ICAS-92-2.4.4

A NEW DYNAMIC PERFORMANCE IMPROVEMENT METHOD FOR MULTI–SENSOR SYSTEMS

Jun–Qin Huang, Xiaomao Xiao
No.302, Dept. of Automatic Control
Beijing University of Aeronautics and Astronautics
Beijing 100083, P.R.China

Keywords. Dynamic performance improvement method, multi–sensor system

Abstract

A new dynamic performance improvement method for multi–sensor measurement systems is presented in this paper. At the beginning a more general multi–sensor measurement system is given which includes analog sensor, frequency–output sensor, digital sensor and optical signal output sensor. Each sensor with its signal conditioner, signal–digital convertor and dynamic compensated digital filter chip form a channel of the measurement system. The dynamic compensated digital filter (DCDF) can improve the dynamic performance of the sensor, signal–conditioner and signal–digital convertor, i.e., DCDF can make the dynamic performance of the whole channel to meet the practical requirement. The DCDF is realized by using single chip microprocessor. A lot of experimental results are also given in this paper.

I. Introduction

There are a lot of multi–sensor systems in the aircraft, shuttles and their experimental equipment. A new dynamic performance improvement method for multi–sensor is established in this paper. It can be effectively applied to the aircraft, shuttle instrumentation, their experimental equipment and the industrial multi–sensor measurement systems.

II. Multi–sensor systems

The multi–sensor systems include different kinds of sensors and transducers which can be mainly divided into following four kinds according to the sensors′ output signals: analog sensors (AS), digital sensors (DS), frequency output sensors (FS) and optical signal output sensors (OS). They can be connected to the computer with analog–digital convertor(ADC), digital data convertor(DDC), frequency–digital convertor(FDC), optical–digital convertor(ODC). We consider a more general multi–sensor system in order to indicate that the method established in this paper can be used for improving the dynamic performance of different kinds of multi–sensor systems.

Figure 1 shows the block diagram of the multi–sensor measurement system. The number of the signal–digital convertor can be less than that of the sensors, with the use of multiplexers.

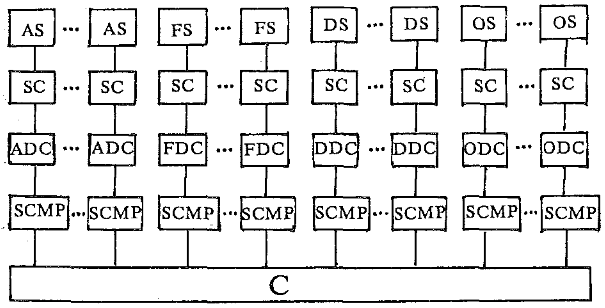


Fig. 1 Block diagram of general multi–sensor measurement system
AS –Analoy sensors
FS –Frequency output sensors
DS –Digital sensors
OS –Optical output sensors
ADC–Analog–digital convertor
FDC–Frequency–digital convertor
DDC–Digital–digital convertor
ODC–Optic–digital convertor
SCMP–single chip microprocessor
C–Computer

Similarly, the number of the single chip microprosser can also be less than that of sensors.

Ⅲ. The principle of the dynamic performance improvement method for multi–sensor systems

The dynamic calibration must be performed for each sensor with its signal conditioner (we also call it sensor bellow) and its dynamic mathematical model (DMM) can be built up according to the experimental data of dynamic calibration by using the effective dynamic modeling method. The dynamic performance of sensor can be found from the dynamic mathematical model. A new kind of digital filter (dynamic compensated D.F., i.e., DCDF) can be designed by using a new design method for DCDF in time domain if the dynamic performance does not meet the practical requirements. The actual effect of dynamic performance improvement can be checked and regulated to the optimistic condition by using the experimental study method. The optimized DCDF has to be built in a single chip micro–processor. A sensor, a signal conditioner, a convertor and a DCDF chip form a channel and the dynamic performance of this channel is improved to meet the requirement. A lot of DCDF chips for multi–sensor systems construct a chip matrix which can further become a single chip by using the micro–structure (VLSI) technology for large scale production.

