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An Ultra-low Frequency Modal Testing Suspension System for High Precision Air Pressure Control

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Abstract: As a resolution for air pressure control challenges in ultra-low frequency modal testing suspension systems, an incremental PID control algorithm with dead band is applied to achieve high-precision pressure control. We also develop a set of independent hardware and software systems for high-precision pressure control solutions. Taking control system versatility, scalability, reliability, and other aspects into considerations, a two-level communication employing Ethernet and CAN bus, is adopted to complete such tasks as data exchange between the IPC, the main board and the control board ,and the pressure control. Furthermore, we build a single set of ultra-low frequency modal testing suspension system and complete pressure control experiments, which achieve the desired results and thus confirm that the high-precision pressure control subsystem is reasonable and reliable. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Ultra-low frequency modal testing, Suspension system, PID control, Air pressure control.

1. Introduction

Fundamental frequency of large aerospace equipment structures is usually lower than 0.3 Hz [1, 2]. The parameters of the suspension system include mass, stiffness, damping air force. To control the impact of these parameters on real dynamic characteristics of test piece, the natural frequency of the modal testing should be an order of magnitude smaller than that of test piece [3-5]. Therefore, the lowest hanging frequency should be no more than 0.03 Hz, which is within the range of low or ultra-low frequency. To achieve this, the related studies such as high-precision pressure sampling and high-precision pressure control become a major difficulty in low frequency modal testing suspension system [6-8]. Because according to the formula F = PS, the pressure fluctuation in the zero friction cylinder needs to be as small as possible (preferably controlled within 50 pa). Digital PID control is one of the most commonly used control method in the production process. Because of its simple algorithm and good robustness, it's widely used in industrial controlling [9, 10]. Aimed at attaining the requirements of the high precision air pressure control system [11, 12], this paper puts forward the application with a dead band incremental digital PID control algorithm for closed-loop air pressure control.

2. Control System Overall Design

In the air pressure system, the control system host, YC – 1001, and the control board, MCB – 1801, are developed based on a microprocessor embedded

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computer of Stm32f10x series model (industrial-grade ARM, Cortex-M3 core). The system described in this article, needs to complete modal tests of large aerospace structural components in vertical direction. Due to the huge volume and the relatively heavy quality, we use six suspension points hanging together, which are controlled by independent control system respectively. Each control system is responsible for two tasks: to complete the piston in the cylinder pressure sensor data sampling, process and upload the first machine; and to realize closed loop control algorithm based on the feedback sampling data, and output simulation to control the opening of proportional pressure valve, which can adjust the pressure in the cylinder, and thus regulate suspension force.

Fig. 1 depicts the composition of the air pressure control system, which eliminates the specific implementation details. The hardware components include: an industrial control computer, the host control system YC-1001, 6 sets of the control board MCB-1801, a storage tank, a throttle, an air dryer, a proportional pressure valve, a direct pressure sensor, a cylinder piston, etc.

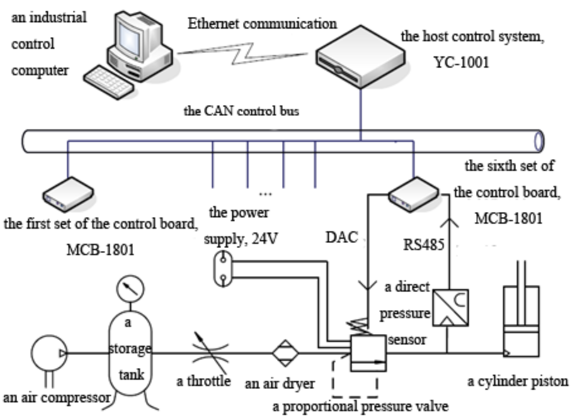

Fig. 1. Pressure control system overview.

