The research on the dynamic compensation and real-time processing method of the shock wave's pressure sensor

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Abstract

The dynamic compensation technology is an effective approach to improve the dynamic response characteristics of the sensor. Based on the improved Quantum-behaved Particle Swarm Optimization (QPSO), a sensor dynamic compensation method is put forward with the shock wave's pressure testing as background. This method is according to the experimental data of the sensor dynamic calibration experiment for the system identification, thus creating the sensor and the reference model which can get the weight and coefficient of the Dynamic Compensation Filter quickly and accurately. After the MATLAB simulation, the results show that the response speed of the sensor model which is compensated by this method accelerates, the working frequency bandwidth is expanded, and meanwhile the noise is restrained effectively. In addition, based on the FPGA data acquisition system, the distributed arithmetic is introduced, and the parallel structure design of the Sensor is completed so as to realize the real-time correction of the dynamic error of the pressure sensor.

Keywords: Quantum-behaved Particle Swarm Optimization (QPSO), Dynamic Compensation, FPGA

1 Introduction

The dynamic errors of the dynamic testing is mainly due to the imperfection of the dynamic characteristic of the sensor, thus, improving the dynamic characteristic of the sensor is the most effective way to reduce the dynamic errors. The study basis of the dynamic characteristic of the sensor is to establish the sensor dynamic model to improve its dynamic performance by compensation [1].

With the popularization of computer technology, the outputs of the sensor can be processed subsequently, and the design of dynamic compensation method has been widely applied. The usual design methods of the dynamic compensator are pole-zero placement and system identification method. But in these methods, the structure of the dynamic compensator must be set in advance, and when the characteristics of the sensor is the advanced nonlinear system, the design of the dynamic compensator structure is quite complex. This essay focuses on the design method of the Dynamic Compensation Filter which is based on the Quantum-behaved Particle Swarm Optimization (QPSO) [2]. This approach belongs to the system reference model, in which it is not necessary to know the sensor dynamic model in the whole process, so as to avoid the influence of the error of the sensor dynamic modelling on the dynamic compensation. And then, through the simulation and experiment, the feasibility of the obtained dynamic compensation filter, the dependence of the training samples and the sensitivity to the noise are validated and analyzed. In order to correct the sensor dynamic error in time, in this essay a testing system based on FPGA is designed and the compensator will be implemented in FPGA through the distributed arithmetic. Finally, the system can be used for data collection of the output of the sensor simulator, and the accurate acquisition ability towards the system and the real-time correction ability are verified.

2 The principle of the QPSO algorithm

QPSO algorithm is no longer described by particle velocity and position, but through the wave function, finally the evolution equation of particle state for each dimension can be got [3]:

$$\mathrm{p_{id}}\left(t\right)=\phi_{id}\left(t\right)p_{id}\left(t\right)+\left(1-\phi_{id}\left(t\right)\right)p_{gd}\left(t\right), \quad (1)$$

$$X_{id}\left(t+1\right)=p_{id}\left(t\right)\pm\frac{l_{id}\left(t\right)}{2}\times\ln\left[\frac{1}{u_{id}\left(t\right)}\right]. \quad (2)$$

Among them $p_i=\left(p_{i1},p_{i2}\cdots,p_{iD}\right)$ is the ith particle which is the attractor in the evolution and iteration process, $X_i=\left(X_{i1},X_{i2},\cdots,X_{iD}\right)$ is the present position of the ith particle, φ_{id} and u_{id} are all the random numbers which are uniformly distributed on the [0,1].

In the state equation of the particle, the feature length of δ Potential well for each dimension $L_{id}\left(t\right)$ is very important for the control iterative method, how to control $L_{id}\left(t\right)$ the iteration converges to 0 has a great impact on the algorithm. Through the introduction of an average optimal position, $MBP(T)$. $L(t)$ can be evaluated:

$$MBP(\mathrm{t})=\left(MBP_1(t),MBP_2(t),\cdots,MBP_D(t)\right)$$

$$\frac{1}{M}\sum_{i=1}^{M}p_i\left(t\right)=\left\{\frac{1}{M}\sum_{i=1}^{M}p_{i1}(t),\sum_{i=1}^{M}p_{i2}(t),\cdots\sum_{i=1}^{M}p_{iD}(t)\right\}, \quad (3)$$

$$L_{id}\left(t\right)=2\alpha\times\left|MBP_d\left(t\right)-X_{id}\left(t\right)\right|. \quad (4)$$

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Among them, α is the only parameter which requires to be certain in the QPSO algorithm and is called compression- expansion factor.

