Identification of Active Magnetic Bearing System Based on Virtual Instruments

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***Abstract* – The dynamics of the contact-free hovering active magnetic bearing (AMB) depends mainly on the implemented control law. The more of the whole rotor system characteristics are known, the higher quality controller is designed, and the more reliable rotating operation can be realized. In order to make the identification procedure more convenient, a new development platform based on virtual instruments was chosen to design the identification system. Experiment was done on an active magnetic bearing system after the identification system was finished. The model parameters of HTR-10GT principle AMB system were identified by the help of the designed identification system, and the amplitude-frequency curve, phase-frequency curve and transfer function of the AMB system in the working frequency-domain were achieved. The identified information not only lays foundation for analyzing the characteristics of the AMB system (such as zero-pole distribution, stability margin, stiffness and damping), but also offers a kind of analysis and experimental tool for the optimized designing of the control system.**

I. Introduction

After successful operation and experiments on the steam-turbine circle of the 10 MW high temperature gas cooled reactor (HTR-10), the project of the HTR-10 coupled with direct gas-turbine circle (HTR-10GT) is designed by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University. In this project, active magnetic bearings (AMBs) are chosen to support the generator rotor and the turbo compressor rotor in the power conversion unit because of their numerous advantages over the conventional bearings. The HTR-10GT is designed in order to experimentally validate the possibility of creating high performance plants with direct closed gas-turbine cycle and the technology for the future commercial applications. The preliminary rotor dynamic analysis shows that both the generator rotor and the turbocompressor rotor have to pass the second bending critical speed during the acceleration from startup to the rated operating speed of 15000rpm. Because the AMBs will be applied in the pressure vessel of the nuclear power conversion unit, the reliability and safety of the AMBs are of overwhelming importance. In order to achieve more reliable, safer and more stable rotating operation and design a high quality controller, especially for an elastic rotor system, the whole rotor system characteristics should be identified clearly. The accurate modeling of the complete controlled plant is the core task of system identification, which is usually an iterative procedure going from model to experiment and back to modification of the model until the behavior of model and the real system agree to a sufficient degree to procedure meaningful results. Even though, with a certain experience, the mechanical parts can be modeled quite accurately, the identification of the electromagnetic bearing itself is often quite difficult. The nonlinearities are strong and the inductance, force-displacement factor and force-current factor are all frequency dependent functions. So an easier and more reliable identification system is urgently needed. [1~3]

II. Virtual Instruments Development Platform

Virtual Instruments (VI) is based on computer and matched relevant hardware as input/output interface. We can design different kinds of instrument panel

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(such as display screen, indicating lamp, knob, switch, key-press etc) in the computer screen by the help of the virtual instruments software development platform (such as LabVIEW, CVI). The input/output signal is processed and analyzed by the computer and the data, waveform, curve are displayed. Virtual instruments not only can carry out the task that the true traditional instruments could do, but also can provide a more visual, convenient and smart operation mode. A lot of virtual instruments with different functions can be in a computer and can carry out a lot of tasks that the traditional instruments can't do.

To make the identification procedure more convenient and easier to operate, the NI (National Instruments) LabVIEW (Laboratory Virtual Instrument Engineering Workbench) and PCI Analog Input/Output devices are chosen to design the identification system. PCI 6251M is selected as the PCI Analog Input/Output device, which has 16 channels analog input and 2 channels analog output. With this powerful platform, we can program in graphs instead of programming in codes to build the system, which absolutely facilitates our work. On the other hand, based on the VI technology, LabVIEW undoubtedly endows the system with good performance on reusability, openness, and expansibility. Besides, this identification system runs in the Windows XP operating system, which is easily understood and mastered by most common users.

Ⅲ. Modal Analysis and Identification System Design

If **M**、**C** and **K** stand for the mass matrix, damping matrix and stiffness matrix separately, X stands for the displacement of every nodes of the rotor and f stands for the outside force of every nodes , then the AMBs system can be description as

$$[\boldsymbol{M}]\ddot{X}+[\boldsymbol{C}]\dot{X}+[\boldsymbol{K}]X=f(t) \qquad (1)$$