Considering the reliability of communication, data throughput and development complexity, the Ethernet communication is used to achieve the interaction between the industrial computer and the embedded host. Since the industrial environment is harsh, and the six sets of control board are relatively far from the installation site (more than 10 m), and are even more than 30 m far from the control panel, we adopt industrial control field CAN bus to complete the board-level communication tasks.

1.1. Control Algorithm Design

The closed loop control system consists of control object, air pressure, actuators, the proportional valve and sampling feedback, the direct pressure sensor. The control block diagram is shown in Fig. 2.

Set *r(t)* as the control target, *y(t)* as the actual output value, and control deviation *e(t)* as the deviation between control target and the actual output value. Set *e(t)* as the PID control of the input, *u(t)* as the output of the PID controller and the input of the object, then we can get the following control law [9]:

$$u(t) = Kp[e(t) + \frac{1}{Ti}\int_0^t e(t)dt + Td\frac{de(t)}{dt}], \quad (1)$$

where *Kp* denotes controller scale coefficient, *Ti* denotes controller integral time, namely integral coefficient, and *Td* denotes controller differential time, namely differential coefficient.

Whereas the real control system tries to eliminate static errors, it is required to speeds up the adjustment process.

An immediate response to the value when the deviation occurs or change, or making appropriate adjustment in advance based on the trend of deviation change is desirable. To achieve this, we introduce the differential link. In this case, although the differential link cans response to the change trend of control object in advance, the sensor sampling precision requirement is very high. Once there exists sampling burr, there will be a large amount of controlled quantity in the differential part. Therefore, hardware filtering or digital filter of sampling value is necessary beforehand.

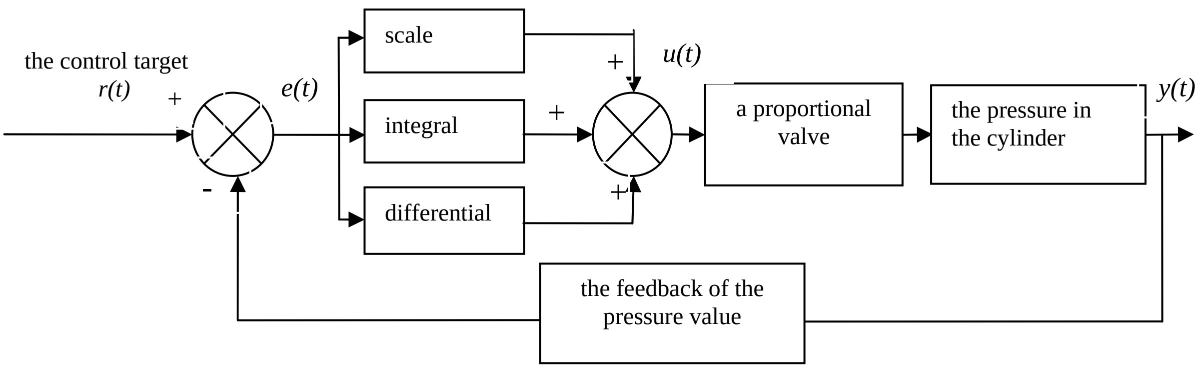

Fig. 2. PID control block diagram.

In order to avoid frequent control movements, and to prevent the consequent oscillation, we add the PID control algorithm to control the dead band. Only when the deviation exceeds the dead band control, PID can begin calculation. Otherwise the output is a constant value that equals the last output. Fig. 3 shows the software flow chart of the algorithm (3):

