is implemented under the drive of hydraulic system. To master the operation state of vehicle control system and avoid accident, it's necessary to study the condition monitoring and fault diagnosing of vehicle control system.

To monitor and diagnose the system condition, the first considered problem is the place where the sensors are located. In vehicle control system, there are a lot of point positions which can be used to place sensors. It's impossible to acquire all data which can be acquired for the aim of economizing cost and ensuring reliability. So, the optimal place, which can reflect the fault condition information maximally, must be found to place sensors among all the acquired places, and obtain the rich information of the system at a lowest cost.

Comparing with rapid development of condition monitoring and fault diagnosis, the optimal sensor placement problem has not provoked the attention at all times [1]. The beginning research of the optimal sensor placement was executed in 1970s [2-4], in 1997, Lambert had analyzed sensor placement using fault tree and based on the influence of fault resource to procedural variable. But this method had no capability to deal with loop and the aging was very strong, besides, developing a fault tree will lead to error by itself. In 1979, Iri put forward the causality analysis idea for system fault based on Directed Graphs and studied the optimal sensor placement problem. After that, many scholars studied Directed Graphs profoundly and constructed fault diagnosis

system based on rule [5-7]. Directed Graphs model provides a figure expression method aiming at monitoring process, which has the advantages that it's easy to be built and can use vested algorithm of graph theory. But, the restriction factors of this method are very strictly and not easy to meet. In 2003, to linear structured system which contains disturb signals, to meet the solved conditions of fault detection identify, Commault had completed the research work through adding sensors at the lowest cost [8]. But its solution procedure which has excessive subjective component was too complicated. Comparing with this method, the optimal sensor placement theory based on Bode sensitivity function which was provoked by Yonghui Xu provides an important reference and guidance especially for the complicated system [9], such as vehicle control system which has many small subsystems.

2. Optimal Sensor Placement Theory Based on Bode Sensitivity Function [10]

2.1. Bode Sensitivity Function

Reviewing the linear time invariant system shown in Fig. 1, it's a single input and single output system. The transfer function of the system mainly depends on s and parameter vector a, where $\mathbf{a}=\left[a_1,a_2,\cdots,a_r\right]^T$.

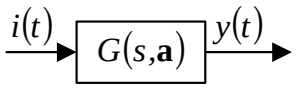


Fig. 1. A typical linear time invariant system.

Supposed $G=G\left(s,\mathbf{a}\right)$, $G_0=G\left(s,\mathbf{a_0}\right)$, where G and G_0 are the real transfer function and nominal transfer function separately, the Bode sensitivity function can be defined as:

$$S_{a_i}^{G}\left(s\right)=\left.\frac{\partial \ln G}{\partial \ln a_i}\right|_{\mathbf{a}_0}=\left.\frac{\partial G}{\partial a_i}\right|_{\mathbf{a}_0}\frac{a_{i0}}{G_0}, \tag{1}$$

In general, $S_{a_j}^{G}\left(s\right)$ is the complex frequency function of s $(s=\sigma+jw)$. When $s=jw$, $S_{a_j}^{G}\left(jw\right)$ is the frequency response of the function. To apply conveniently, the amplitude or modulus of $S_{a_j}^{G}\left(jw\right)$ is adopted as reference value. If the amplitude or modulus is too big in special frequency-domain that is to say, the influence generated by parameter vector to the system is very large, contrary is the same. So, the magnitude of amplitude of the Bode sensitivity function can be used to instruct the sensor placement.

2.2. Optimal Sensor Placement Method Based on Bode Sensitivity Function

Fig. 2 shows a typical closed loop system. $G_c\left(s\right)$, $G_a\left(s\right)$, $G_z\left(s\right)$ and $G_b\left(s\right)$ are defined as the transfer function of control unit, driver unit, performance unit and feedback unit separately. A, B, C are the monitoring points which stand of system output, feedback output and control unit output separately.

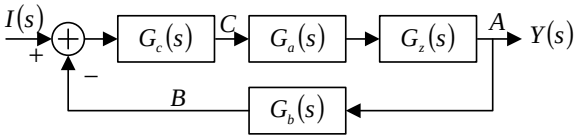


Fig. 2. A typical closed loop system.