If $\{x\}=\{X\}e^{j\omega t}$, $\{f\}=\{F\}e^{j\omega t}$ then " (1)" can be described as

$$\{X\}=(-\omega^2[M]+i\omega[C]+[K])^{-1}\{F\} \qquad (2)$$

If ω_r and Φ are the eigenfrequency and the eigenvector of "(2)"separately, equation (2) can be transformed as "(3)" based on the modal transform and truncation principle

$$\begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1n} \\ H_{21} & H_{22} & \cdots & H_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ H_{n1} & H_{n2} & \cdots & H_{nn} \end{bmatrix} = \qquad (3)$$

$$\sum_{r=1}^{m}\frac{1}{k_r-\omega^2 m_r+j\omega c_r}\left[\begin{bmatrix}\varphi_{1r}\\ \varphi_{2r}\\ \vdots\\ \varphi_{nr}\end{bmatrix}\begin{bmatrix}\varphi_{1r} & \varphi_{2r} & \cdots & \varphi_{nr}\end{bmatrix}\right]$$

$c_r=2\xi_r k_t/\omega_r$; $H_{MN}=X_M/F_N$ in "(3)"[4].

The rotor eigenfrequency can be considered as the superposition of a lot of single modes if adopting modal coordinate. In this condition, the energy is not transferred between the different modes and the movement of different modes is independent. The amplitude-frequency and phase-frequency function of single mode can be description as

$$|Y_t|=\frac{1/k_r}{\sqrt{\left(1-\left(\frac{\omega}{\omega_r}\right)^2\right)^2+\left(2\xi_r\frac{\omega}{\omega_r}\right)^2}} \qquad (4)$$

$$\Phi=\arctan\left|\frac{\left(2\xi_r\frac{\omega}{\omega_r}\right)}{\left(1-\left(\frac{\omega}{\omega_r}\right)^2\right)}\right| \qquad (5)$$

The identification experiment was carried out on an AMB test rig in closed-loop. As Fig 1 showing, the control system and the identification system are working separately.

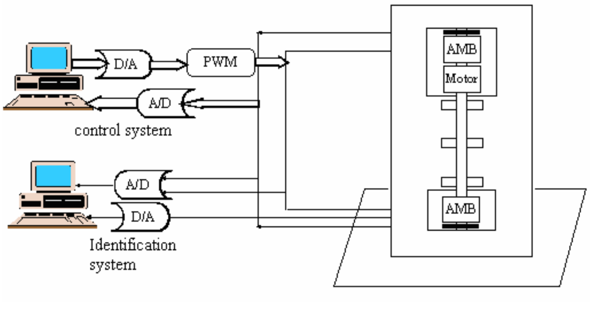


Fig 1 system identification experiment schematic diagram

To get higher SNR (signal to noise ratio) and excite the AMBs system sufficiently, the stepping sinusoidal signal was chosen as the exciting signal.

The flow diagram is shown as Fig 2

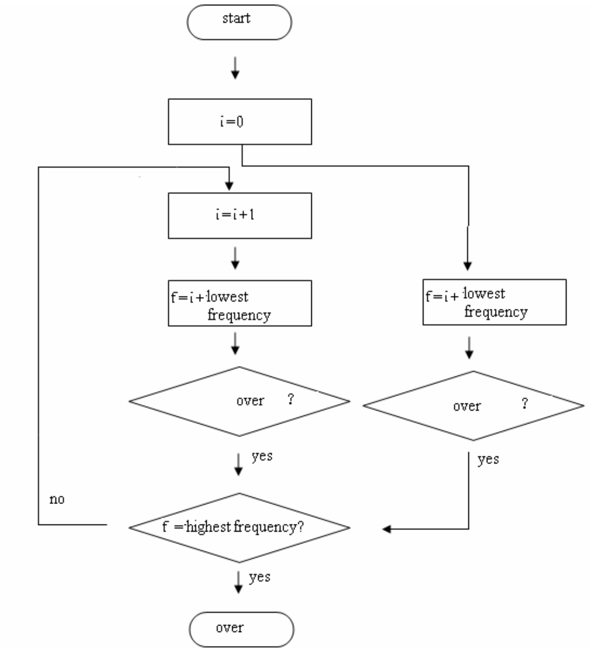


Fig 2 stepping sinusoidal generating flow diagram

While the exciting signal is generated, the input/output signal should be real-timely acquired and processed. Fig 3 and Fig 4 show the real-time data acquisition and processing.