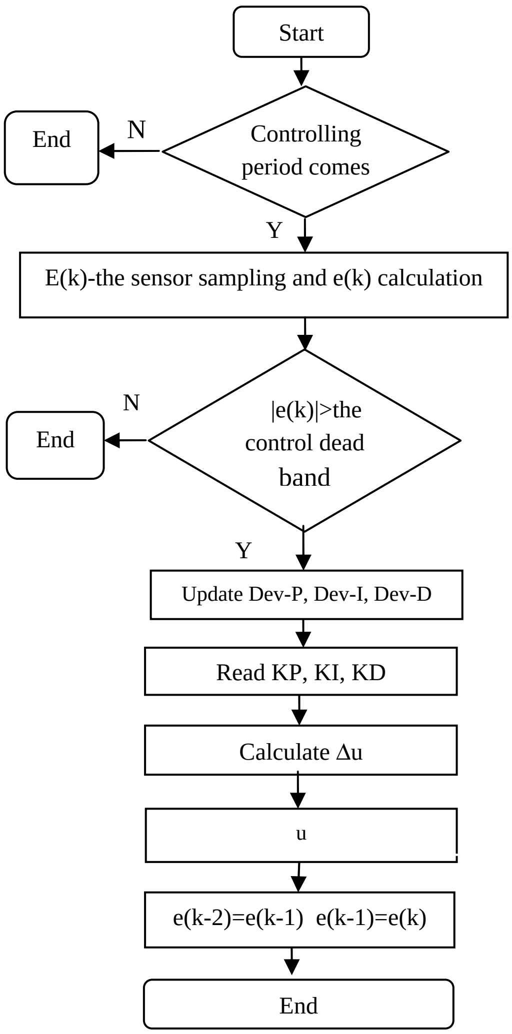

Fig. 3. The flow of incremental PID algorithm with dead zone control.

Since embedded computer control is adopted in the system, continuous control cannot be achieved. We need to discretize analog algorithm of the formula (1) to digital PID algorithm, which can be described as: set T as sampling period, k as sampling number, correspond continuous time to discrete time kT, and use the numerical integral approximation instead of integral, use first-order differential-difference approximation instead of differential, and then the expression is converted into the following form:

$$u_k = Kp[e_k + \frac{T}{Ti}\sum_{j=0}^{k} e_j + Td\frac{e_k - e_{k-1}}{T}], \quad (2)$$

Generally using 1 kHz as sampling period can satisfy the requirement of the mechanical control precision. However, the algorithm adopts the full amount of output, in which each output is cumulative on e_k, causing a heavy workload. Any calculation error will bring great impact on the entire output. Therefore we use the incremental PID to calculate the output. These two methods are essentially the same, since the latter is deduced from the former one. Its expression is:

$$\Delta u_k = u_k - u_{k-1} = KP*(e_k - e_{k-1}) + KI*e_k + KD*(e_k - 2e_{k-1} + e_{k-2}), \quad (1)$$

where $KP = Kp$, assuming $Dev\_P = e_k - e_{k-1}$,

$KI = Kp\frac{T}{Ti}$, assuming $Dev\_I = e_k$,

$KD = Kp\frac{Td}{T}$,

assuming $Dev\_D = e_k - 2e_{k-1} + e_{k-2}$.

2. Control System Hardware Design

2.1 Control Host YC-1001 Hardware Design

The control host hardware circuit is mainly composed of a microprocessor, a power module, the external high-speed crystal oscillator, a high-speed CAN transceiver, an Ethernet interface chip, a DIP switch of IP addresses and so on, as shown in Fig. 4. The microprocessor adopts Stm32f103VC series.

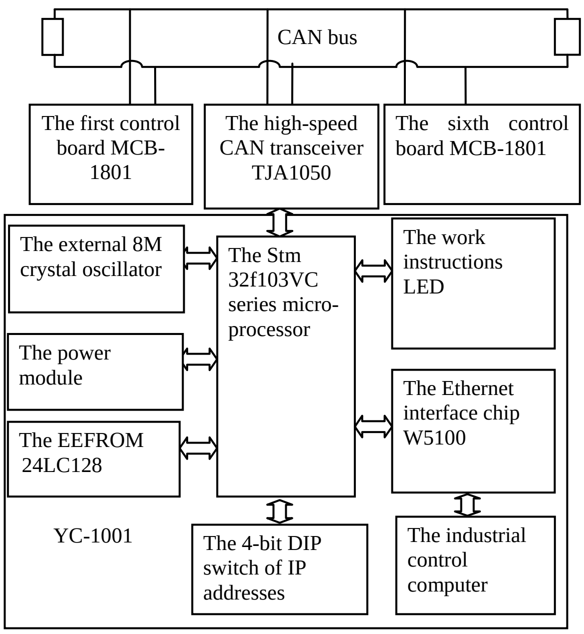

Fig. 4. Hardware block diagram of control host YC-1001.