Associate with equation (1), the number of Bode sensitivity function is 9 on the three given points, which can be expressed as a matrix form (equation (2)). The row of the matrix stands for the possible place of sensors, and the array stands for the influence to unit output by the fault. To express simply, the position of detection point and the name of fault unit are used to denote the superscript and subscript of the sensitivity function.

$$S=\begin{bmatrix} S_{G_b}^{Y} & S_{G_b}^{B} & S_{G_b}^{C} \\ S_{G_a}^{Y} & S_{G_a}^{B} & S_{G_a}^{C} \\ S_{G_z}^{Y} & S_{G_z}^{B} & S_{G_z}^{C} \end{bmatrix}, \tag{21}$$

The solved result can be expressed as:

$$S=\begin{bmatrix} 1 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix}$$

The monitoring point place is the more portable place to mount sensor where the calculation result is 1. Hence, from the above sensitivity vector we can infer the conclusions:

1) If the sensor is mounted on point C, the gained information is the most which include the condition information of driver unit, performance unit and feedback unit.

2) If the sensor is mounted on point A, the small quantities information can be achieved.

3) If the sensor is mounted on point B, it's difficult to achieve any information about system condition.

Extending the above conclusions to the typical closed loop nested system, as shown in Fig. 3, if the response of outermost layer (G_{b1}) contains integration components, the numerical tabular of sensitivity function illustrated in Table 1 can be achieved. The sensitivity function value in the table can be used to guide the placement of sensor.

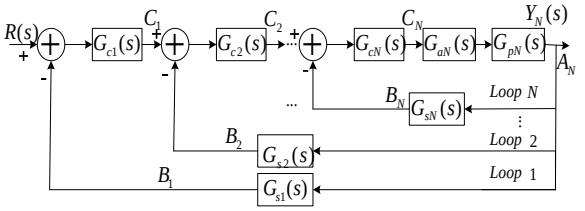


Fig. 3. Typical closed loop nested system.

Table 1. Numerical tabular of sensitivity function for typical closed loop nested system.

	A_N	B_1	...	B_N	C_1	...	C_N
G_{aN}	0	0	0	0	0	0	1
G_{pN}	0	0	0	0	0	0	1
G_{s1}	1	0	1	1	1	1	1
G_{s2}	0	0	.	0	0	0	0
⋮	0	0	.	0	0	0	0
G_{sN-1}	0	0	.	0	0	0	0
G_{sN}	0	0	0	1	0	0	0

From Table 1 we can achieve the following conclusions which can be used to guide the sensor optimal placement of vehicle control system:

1) The output of the system and sensors show no sensitivity to the faults of performance unit.

2) The output of the system shows sensitivity only to the sensor fault of the outermost layer.

3) Except for the output of outermost layer sensor, the output of the sensor shows sensitivity to the faults which appeared in the outermost layer sensor and itself loop sensor.

3. Simulation Experiment Analysis

The validity of optimal sensor placement method based on Bode sensitivity function is certified through a two circuits closed loop system simulation model. The constructed closed loop is shown in Fig. 4.

In the case of guaranteeing the validity of simulation experiment, to reduce calculation, the transfer functions in Fig. 4 are set as:

$$G_{c1}(s)=30, G_{c2}(s)=1, \tag{3}$$

$$G_z(s)=\frac{1}{s^2+7s+10}, \tag{4}$$

$$G_{b1}(s)=1, G_{b2}(s)=0.5, G_a(s)=1, \tag{5}$$

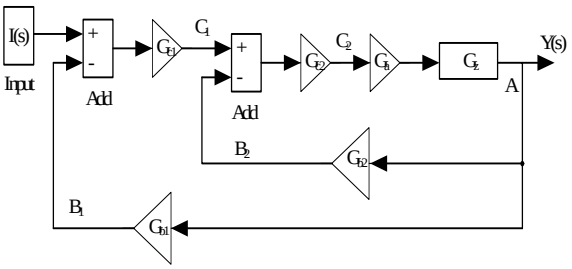


Fig. 4. Simulink simulation model of two circuits closed loop system.