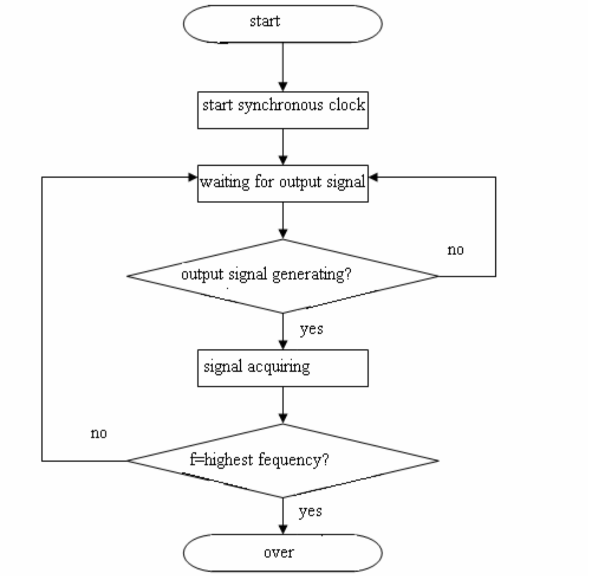


Fig 3 real-time data acquisition flow diagram

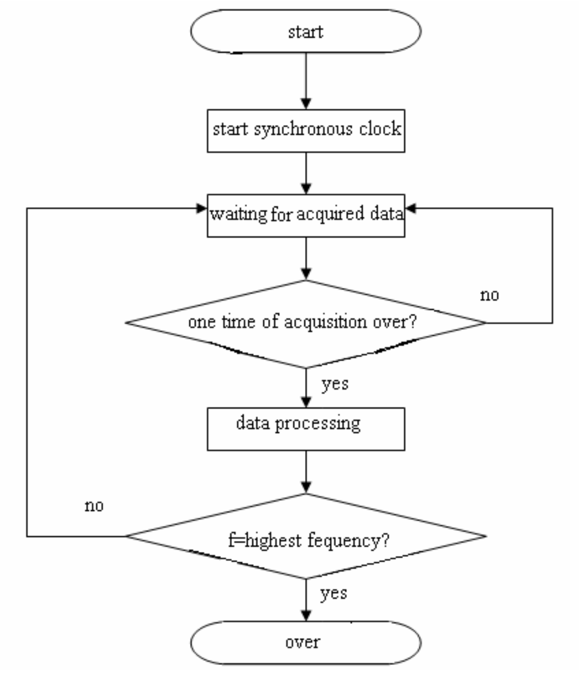
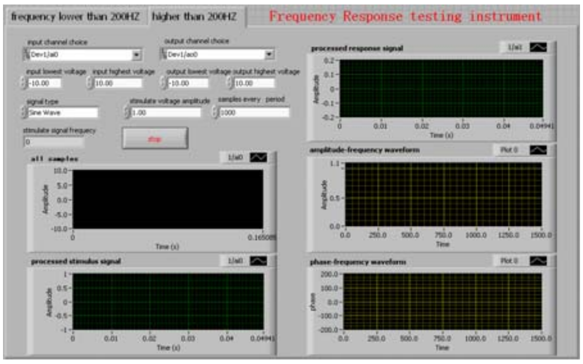


Fig 4 real-time data processing flow diagram

Fig 5 shows the front board of the identification system.



input channel choice Dev1/ai0
output channel choice Dev1/ao0
input lowest voltage -10.00
input highest voltage 10.00
output lowest voltage -10.00
output highest voltage 10.00
signal type Sine Wave
stimulate voltage amplitude 1.00
samples every period 1000
stimulate signal frequency 0

Fig 5: front board of the identification system

The amplitude-frequency and phase-frequency curve of the AMBs system can be shown in the front board of the identification system and the data can be conserved in the computer.

The least-square method was applied to fit the amplitude-frequency and phase-frequency curve. Fig 6 and Fig 7 show the curve fitting flow diagram and front board

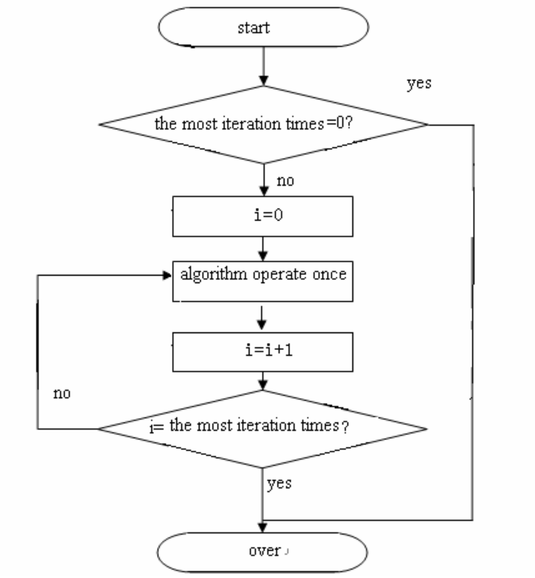
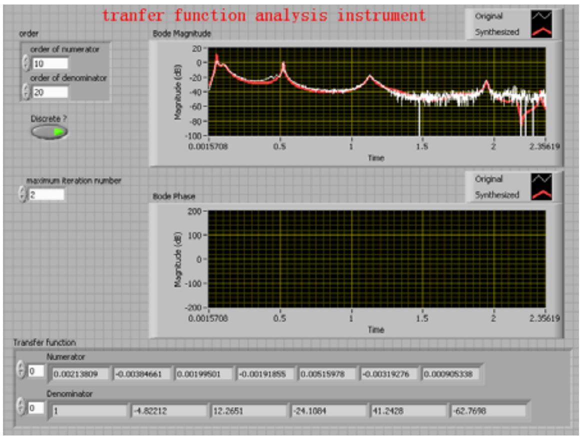