(A) Dynamic calibration methods and systems of sensors

The dynamic calibration methods and systems are quite different from each other for different kinds of sensors. Generally the dynamic calibration methods for sensors can be divided into three main kinds: (1) dynamic calibration method in time domain, (2) dynamic calibration method in frequency domain, (3) dynamic calibration method using random signal and pseudo random signal. The dynamic calibration systems for the same sensor are also quite different for different methods. For example, figure 2 shows the dynamic calibration system of pressure sensor in time domain.

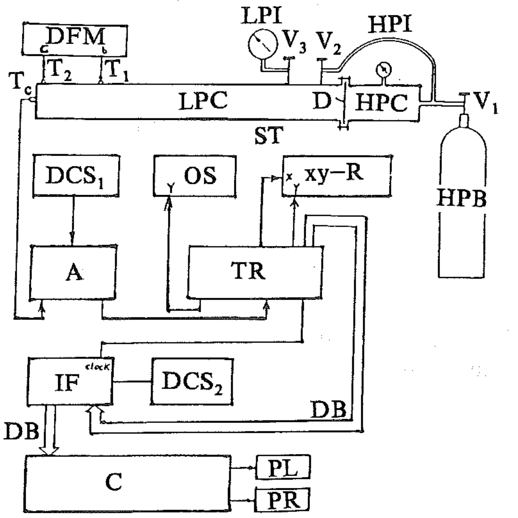


Fig. 2 Block diagram of the dynamic calibration system of prcssurc transducers with shock tube

HPB–High prcssure bottle;
ST–Shock tube;
LPC–Low pressure chamber;
HPI–High prcssure indicator;
T_1, T_2–Trigger transducers;
T_c–Calibrated transducer;
DCS_1,DCS_2–D.C. sources;
OS–Oscilloscope;
DB–Data bus;
C–Computer;
PR–Printer

v_1, v_2, v_3–Valves;
HPC–High pressurc chamber;
D–Diaphragm;
LPI–Low pressure indicator;
DFM–Digital frequency meter;
A–Amplifier of transducer;
TR–Transient recorder;
xy–R–XY Recorder;
IF–Interface;
PL–Plotter;

In our laboratory [1] where the shock tube is a very good step function generator of pressure. Figure 3 shows one of the transient force generator of the dynamic calibration system of forec sensor (load cell) in time domain in our laboratory [2] where the maximum transient force up to IMN and beyond can be generated by the transient–force generator. The transient recorder and the computer of this system are the same as that of the dynamic calibration system of pressure sensor.

The curve 1 of figure 4 shows the experimental curve of unit–step response of an inductive differential pressure transducer [3]. The curve 1 of figure 5 shows the experimental curve of unit–step response of an aircraft engine thermocouple

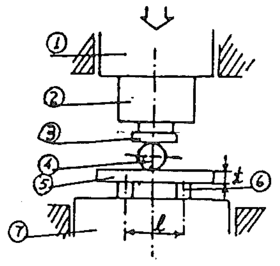


Fig. 3 Dynamic force calibration method up to 1MN and beyond

1–Loading column of press	5–Fragile material rod
2–Calibrated force transducer	6–Supporting block
3–Plate	7–Bottom column of press
4–Cylindrical bar	

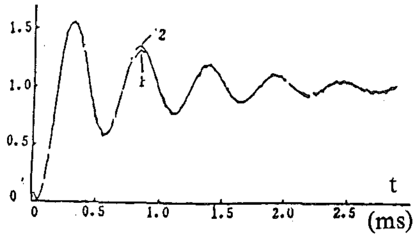


Fig. 4 The unit–step responses of an inductive differential perssure transducer

1–Experimental data; 2–Model calculated data.

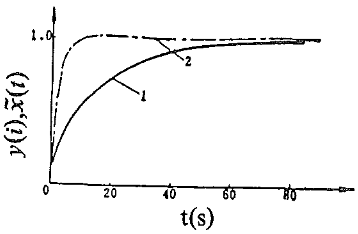


Fig. 5 Unit–step responses of the aircraft engine thermocouple.