To two circuits closed loop system, the monitoring points are placed on the given points A, B_1, B_2, C_1 and C_2. According to the calculation method, the sensitivity function expressions of fault units in the monitoring points can be expressed as:

$$\left|S_{G_{b1}}^{A}\right|=\left|S_{G_{b1}}^{B_2}\right|=\left|S_{G_{b1}}^{C_1}\right|=\left|S_{G_{b1}}^{C_2}\right| =\left|\frac{-G_{c1}G_{c2}G_aG_zG_{b1}}{1+G_{c2}G_aG_zG_{b2}+G_{c1}G_{c2}G_aG_zG_{b1}}\right|, \tag{6}$$

$$\left|S_{G_{b2}}^{A}\right|=\left|S_{G_{b2}}^{B_1}\right|=\left|S_{G_{b2}}^{C_2}\right| =\left|\frac{-G_{c2}G_aG_zG_{b2}}{1+G_{c2}G_aG_zG_{b2}+G_{c1}G_{c2}G_aG_zG_{b1}}\right|, \tag{7}$$

$$\left|S_{G_a}^{A}\right|=\left|S_{G_z}^{A}\right|=\left|S_{G_a}^{B_2}\right|=\left|S_{G_a}^{B_1}\right|=\left|S_{G_z}^{B_1}\right| =\left|\frac{1}{1+G_{c2}G_aG_zG_{b2}+G_{c1}G_{c2}G_aG_zG_{b1}}\right|, \tag{8}$$

$$\left|S_{G_{b1}}^{B_1}\right|=\left|\frac{1+G_{c2}G_aG_zG_{b2}}{1+G_{c2}G_aG_zG_{b2}+G_{c1}G_{c2}G_aG_zG_{b1}}\right|, \tag{9}$$

$$\left|S_{G_{b2}}^{B_2}\right|=\left|\frac{1+G_{c1}G_{c2}G_aG_zG_{b1}}{1+G_{c2}G_aG_zG_{b2}+G_{c1}G_{c2}G_aG_zG_{b1}}\right|, \tag{10}$$

$$\left|S_{G_{z_2}}^{C_1}\right| =\left|\frac{G_{c1}G_{c2}^2G_a^2G_z^2G_{b1}G_{b2}}{\left(1+G_{c2}G_aG_zG_{b2}\right)^2+G_{c1}G_{c2}G_aG_zG_{b1}+G_{c1}G_{c2}^2G_a^2G_z^2G_{b1}G_{b2}}\right| \tag{11}$$

$$\left|S_{G_z}^{C_1}\right| = \left|S_{G_z}^{C_1}\right| = \left|\frac{G_{c1}G_{c2}G_aG_zG_{b1}G_{b2}}{\left(1+G_{c2}G_aG_zG_{b2}\right)^2 + G_{c1}G_{c2}G_aG_zG_{b1} + G_{c1}G_{c2}^2G_a^2G_z^2G_{b1}G_{b2}}\right| \quad (12)$$

$$\left|S_{G_a}^{C_2}\right| = \left|S_{G_z}^{C_2}\right| = \left|\frac{-G_{c2}G_aG_zG_{b2} - G_{c1}G_{c2}G_aG_zG_{b1}}{1+G_{c2}G_aG_zG_{b2} + G_{c1}G_{c2}G_aG_zG_{b1}}\right|, \quad (13)$$

Substituting equations (3), (4) and (5) into equations (6)~(13), the explicit expression of the corresponding sensitivity function can be achieved, and the amplitude frequency curve is shown in Fig. 5.

From Fig. 5, in low frequency, the amplitude of sensitivity function indicates that the fault condition detection of feedback unit G_{b2} can be fulfilled through placing monitoring points in C_1, C_2, B_2 and A, the fault condition detection of feedback unit G_{b1} can be fulfilled through placing monitoring point in B_2, and to the fault detection of drive unit and performance unit, the sensors must be placed in points C_1, C_2.