3 Quantum-behaved Particle Swarm Optimization based on the random weighted average of the optimal position

The average best position of the QPSO, $MBP(\mathrm{t})$, is obtained by the optimal position of each particle in the population, the optimal position of each particle makes the same contribution to $MBP(\mathrm{t})$. Here $MBP(\mathrm{t})$ is to be modified and $L(t)$ is to be re-evaluated so as to improve the QPSO algorithm [4].

3.1 THE IMPROVED ALGORITHM

In order to re-evaluate the $L(t)$, we no longer allow each particle at the current optimal position in the group to make the same contribution. Instead, the random principle is used to generate the random contribution rate for each particle, and to get the random-weighted mean best position of $L(t)$, recorded as $RMBP(\mathrm{t})$.

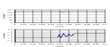
3.2 THE PRODUCTION OF THE RANDOM WEIGHT

First of all, M random numbers can be generated in the interval [0,1] by using the random function. Suppose the M random numbers generated in the interval [0, 1] in the tth generation make up vector

$$R_1(\mathrm{t}): R_1(\mathrm{t}) = (R_{11}(t), R_{12}(t), \cdots R_{1M}(t)). \quad (5)$$

Secondly, the vectors composed by M random numbers are using normalized treatment. Suppose the normalized vector is $R_2(\mathrm{t})$: $R_2(t) = (R_{21}(t), R_{22}(t), \cdots R_{2M}(t))$.

$$R_{2i}(t) = \frac{R_{Ir}(t)}{\sum_{i=1}^{M} R_{1i}(t)}, i = 1,2,\cdots,M . \quad (6)$$

As being the current optimal position of each particle, each component in $R_2(t)$ can just be the contribution rate to the  .

3.3 THE OPTIMAL POSITION OF THE RANDOM WEIGHTED MEAN

Applying the components in $R_2(t)$ to $\mathrm{P_i}(t)$ of each particle, the optimal position of the random weighted mean $RMBP(t)$ of the evaluated $\mathrm{L}(t)$ can be got, and the corresponding algorithm QPSO can be recorded as RQPSO.

$$P(t) = (P_1(t), P_2(t), \cdots P_M(t))^T , \quad (7)$$

$$RMBP(t) = R_2(t) \times P(t) =$$

$$\sum_{i=1}^{M} R_{2i}(t) P_{i1}(t), \sum_{i=1}^{M} R_{2i}(t) P_{i2}(t), \cdots \sum_{i=1}^{M} R_{2i}(t) P_{iD}(t) . \quad (8)$$

The corresponding evaluation formula of the $L(t)$:

$$L_{id}(t) = 2\alpha \times \left| RMBP_d(t) - X_{id(t)} \right| . \quad (9)$$

In it, $i = 1,2,\cdots,M; d = 1,2,\cdots,D$.

4 The dynamic compensation principle based on the Quantum-behaved Particle Swarm Optimization (QPSO)

The measured signal $x(t)$ can be converted to output signal $y(t)$ through the sensor, because of the delayed response of the senor, there is a sharp dynamic error between the output signal $y(t)$ and the measured signal $x(t)$. In order to improve the measuring accuracy, the sensor can be put through a compensator; the output using the compensator $\hat{y}(t)$ can be substitute for $y(t)$, so that the dynamic errors can be modified in this way.

Its basic principle is shown as follows:

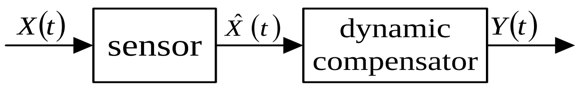


FIGURE 1 The dynamic compensation principle of the sensor

In order to avoid building a dynamic model of the sensor, this essay sets up a dynamic compensator through the experimental data. The essence of this method is to convert the design of the dynamic compensator to the identification of the compensator parameters by experiments. The specific principles are as follows:

In the practical application, the dynamic compensation section of the sensor can be described by univariate difference equation:

$$\hat{y}(t)(1 + a_1 z^{-1} + \cdots + a_n z^{-n}) = y(t)(b_0 + b_1 z^{-1} + \cdots + b_m z^{-m}) + e(t) . \quad (10)$$

In this formula, z^{-1} is delayed operator, n, m is order, $e(t)$ is the output noise. In order to express it in an easy way, the formula (10) can be showed as a compensation vector form [5]:

$$\hat{y}(t) = \omega^t X_t + b . \quad (11)$$

In this formula: b is the constant,

$$\omega = (-a_1, \cdots, -a_n, b_0, b_1, \cdots, b_m)^T ,$$

$$X_t = \left[z^{-1} \hat{y}(t), \cdots, z^{-n} \hat{y}(t), y(t), z^{-1} y(t), \cdots, z^{-m} y(t) \right]^T .$$

The Quantum-behaved Particle Swarm Optimization (QPSO) is applied to design the Dynamic Compensation Filter, the specific method is as follows: first of all, the dynamic experiment is conducted on the sensor, the actual measured pumping signal and the sequence of the response signal is $x(t)$ and $y(t)$, according to the $x(t)$, $y'(t)$ is the signal, which is designed to meet the dynamic capability, $y'(t)$ and $\hat{y}(t)$ are applied to Quantum-behaved Particle Swarm Optimization (QPSO) to get the coefficient of the Dynamic Compensation Filter. The construction methods based on the quantify-behaved Particle Swarm Optimization (QPSO) are as shown in figure 2.