2.2 Pressure Sensor Sampling Unit

If pressure control reaches the precision of 70 Pa, the precision of the pressure sensor must be more than an order of magnitude. After careful selection, Series 35X series pressure sensor of Keller Company is used. The sampling precision of this series can reach 8 Pa. Moreover, using RS485 communication scheme and its sensor data in digital output could greatly simplify the analog design. To make the design generic and extendible, the compatibility with RS485 and RS422 interface is considered when designing the port USART. RS 485 is half duplex. A and B difference bus can send or receive tasks at the same time. Both of interfaces synchronously adopt their own enable pin to complete the task. The signal level should be mutually exclusive, guaranteed by software or hardware.

We choose the latter, so it can save the software workload. Due to full duplex, it can send and receive data at the same time. We use MAX491 low-power RS422/RS485 transceiver of Maxim as bus driver, thus top speed can reach 2.5 Mbps. Fig. 5 shows the RS485 communication interface with isolation method, which is used for the sampling of pressure sensor signal.

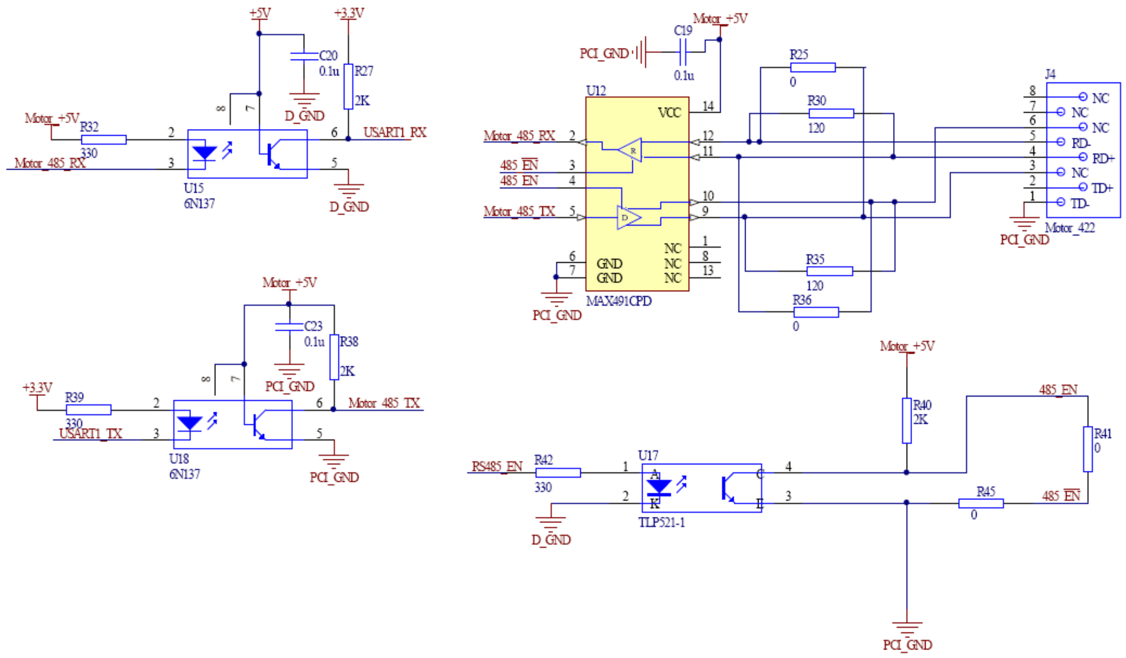

Fig. 5. Air pressure sensor signal sampling.