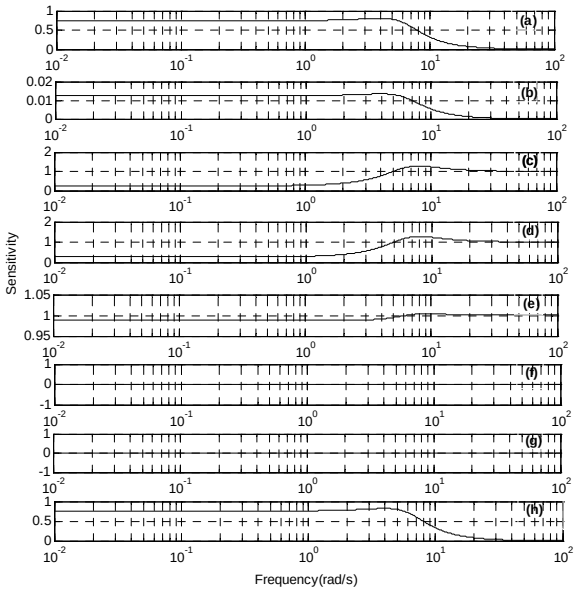


Fig. 5. Amplitude frequency curve of Bode sensitivity function.

To further certify the corresponding relationship between the sensor placement conclusions based on Bode sensitivity function and the relative strength of residual signals of the detecting points in fault condition, a preinstall fault model is adopted to carry out certified experiment. Based on the simulation model, the preinstall fault is set as the gain value of feedback unit, drive unit and performance unit are decreased 10 percent in the time of 10 second, the residual signals of the detecting points in simulation experiment are illustrated in Fig. 6 (a), Fig. 6 (b) and Fig. 6 (c).

The conclusions of sensitivity function are proved by the residual signals curve of the monitored points. If the performance units or drive units appear fault, the residual output signals of control units are not equal to zero, so the monitoring point can be placed on the terminal of control unit. If the feedback unit 1 happens to occur fault, the residual output signals of system output, feedback unit 2 and control unit are all not equal to zero, thus, all these outputs can be used to set monitoring point. When the feedback unit 2 has fault, its residual output signal is a stable nonzero value, the detecting point can be placed in the feedback output position.

Comparing Fig. 5 with Fig. 6 we can infer that at low frequency domain, the corresponding fault unit whose amplitude of sensitivity function is bigger will have a bigger residual value in monitoring point. Thus, the option of monitoring point through amplitude of sensitivity function is reasonable. At circumstance of the three fault condition, the residual value in system output is zero approximately. So in the closed loop system, the traditional system performance judging method from the system output has many flaws and cannot find the incipient fault in the inner system timely.

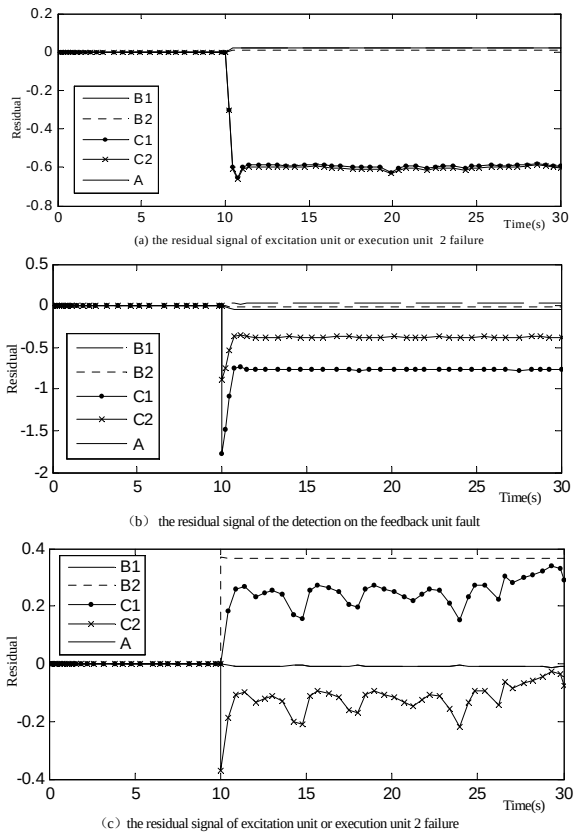


Fig. 6. Relationship curve among fault unit, residual signal and monitoring point.