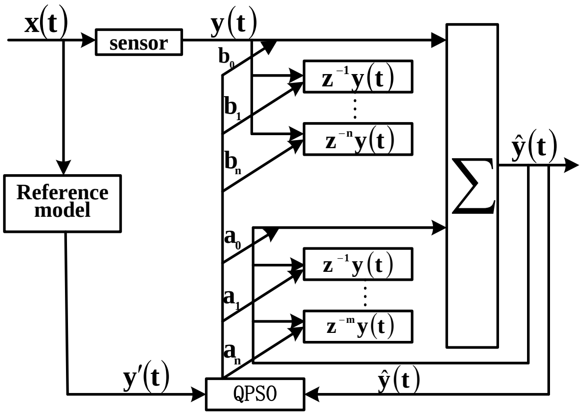


FIGURE 2 The principle diagram of the Sensor Dynamic Compensation Filter based on the Quantum-behaved Particle Swarm Optimization

According to the dynamic calibration experiment of the pressure sensor, the experiment is conducted to validate the algorithm. In the dynamic calibration experiment, the shock tube generate a pulse pressure as a standard signal which is added to the measured pressure sensor, after the analysis of the output response of the sensor to calibrate the pressure sensor and analyze the actual working capacity [6]. The figure 3 is the actual response curve of certain pressure sensor in the dynamic calibration experiment.

The reference model can be built by using the QPSO algorithm, the output of the sensor can be equivalent of the input of the compensation system and the input signal can be equivalent of the output of the compensation system. Thus the curve 1 can be the input of the compensation system and the output of the reference model is the ideal step signal, the coefficient of the Dynamic Compensation Filter a and b can be got.

a=[1.0100,-1.8533,0.9203,0.0543,-0.1770],

b=[0.0174,-0.0018,0.6053,-0.0464,0.1102].

The compensation results is shown in curve 2, the response time after the compensation is 10us, the overshoot is 10%, all achieving the technical requirements.

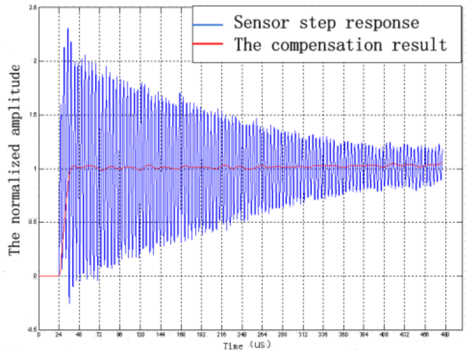


FIGURE 3 The compensation results of the sensor

In order to verify the effects of the compensation, the amplitude-frequency characteristics of the system are analyzed before and after the compensation in this essay. The model of the sensor can be set up in the same way, and get the amplitude response curve 1 shown in the figure4. At last, the amplitude-frequency characteristics after the compensation by calculation are shown in the curve 3. The sensor has a well "straight section" under the 70KHz, but around the resonant frequency (245KHz), there is a big amplitude error. Through the Dynamic Compensation Filter [7], the "straight section" can be enlarged to 400KHz, from the perspective of the amplitude-frequency characteristics, the method of the dynamic compensation has largely expanded the effective working band of the sensor.

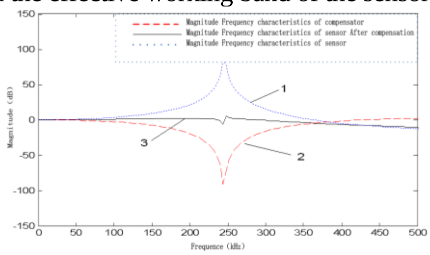


FIGURE 4 The comparison chart of the amplitude-frequency characteristics before and after the compensation

5 FPGA achieving the real-time processing platform

5.1 THE OVERALL STRUCTURE DESIGN OF THE SYSTEM

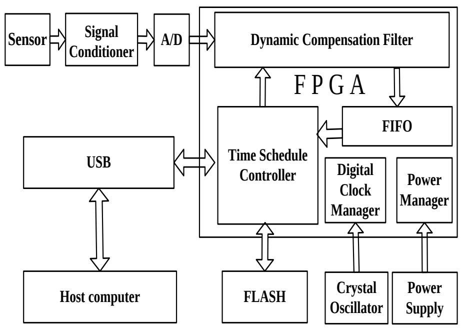


FIGURE 5 The overall structure diagram of the storage testing system based on the FPGA

The overall structure diagram of the storage testing system based on the FPGA are shown in the figure 5, the system uses the chip XC3S500E-PQ208 from the XILINX company as the core control unit of the system and the

AD7482 from the AD company as the analog to digital converter. The main technical indicators of the chips in the system are as follows:

(a) system clock 20MHz

(b)AD is the 12 Bit resolution, quantum 0~2.5V

(c)The sampling frequency can be adjusted within 2Mbps.