1–Experimental unit–step response

2–Unit–step response after compensation

sensor [4] . The small triangles of figure 6 shows the experimental curve of unit–step response of a resonant vibration cylinder pressure transdacer [5] which can be used as the dynamic pressure transducer of air data computer.

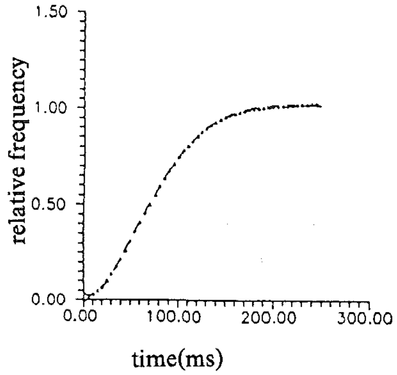


Fig. 6 Unit–step responses of resonont vibration cylinder pressure transducer

Δ —Exprimental data

– —Model calculated data

(B) Dynamic mathematical model of sensors

The dynamic mathematical models of sensors must be built up by using effective identification methods according to the dynamic calibration results. The identification methods in time domain or in frequency domain have to be selected according to the dynamic calibration methods. Figure 7 shows the block diagram of identification methods in time domain [2] . The dynamic mathematical models (DMM) of the inductive differential pressure transducer and resonant vibration cylinder pressure transducer are given below which are built up by using the identification method shown in figure 7 according to the dynamic calibration results shown in figures 4 and 6 respectively:

DMM of inductive differential pressure transducer [3] is

$$G(Z)=\frac{b_0+b_1Z^{-1}+b_2Z^{-2}+b_3Z^{-3}+b_4Z^{-4}}{1+a_1Z^{-1}+a_2Z^{-2}+a_3Z^{-3}+a_4Z^{-4}} \tag{1}$$

Table of parameters of DMM of inductive differential pressure transducer

$a_0=1$	$b_0=0.06938612$
$a_1=3.666901$	$b_1=-0.3086321$
$a_2=5.109641$	$b_2=0.5609838$
$a_3=3.202806$	$b_3=-0.4647373$
$a_4=0.7617944$	$b_4=0.1447428$

DMM of resonant vibration cylinder pressure transducer [5] is

$$G(Z)=\frac{1.78381\times10^{-3}-3.28818\times10^{-2}Z^{-1}+1.64004Z^{-2}}{1+0.983289Z^{-2}-1.98315Z^{-2}} \tag{2}$$

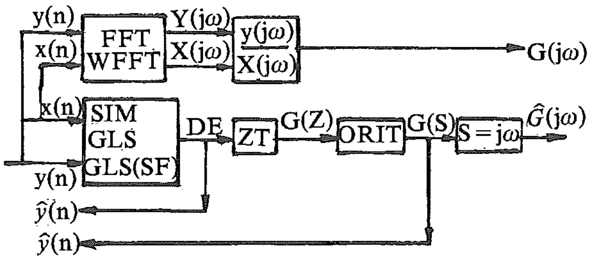


Fig. 7 Black diagram of processing method of dynamic calibrotion in time domain
x(n)—Input excitation signal
y(n)—Output transient response (experimental data)
ŷ(n)—Model calculated output respose
SIM—Simultaneous identification method of model order and parameters
GLS— Generalized least square method
GLS(SF)—Gereralized least square method with special whitening filter
DE—Difference equation
ZT—Z transform
ORIT—Output response invariant transformation
WFFT—An approximate algorithm of Fourier transform

The model testing method is an effective method for testing the quality of the dynamic mathematical models. The model calculated data of equations (1) and (2) are well coincided with the corresponding experimental data shoun in figure 4 by curre 2 and 6 by dash line. This result indicates that the qualities of these DMM are pretty good.