2.3 CAN Communication Interface Design

To ensure that the control mainboard and control board do not interfere with each other, an isolation method is adopted to realize the communication. The top CAN communication speed of this system can reach 500 Kbps. Fig. 6 is a CAN interface circuit. We adopt a high-speed optocoupler, 6N137, to isolate signals whose highest support speed reaches 10 Mbps. Optocoupler isolation has two advantages:

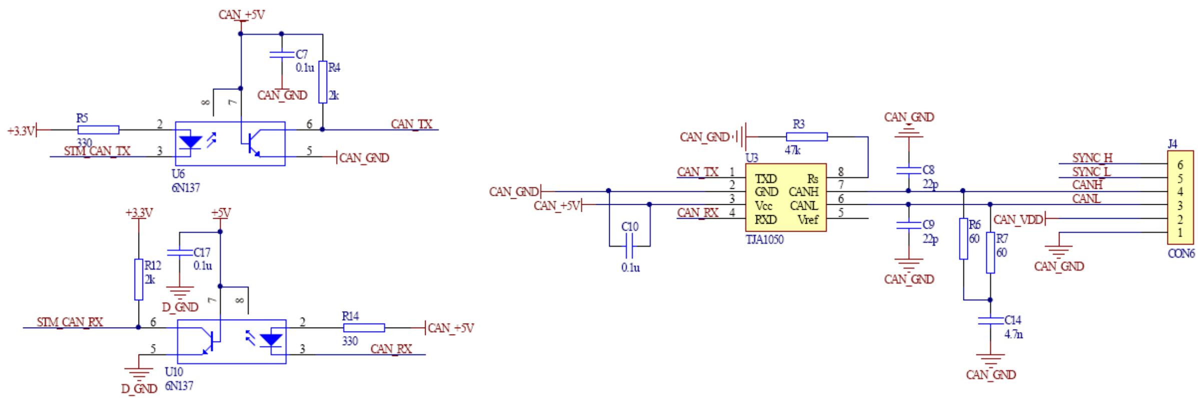

Fig. 6. CAN bus interface circuit.

By isolating both ends of the signal, it can improve the anti-interference; and while TJA1050 work voltage is 5 V, and Stm 32f103 is 3.3 V, 6N137 can solve the signal level matching problem. J4 serves as external CAN bus interface of the control main board, which raises the CAN power supply, one set of synchronous signal and CAN difference signal (CANH, CANL). Generally, to solve such problems as transmission line crosstalk and reflection, we need to set up terminal matching resistances, typically at 120 Ohms, at both ends of the bus.

3. The Application Software Design

Essentially, the mainboard programming can be summarized as follows: resolve IPC and send to the Ethernet command of the control board; forward Ethernet commands in CAN messages formation to the control board; receive instructions from the board, return and upload CAN data; return data as Ethernet port and the command port. The main program flow of control mainboard is shown in Fig. 7.