(b) 256 M×8bit memory

The overall work-flow of the system is as follows: the analog output signal of the sensor will be switched by the AD converter, and the FPGA provides the clock for the AD conversion, in an analog-to-digital conversion period, the dynamic compensation filter module completes the correction of the last data and the modified data is stored in FIFO of FPGA. Finally, the data in the FIFO will be stored in the FLASH under control of the FPGA. When the whole collection is over, the data in the FLASH can be transferred to the host computer through the USB interface to display and analyze when necessary.

5.2 THE DESIGN AND IMPLEMENTATION OF THE DYNAMIC COMPENSATION FILTER BASED ON THE FPGA

The distributed arithmetic is a very important FPGA technology, which is widely used in the calculation of the digital signal processing. This arithmetic can convert the multiplication to addition and shift arithmetic, which can complete a great number of multiplication at high speed and greatly improve the efficiency in the use of the chip [8].

$$z(k)=\sum_{l=0}^{m} A_l \cdot y(k-l). \tag{12}$$

y(k-l)are expressed as follows:

$$y(k-l)=\sum_{b=0}^{B-1} y_b(k-l)\times 2^b. \tag{13}$$

In this formula $y_b(k-l)$ represent the b bit of the $y(k-l)$, which takes the value of 0 or 1, and $y(k-l)$ is the k-l the time of the AD conversion, put the formula (13) into formula (12), the output of the compensator is:

$$z(k)=\sum_{b=0}^{B-1} 2^b \cdot \sum_{l=0}^{m}[A_l \cdot y_b(k-l)]. \tag{14}$$

In the (14) formula, the product term in the square brackets represent the "and" operation between a bit of AD conversion result and the compensation coefficient, the plus sign represents the arithmetic and operation, index factor weights the value in the parentheses. If a look-up table is constructed in advance, which stores the operation result between the input signal including all possible logical value with a binary representation and the coefficient of dynamic compensation filter , then we can look up this table through the combination values for the corresponding bits of the input variable, avoiding to get the result in the condition of the multiplication. [9] When the FPGA is being designed, this table is constructed in the form of component, set to the ROM structure, and provide the input addressable port and output port, Combined with the formula (14) the diagram of the high speed parallel dynamic compensator is shown in figure 6 [10]:

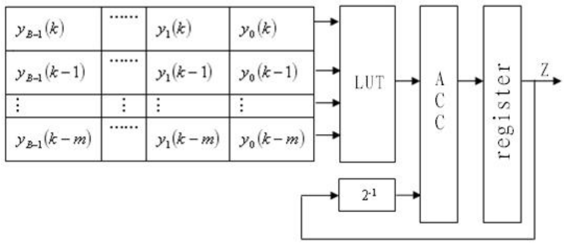


FIGURE 6 The structure diagram of the parallel dynamic compensator

The figure 7 below is the actual shock wave curve of a certain sensor of a measurement.

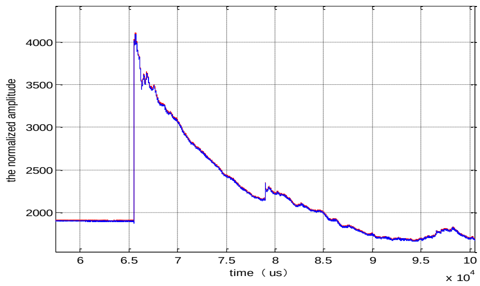


FIGURE 7 the actual shock wave curve of a certain sensor

6 Conclusion

Adopting the approach of using the technology of dynamic compensation to expand the sensor or the pass bands of the testing system to reduce the dynamic measurement errors is one of the most important study fields of the dynamic testing. The design method based on the QPSO, which gets the optimal dynamic compensator through the optimization of the input and output in the calibration of the sensor without dynamic modeling of the sensor, avoids the influence of the modeling errors on the dynamic compensation of the sensor. The feasibility of the compensation is verified in this essay, and the results of the experiment show that the application of the Quantum-behaved Particle Swarm Optimization (QPSO) is an effective way of the dynamic compensation of the sensor.

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