The frequency response of sensors can be calculated from DMM of sensors. For example, the frequency responses of the inductive differantail pressure transducer and the resonant vibration cylinder prassure transducer are shown in curve 1 of figures 8 [3] and 9 [5] calculated by equation (1) and (2) respectively.

The practical useful dynamic performance indexes of sensors are the operational frequency bandwidth corresponding to given assigned amplitude error and phase shift. Figure 10 (a) and (b) show the operational frequency bandwidth $\omega_{g1}$and ω_{g2}corresponding to ± 10% and ± 5% amplitude errors and phase shift $\varphi(\omega_{g1})$ and $\varphi(\omega_{g2})$ of under damped and over damped systems. For example, the dynamic performance indexes in frequency domain can be calculated from figure 9 for the resonant vibration pressure transdusers [5], the calculated results are as follows: $\omega_{g1}=2.8\text{Hz}$, $\varphi(\omega_{g1})=-51.2395\text{deg.}$, $\omega_{g2}=3.4\text{Hz}$, $\varphi(\omega_{g2})=-63.6674\text{deg.}$,

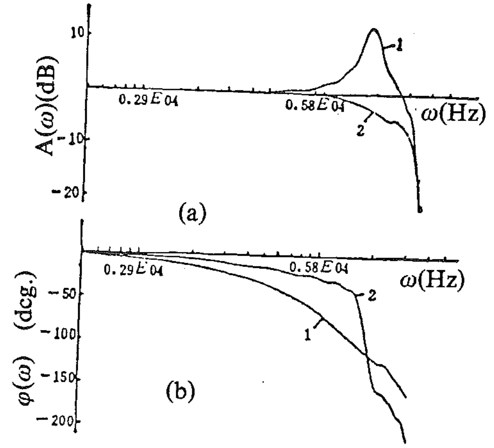


Fig. 8 The frequency responses of inductive differentail pressure transducer before and after compensation
1—Before compensation; 2—After compensation
(a) Amplidude frequency response
(b) Phase fequency response

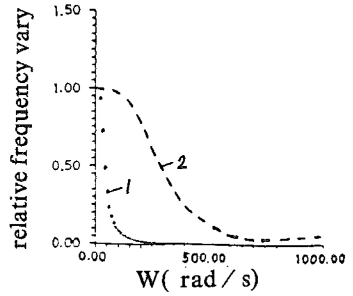
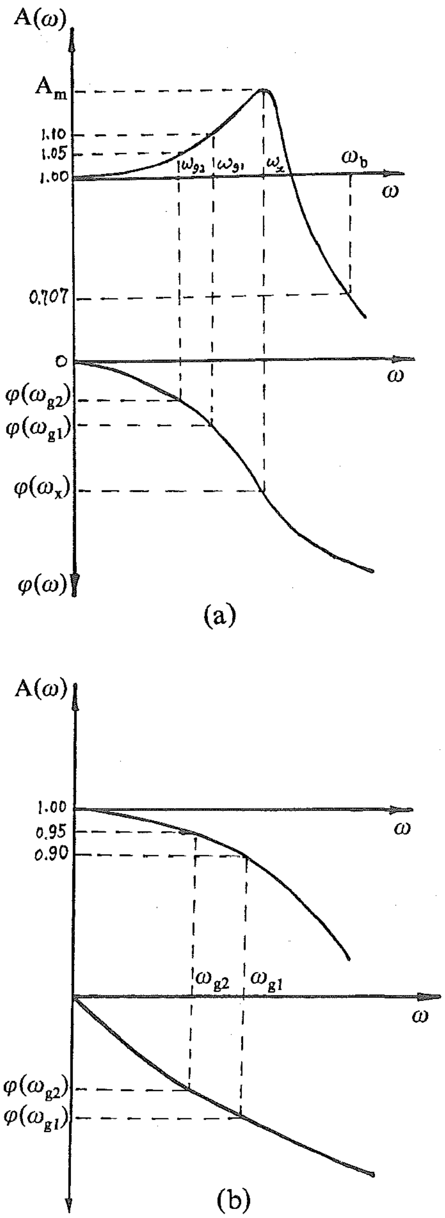