Fig 6 curve fitting flow diagram



order

order of numerator: 10

order of denominator: 20

Discrete ?

maximum iteration number: 2

Transfer function

Numerator: 0 | 0.00213809 | -0.00384661 | 0.00199501 | -0.00191855 | 0.00515978 | -0.00319276 | 0.000905338

Denominator: 0 | 1 | -4.82212 | 12.2651 | -24.1084 | 41.2428 | -62.7698

Fig7 curve fitting front board

Ⅳ. Experiment and Results

Because the rotor is rotational symmetry, we just only need to identify one plane of the rotor when it is in static suspension. We are interested in the two stiffness modes and the first three bending modes. Fig 8 shows the experiment equipment working together with the AMBs system. If one end of the rotor is excited, the first five modes can be displayed in the amplitude frequency and phase frequency curves.

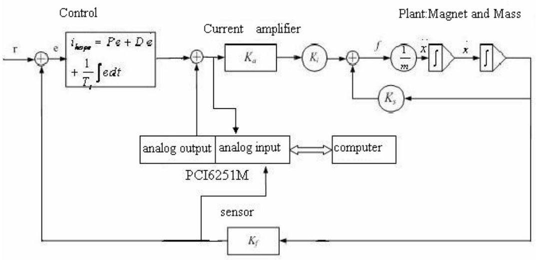


Fig 8 AMBs system and identification experiment equipment

But in this case, the two stiffness modes in the curve are not clearly separated. To separate the two stiffness modes, the parallel excitation is adopted. Fig 9 shows the original input and output signal with transient curve of the special frequency. Fig 10 shows the processed signal without transient curve.

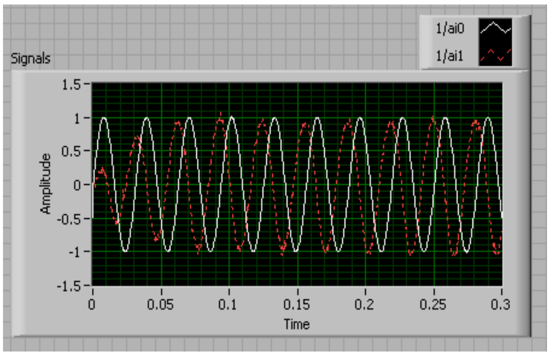


Fig 9 original input and output signal with transient curve

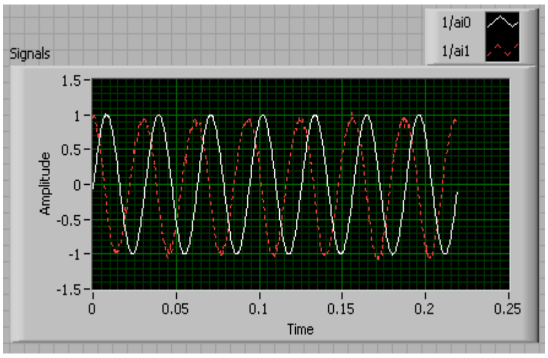


Fig 10 input and output signal without transient curve

Fig 11 shows one end excitation amplitude frequency curve and phase frequency curve, while Fig 12 shows parallel excitation amplitude frequency curve and phase frequency curve. There are five peaks in Fig 11. The first two peaks are not separated. The five peaks distribute the frequency 25Hz, 55Hz, 330Hz, 720Hz and 1220Hz. The first two engine frequencies are stiffness modes and the last three engine frequencies are bending modes. There are three peaks in Fig 12. All of the peaks are separated.