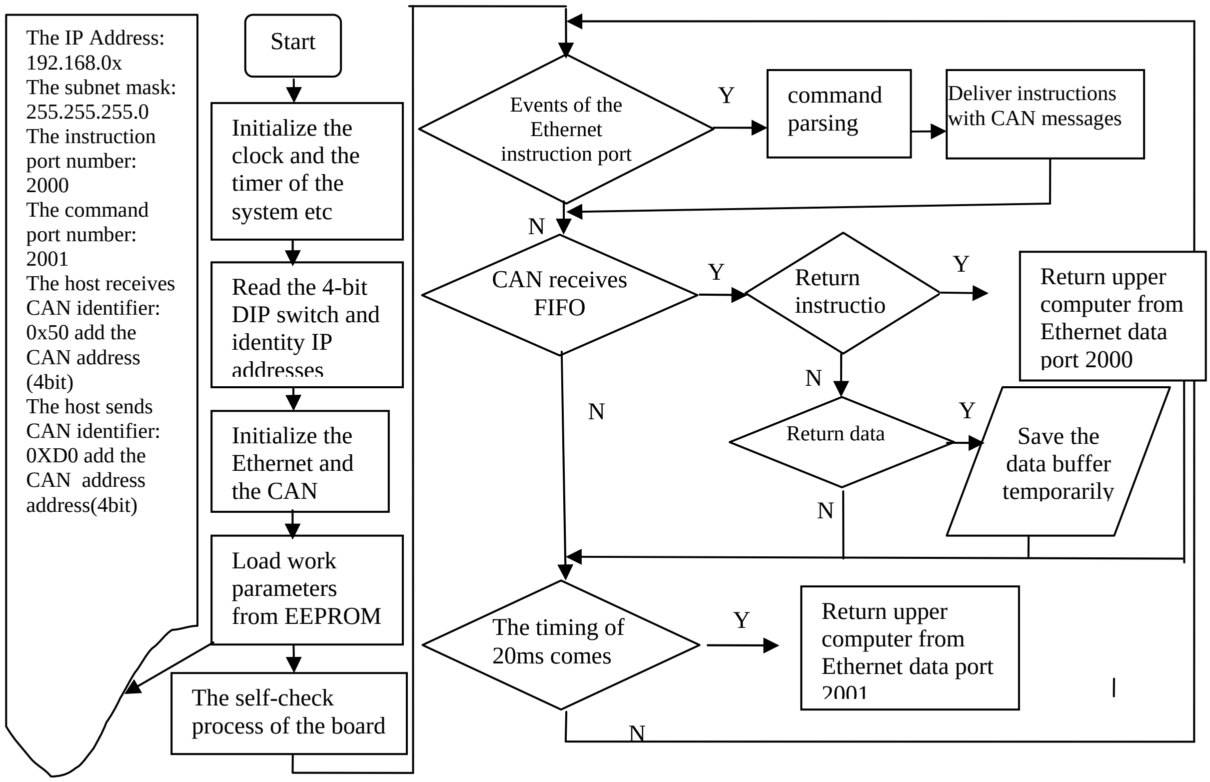

Fig. 7. Main program flow of control mainboard.

Board procedures mainly need to implement following functions: storage and loading operating parameters; sensor data sampling, processing and uploading; control algorithm; control channel output; CAN command parsing, execution and return. CAN data buffer storage and return.

4. Pressure Control Experiments

4.1 Experiment Device

The range of pressure control fluctuations has a great influence on the performance of suspension system. To ensure that the following experiments are accurate and reliable, pressure control experiments are necessary to be carried out. We build up a set of experimental modal testing suspension to test the performance of the ultra-low frequency suspension system. Fig. 8 is a set of experiment platform suspension, which mainly contains a gas tank, a laser displacement sensor, a zero friction cylinder piston, a pressure sensor, a permanent magnet, an electromagnetic force sensor, a suspension host, and test pieces, etc.

Fig. 8. Single set of modal testing suspension device experimental platform.

The system control panel is mainly composed of a control computer, a processing board and an executive board, as shown in Fig. 9.

Fig. 9. Experimental control PCB circuit boards.

4.2. The Results of Pressure Control Experiments

The pressure sensor is a KELLER's 33x series model, whose microprocessor is a XEMICS model, which integrates a 16-bit AD converter, reaching a precision of 0.01 %. The output of analog current signal output is 4~20 mA. The analog voltage signal is 0~10 V, and the output frequency is 400 Hz. In order to guarantee the precision, this research adopts the digital output interface RS485, which is capable of turning the pressure sampling results into digital values in the form of digital pulse outputs. The Actuator incorporated a proportional pressure valve – SMC's ITV2031-312BS model. The data of Stm32F103 microcontroller from the laser displacement sensor yields the AD value, so it needs to be calibrated to display the distance value.