Fig. 9 amplitude frequency response of the resonant vibration cylinder pressure transducer
1—Amplitude frequency response befor compensation
2—Amplitude frequency response after compensation



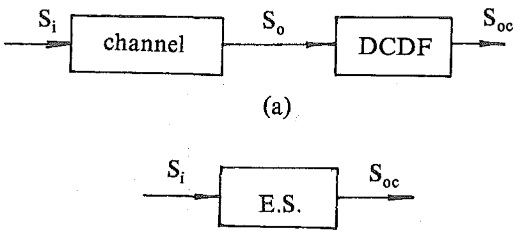
(a)

(b)

Fig. 10 Operational frequency bandwidth ω_g
(a) Under damped system
(b) Over damped system
$A(\omega)$–Amplitude frequency response
$\varphi(\omega)$–Phase frequency response
ω_b–Frequency bandwidth
ω_x–Resonant frequeney
ω_g–Operational frequency bandwidth

(C) Design of dynamic compensated digital filters

The dynamic compensated digital filter must be used in order to improve the dynamic performance if the dynamic performance of the sensor does not meet the practical requirement. The dynamic performance of the sensor would include both its′ signal conditioner and signal–digital convertor (e.g. ADC, FDC, etc), because the dynamic compensated digital filter is stored in the single chip microprocessor. This means that the dynamic performance of the sensor should be locked as the dynamic performance of the whole channel including sensor, signal conditioner, signal–digital convertor and single chip micropressor, hence, the dynamic compensated digital filfer is used to improve the dynamic performance of the whole channel. The design idea of the dynamic compensated digital filter can be illustrated by using figure 11 [4] , i.e., the dynamic compensated digital filter is connected in series with the channel, if the dynamic performance of the channel does not meet the practical requirement, but the dynamic performance of the equivalent system (E.S.) of both channel and DCDF satisfies the practical requirement.



(a)

(b)

Fig. 11 Design idea of DCDF
S_i–Input signal (measurand)
So–Output signal of the channel
Soc–Output signal of DCDF
E.S.–Equivalent system

Two design methods [3,4] of dynamic compensated digital filters have been established by us. The first one is actually a design method for recursive digital filter in time domain [7] by using data sequences $S_o(n)$ and $S_{oc}(n)$ ($n=0,1,2,\cdots,N$). For axample the designed dynamic compensated digital filter for resonant vibration cylinder pressure transducer with its′ amplifier and frequency–digital convertor [5] is as follows:

$$G_c(z)=\frac{6.222658\times 10(Z^2-1.98315Z+0.983289)}{Z^2-1.86522Z+0.8738733}$$

The main design procedures of the second design method are as follows:

(1). Build up the dynamic mathematical model (discrete transfer function) of the compensated system(channel).

(2). Find the poles of the discrete transfer function. The compensated system may be considered as a system composed of many subsystems of the poles.

(3). Find the response times of every subsystem. The response time of compensated system is mainly determined by the maximum response time of subsystems.

(4). Give the expected improved response time ratio according to the requirement.

(5). Find the zero and pole of the dynamic compensated D.F..

(6). Calculate the frequency response of the system before and after compensation

For example, the discrete transfer function of the dynamic compensated digital filter of the inductive differential pressure transducer is as follows:

$$G_c(z)=\frac{0.671201Z^2-0.1276592Z+0.641374}{Z^2-1.764613Z+0.8006478}$$

Figure 12 shows the unit–step responses of the inductive differential pressure transducer before and after compensation with dynamic compensated digital filter. It is seen from figure 12 that the unit–step response becomes nearly critical damping after compensation and the actual responsed time is reduced to 365μs which is only 1 / 7.23, of the original response time.

Obviously, there is much improvement in time domain.

Figure 8 shows the frequency responses of the inductive differential pressure transducer before and after compensation with the dynamic compensated digital filter. It is seen from the figure 8 that the operational frequency bandwidth is expanded to 2 times after compensation by using designed digital filter.