4. Basic Scheme of Optimal Vehicle Control System Sensors Placement

According to difference of structure and function, the vehicle control system can be parted into three main components, hydraulic system, electric system and mechanism system. The monitoring and diagnosis of mechanism system does not need to major consider for its high reliability. So the problem of optimal sensor placement mainly aims at hydraulic and electric system.

4.1. Sensor Placement of Hydraulic System

As a complex system, according to the different operation procedure, hydraulic system is constructed by many subsystems and the fulfillment of the function are all realized by these subsystems. So, when placing sensors, every subsystem should be considered. If the subsystem is a closed loop system which contains integrating element, the optimal sensor place can be found through applying the above result simply, generally speaking, the optimal position is directional control valve. If the subsystem does not contain integrating element, the front-end or rear-end of the high fault rate elements such as pump, hydraulic cylinder are often chosen as the setting point of sensor. To oil system, for the self-complex, vibrating sensor and temperature sensor all added to achieve good monitoring effect.

4.2. Sensor Placement of Electrical System

For the restriction of space dimension, weapon system often applies modularized design, so, it's difficult to measure the inner of element or circuit. The positions which can be measured only include the I/O port of control system and individual element. In traditional, the sensors are often placed in the I/O port of electric equipment according to the importance and malfunction probability. But, if the monitored unit is a closed loop system which has integrating element, it's difficult to make a correct judgment of operation state of electrical system only through measuring the I/O of the system. The main reason lies in, to closed loop system, even if the parameter of the inner circuit element has been changed, the measured signal in the output position of system may just deviate the normal range instantly, it will restore rapidly for the regulating action of feedback. So, in this circumstance, the fault signal is a transient signal which can not be achieved easily. According to the sensor placement theory based on sensitivity function, only the signal which is extracted from the front-end of trouble unit is a continuous and stable fault signal which deviates from the normal domain. Accordingly, new scheme of sensor placement is adopted which places the sensor in the front-end of performance unit possibly.

4.3. Matters Need Attention

To the whole vehicle control system, hydraulic system, electric control system and mechanism system compose a united whole body, where hydraulic system is equivalent to performance unit, electric control system is looked on as controller, and mechanism system is thought to be performance unit. In operation, the three components added sensors construct a closed loop control system. Therefore, the corresponding sensors are placed in the output terminal of electric system is the optimal scheme. On the other hand, for the cross and mergence of subsystems, the vehicle system is made quite complex. One component of the system which is recognized as closed loop system at first will be changed into a performance unit or controller at an open loop system with the enlargement of observation domain. Thus, when optimizing the placement of sensor, the rule that placing sensor from the big system to small system should be obeyed. The position of sensor in big system should be considered firstly according to its structure, then, the second step is to consider the placement of sensor in small system. At the same time, the reliability, significance and other factors should also be considered.

Of course, besides thinking about the effect of fault monitoring and diagnosis, the addition of sensors also consider the realization cost, processing capability and improving complexity and decreasing reliability which are generated by adding sensors. The option of the optimal scheme is a synthesis of many influencing factors which should be considered seriously in realizing, and the scheme also should be checked by experiments and practice.

5. Conclusion

The sensor placement based on Bode sensitivity function is a mathematic model-based method in essence, which is quite fit to the system which operated along preinstall track, such as the vehicle control system of the weapon system. The consideration starting point of sensor placement of detected unit is not the appearing of functional fault in traditional sense, but the performance parameter changeable. In other words, the system may operate at normal station even if the fault phenomenon based on Bode sensitivity function happened, especially for those systems which have feedback modulation capability. In case of this circumstance, the provided sensor placement method based on Bode sensitivity function can find the incipient fault of the system as soon as possible, and the method also has the forecast capability which is quite important to weapon system.

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