Because of the effects of the circuit control, the linear relationship between duty ratio of PWM wave and the corresponding pressure may be changed. Therefore calibration is needed to determine the relationship between the voltage acted on the proportional pressure valve and the actual pressure value. The calibration results are shown in Table 1.

Table 1. Proportional pressure valve calibration

The actual pressure (V)	The actual pressure (bar)	The actual pressure (V)	The actual pressure (bar)
0.5	0.32	4.99	2.50
1.00	0.51	5.98	3.05
2.03	1.07	7.01	3.51
3.01	1.46	8.08	4.10
4.03	2.08	9.10	4.53

When using incremental PID algorithm with control dead band to control closed-loop proportional pressure valves, as a routine, we first adjust the proportional control value P, then we adjust the integral control value I. This process is repeated until a PID control value is found, which can keep air pressure stable. The final control results of actual pressure (shown in absolute value on the y-axis) fluctuation over time (x-axis) are shown in Fig. 10 and Fig. 11:

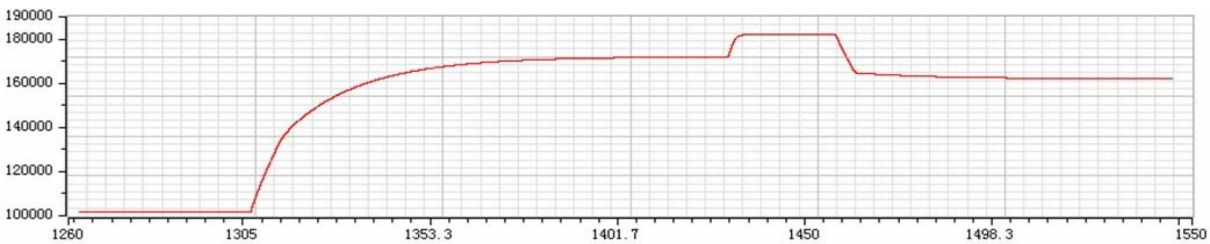

Fig. 10. Pressure closed-loop control response curve.

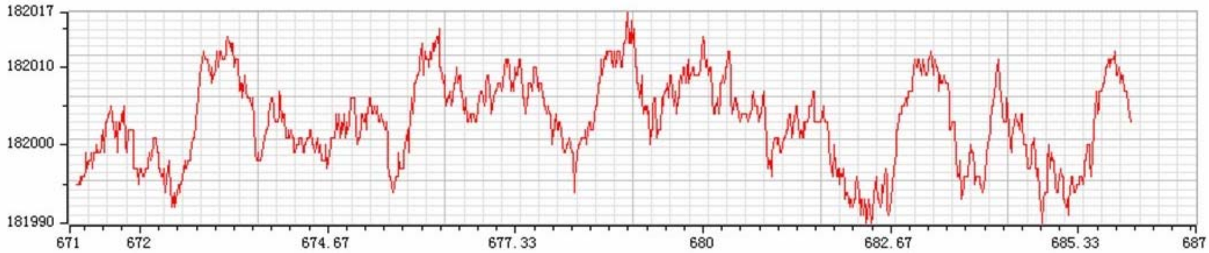

Fig. 11. Pressure control fluctuation.

Fig. 10 shows the changes of the duty ratio of the PWM waves. Significant variation in the pressure response curve can be observed. The curve is smooth and renders steady values on multiple intervals. We first adjust the pressure to 0.17 MPa, and then to 0.18 MPa, finally transfer it to 0.16 MPa. Fig.11 shows the fluctuation when the pressure is adjusted to 0.18 MPa. Amplify the curve once the pressure is stable, we can observe that the difference between the maximum and minimum pressure is 27 Pa, which satisfies the pressure control requirement of keeping the difference below 50 Pa. Therefore it can resolve the challenge of pressure control in the suspension system, and provide a good environment for the following friction experiments and suspension frequency experiments.