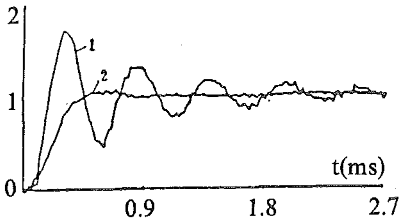


Fig. 12 The experimental unit–step responses of the inductive differentail pressure transducer before and after compensation

1–Before compensation 2–After compensation

(D) Optimizing the parameters of dynamic compensated D.F. by using the experimental study method

The actual effect of dynamic performance improvement can be checked and regulated to the optimistic condition by using the experimental study method [6]. Figure 13 shows the block diagram of the experimental study method. The dynamic calibration system (DCS) gives a dynamic excitation signal (e.g. unit–step function, δ–function etc.) to the sensor, the effect of dynamic performance improvement can be seen by comparing the channel output response and the dynamic compensated D.F. output response. The effect of dynamic performance improvement can be adjusted to the optimistic state by regulating the parameters of dynamic compensated D.F. Curve 2 in Figure 5 shaws the final unit–step response of thermocouple. Compare curves 1 and 2 in figure 5, it is seen that the responsed time is only 1 / 7.4 of that before compensation, Figure 14 shows the frequency responses before and after compensation of the aircraft engine thermocouple. It is seen from the figure 14 that the operational frequency bandwidth is extended to 7.5 times after compensation by using dynamic compensated D.F.

Fig. 13 Block diagram of experimental study method

DCS–Dynamic calibration system

S–Input of dynamic calibration system

S_i–Dynamic excitation signal generated by DCS

S_o–Output signal of the channel

S_{oc}–Output signal of DCDF

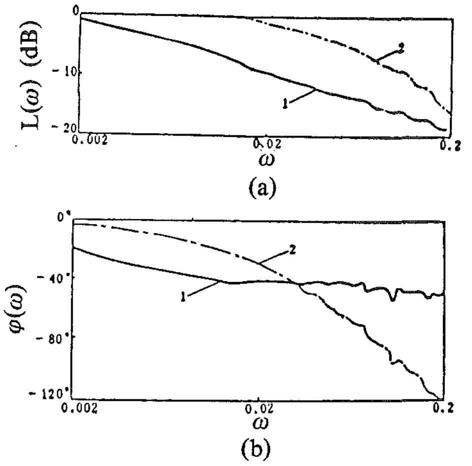


Fig. 14 Frequency response of the aircraft engine thermocouple
(a) Amplitude frequency response
(b) Phase frequency response
1–Before compensation
2–After compensation

(E) The DCDF is realized by using single chip microprocessor

The optimized dynamic compensated digital filter can be built in a single chip microprocessor. There are analog–digital convertor (ADC) and frequency–digital conrertor (FDC) in some single chip microprocessor, e.g., there are 4 ADC and 4 high speed input ports, which can be used as FDC, in MCS 8098 single chip microprocessor. Both the FDC and the dynamic compensated D.F. of our resonant vibration cylinder pressure transducer are realized by using MCS8098 single chip microprocessor as shown in figure 15 [5] . The curves 1 and 2 of figure 16 are the unit–step responses of this system before and after compensation respectively. The responsed time of the whole system is only 1 / 8 of that of the system without dynamic compensated digital filter. The curve 2 of figure 9 shows the amplitude frequency response after compensation. Compare curve 1 and 2 of figure 8 it is seen that the operational frequency bandwidth of the whole system is extended by 7.8 times. Combine figures 9 and 16, we can learn that the dynamic performance improvement method is very effective both in time domain and in frequency domain.