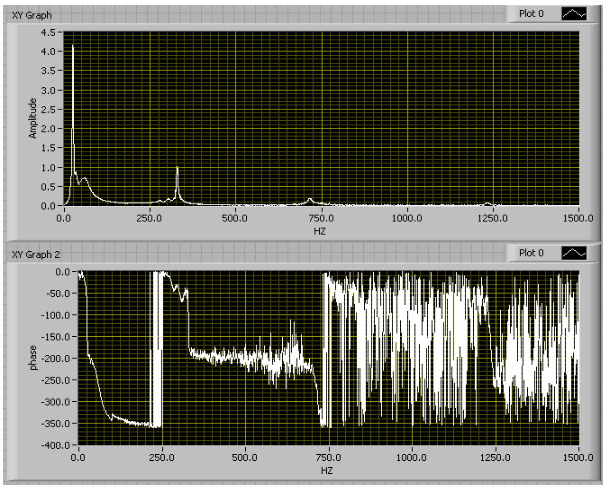


Fig 11 one end excitation amplitude frequency curve and phase frequency curve

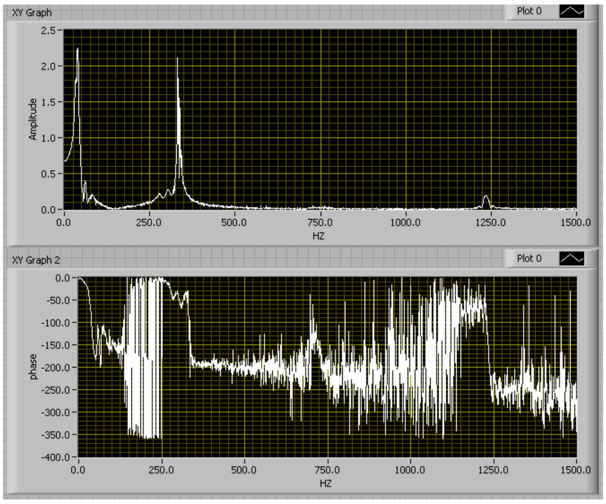


Fig 12 parallel excitation amplitude frequency curve and phase frequency curve

In order to get the single mode transfer function, the curve are separated to every single mode. Taking the first stiffness mode for example, Fig 13 shows the fitting result.

And the transfer function is shown in equation 6

$$h_1 = \frac{1}{3.274\times10^{-5}s^2+1.893\times10^{-3}s+1.823} \qquad (6)$$

Ⅴ. Conclusions

This paper introduces the principle and method of AMBs system identification. Identification experiment on the principle AMB test rig of the HTR-10GT was carried out by using the developed identification system. The result not only validates the principle analysis, but also tests the modes of the rotor and makes the identification more convenient. The stepping sinusoidal signal excits the modes of the rotor sufficiently. The transfer functions obtained from curve fitting offer great help to the controller design.

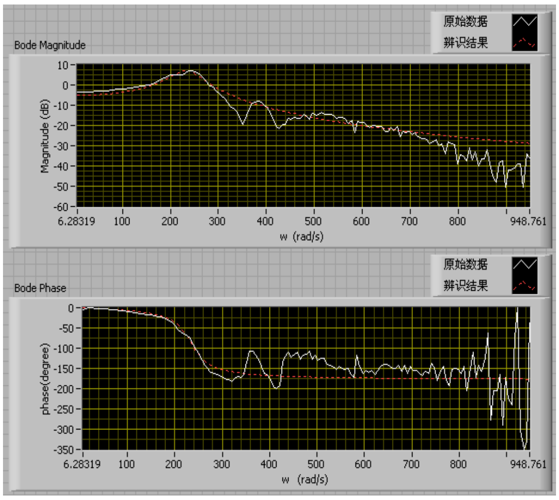


Fig 13: The first stiffness mode curve fitting result

REFERENCES

[1] Schweitzer G, Bleuler H, Traxler A. Active magnetic bearings—basics, properties and application of active magnetic bearings. Switzerland: ETH, 1994

[2] Yuanhui Xu, Kaifen Zuo. Overview of the 10 MW high temperature gas cooled reactor-test module project. Nuclear Engineering and Design,218(2002)13-23

[3] Institute of Nuclear Energy Technology (INET),Tsinghua University, China.Primary design report on the HTR-10GT.INET,2002

[4] Gu Huidong, Zhao Lei, Zhao Hongbin. A LQG Controller Design for an AMB-Flexible Rotor System[C]. ISMB 9th,Kentucky,USA,2004 October 2~6.