6. Conclusions

1) The incremental PID algorithm with control dead band successfully contains the pressure fluctuation within 50 Pa, providing a solution to one of the core challenges in Ultra-low frequency modal testing suspension systems.

2) The high-precision pressure control subsystem developed for Ultra-low frequency modal testing suspension system adopts a two-level communication employing Ethernet and CAN bus, and utilizes independent hardware and software systems. Therefore, this subsystem provides versatility, scalability and demonstrated reliability.

3) Based on the building of a set of ultra-low frequency modal testing suspension device, the experiments of pressure control in zero friction piston and cylinder are carried out. The experimental outcomes are in line with expected values, which confirm that the subsystem is reasonable and reliable.

4) The first set of ultra-low frequency modal testing suspension system has been put into use. All the technical indicators have met the standards during its usage. Nevertheless, the precision of pressure control and the electromagnetic force control can be further improved.

Acknowledgements

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References

[1]. N. M. Qi, W. H. Zhang, J. Z. Gao, et al, The primary discussion for the ground simulation system of spatial microgravity, *Aerospace Control*, Vol. 29, Issue 3, 2011, pp. 95-100.

[2]. N. M. Qi, W. H. Zhang, J. Ma, et al, Intelligent controller design of ground simulation test system for three-dimensional spatial microgravity environment, *Journal of Harbin Institute of Technology*, Vol. 44, Issue 1, 2012, pp. 17-21.

[3]. J. Liu, J. L. Gao, W. L. Xie, et al. Design and application of the experimental model analysis system, *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 40, Issue 2, 2009, pp. 209-213.

[4]. S. Vanlanduit, F. Daerden, and P. Guillaume, Experimental modal testing using pressurized air excitation, *Journal of Sound and Vibration*, Vol. 299, Issue 1–2, 2007, pp. 83-98.

[5]. R. Farshidi, D. Trieu, S. S. Park, et al, Non-contact experimental modal analysis using air excitation and a microphone array, *Measurement*, Vol. 43, Issue 6, 2010, pp. 755-765.

[6]. C. Roland, B. Hermann, K. Daniel, et al, Quality control of vacuum insulation panels, *Methods of Measuring Gas Pressure, Vacuum*, Vol. 82, Issue 7, 2008, pp. 691-699.

[7]. Liv A. Carlsen, Gerhard Nygaard, Michael Nikolaou, Evaluation of control methods for drilling operations with unexpected gas influx, *Journal of Process Control*, Vol. 23, Issue 3, 2013, pp. 306-316.

[8]. S. S. Hong, W. Khan, Y. K. Park, et al, Analysis of pressure distribution for the various gas flow vacuum system in the range from 1 Pa to 133 Pa, *Measurement*, Vol. 46, Issue 2, 2013, pp. 851-854.

[9]. Y. J. Hu, A pneumatic pressure control technology based on PID algorithm, *Measurement & Control Technology*, Vol. 30, Issue 8, 2011, pp. 60-63.

[10]. R. C. Jin, W. J. Zhang, Z. A. Tang, Research on application of fuzzy controller based on self-adjustment of parameters in micro gas pressure sensor testing and controlling system, *Chinese Journal of Sensors and Actuators*, Vol. 21, Issue 3, 2008, pp. 388-392.

[11]. B. J. Cui, G. X. Li, Study on precision pneumatic pressure control method using proportional valves, *Computer Automated Measurement & Control*, Vol. 13, Issue 2, 2005, pp. 1366-1368.

[12]. T. Chen, R. C. Jin, F. T. Zhang, et al. A Matlab-based simulation of pressure control for micro gas pressure sensor testing system, *Chinese Journal of Sensors and Actuators*, Vol. 19, Issue 5, 2006, pp. 1871-1874.