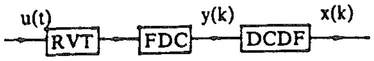


Fig. 15 The block diagram of dynamic performance improvement method for the resonant vibration transducer
RVT–Resonant vibration transducer
FDC–Frequency digital convertor
DCDF–Dynamic compensated digital filter
U(t)–Input measurand
y(k)–Output of FDC
x(k)–Output of DCDF

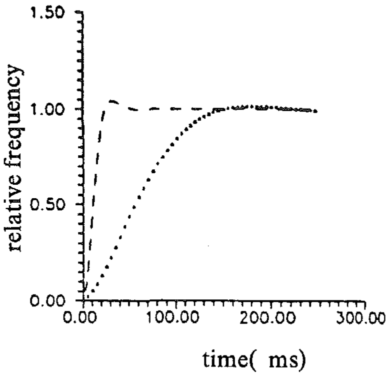


Fig. 16 Unit–step responses of resonant vibration cylinder pressure transducer before and after compensation
Δ —unit–step response before compensateon
– —Unit–step response after compensation

(F) A lot of the DCDF can further become a single chip for multi–sensor system

There are a lot of channels for multi–sensor measurement system as shown in figure 1. Sometimes it is not necessary to use one single chip microprocessor for each channel, it depends upon the detail conditions of the practical multi–sensor measurement system. A lot of single chip microprocessors form a chip matrix of dynamic compensated digital filter. The parameters of all dynamic compensated digital filters are optimized and fixed by using the experimental study method. For some multi–sensor measurement system, e.g., the multi–sensor systems in the aircraft, shuttles and their experimental equipment, etc, a lot of the dynamic compensated digital filters and convertors can further become a single chip by using the micro–structure (VLSI) technology for large scale production. Thus the multi–sensor system becomes a more reliable, smaller, lighter and higher performance system.

Ⅳ. Conclusion

(1). The method established in this paper can be widely used for different kinds of multi–sensor systems.

(2). A lot of programs including algorithms mentioned above (e.g., from dynamic modeling method to design method of DCDF, etc.) form a software package.

(3). The DCDF chips are used effectively to improve the dynamic performance of the multi–sensor systems.

(4). Some design and experimental results are given in this paper.

(5). The final experimental results effectively prove that all principles and methods mentioned above are correct, i.e., the modeling methods for building up the DMM of diffferent kinds of sensors, the design methods for DCDF and the experimental study methods are all correct. These methods are practically useful.

Reference

〔1〕 Jun–Qin Huang, Research for Dynamic Mathematical Model of Pressure Trans–ducer, ACTA METROLOGICA SINICA, Vol.8, No.3, July 1987, pp.201–207.

〔2〕 Jun–Qin Huang, Zheng–she Liu and Xiao–kui Wang, Dynamic Calibration System and Dynamic Mathematical Model of Force Measuring Systems,Procs. of Beijing International Conference on Mechatro– nics (BECM'91), 1991, Beijing, pp.734–741.

〔3〕 Jun–Qin Huang and Ping Ji, A Design Method of Dyanamic Compensated Digital Filter, Chinese J. of Scientific Instrument, Vol.8, No.3, Aug. 1987, pp.330–335.

〔4〕 Jun–Qin Huang and Lion–Sheng Hou, A Design Method in Time Domain of Dynamic Compensated Digital Filter, Signal Processing, Vol. 1, No.3, 1985, pp.212–221.

〔5〕 Qi Tang and Jun–Qin Huang, Study on The Dynamic Calibration Method and The Dynamic Performance Improvement Method for Resonant Vibration Cylinder Pressure Transducers, Procs. of The First Asia / Pacific International Symposium on Instrumentation, Measurement and Automatic Control, Aug. 25–31, 1991, Shanghai, China, pp.49–54.

〔6〕 Jun–Qin Huang and Ping Ji, An Experimental Study Method of Dynamic Compensated Digital filter, ACTA METROLOGICA SINICA, Vol.10, No.1, Jan. 1989, pp.45–49.

〔7〕 Jun–Qin Huang, and Lien–sheng Hou, A Design Method of Recursive Digital Filter in Time Domain, Chinese J. of Scientific Instrument, Vol. 5, No.2, May 1984, pp.164–170.