EXPERIMENTAL RESEARCH ON ACTIVE VIBRATION CONTROL OF PIPE BY INERTIAL ACTUATOR AND ADAPTIVE CONTROL

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Vibration of pipe on ships and submarines is undesirable as it may induce noise and transmit it to the sea, as well as promote fatigue, even cause damage to pipe. The most significant part of its frequency spectrum is shaft frequency. It changes with pump’s rotation speed. Traditional vibration absorber cannot adjust automatically according to the change of vibration frequency and they can only achieve significant result in very narrow frequency range. To improve vibration absorber’s effect, active control technology is introduced. This paper reports experimental research on vibration suppressing of pipe by using inertial actuator. Firstly, present characteristics of vibration in pipe-pump system. Then, present the structure and parameters of inertial actuator, and explaining the control algorithm. It is mainly consist of frequency analysis algorithm and adaptive control algorithm. Control programs were executed on a digital signal processing system. Experiments were carried out on a closed pipe-pump system. Acceleration of with and without control was measured and recorded when the pump in the pipe system is working at different rotation frequency. The results revealed that inertial actuator can suppress the shaft vibration of pipe at both control point and foundation.

1. Introduction

The noise of submarines is mainly consisting of hydrodynamic noise, propeller noise and mechanical noise. Mechanical noise takes a great proportion of the total noise, especially when submarines are in the state of berthing or low-speed cruise. In these conditions, mechanical noise becomes the major obstacle to decrease the radiated noise of submarine. A major pathway for mechanical noise radiated outside to the sea is pipe system. Vibration promotes mechanical fatigue; even break the pipe at the connection part, which is a danger to submarines. To decrease the noise and vibration of pipe system, a lot of works have been devoted to this area. Traditional measures include vibration isolator, flexible pipe, pipe warping and orifice. These measures have limits and deficiencies. For example, vibration isolator cannot decrease low-frequency vibration effectively; flexible pipe cannot apply to those pipe of which convey highly corrosive liquid; pipe warping should not apply to those pipe of which convey high temperature gas or liquid; orifice will decrease the velocity of flow in pipe.

To decrease vibration and noise in pipe system effectively, active control technology was introduced into this area for more than twenty years ago. Brévar et al [1] analysed a control approach to reduce the total power propagating along fluid-filled elastic cylinders analytically.
[2] designed a non-intrusive fluid-wave actuator for use in an active control system to control fluid-borne vibrations. Maillard et al [3, 4] designed and tested a non-intrusive fluid wave actuator for the active control of pressure pulses in piping systems. Pan et al [6, 7] investigated active control of fluid-borne and structure-borne noise in a pipe-pump system with fluid-wave actuator by theoretical study and experimental work. But seldom works concentrated on suppressing vibration of pipe.

This paper focuses on suppressing vibration of pipe by inertial actuator. Firstly, present the schematic of a closed pipe-pump system as well as configuration of acceleration sensor and inertial actuator. Then, explain the structure, function and parameter of inertial actuator, as well as consistent and principle of control algorithm used in this experiment. Lastly, carry out an experiment on the closed pipe-pump system. Acceleration signal was measured on control point and foundation before and after active control turns on. After compare the measured data, it shows that the active vibration absorber can control vibration at shaft frequencies of pump effectively.

2. Vibration of pipe in pipe-pump system

In pipe systems with a centrifuge pump, there are many line spectra in the frequency spectrum of vibration signal. These line spectra are mainly consisting of shaft frequencies and blade pass frequencies. Draft frequencies are multiples of the rotating frequency. Draft frequencies vibration belongs to mechanical sources of vibration in piping systems. Blade passing frequencies are multiples of the rotating frequency and the number of blades. Blade passing frequencies vibration belongs to hydraulic sources of vibration in piping systems.

Experiments in this paper were carried out on the pipe-pump system in Fig. 1. This is a closed pipe system with a motor, a centrifuge pump, a pressure tank, four flexible pipes, seven foundations for pipe and a pedestal for motor. The maximum speed of the motor which drives the centrifuge pump is 2930 rotation per minute. The inertial actuator and acceleration sensor configuration is represented in Fig. 2. In total, nine acceleration sensors were chosen, represented by 1 to 9. Acceleration sensor 1 and acceleration sensor 3 output electrical charge signal, the other output voltage signal. The nine acceleration sensors were installed in the vertical direction. The inertial actuator was acting in the vertical direction.

![Figure 1. Schematic of the pipe-pump system](image)

The spectrum of the acceleration signals measures by acceleration sensor 3 for rotation speed of 1500 rpm and 2500 rpm are given in Fig. 3 and Fig. 4. In Fig. 3 and Fig. 4, there are many linear spectra with high magnitude; they are mainly consisting of shaft frequencies and blade pass frequencies. If the magnitude of these linear spectra decreased significantly, then, the total vibration level will decreased significantly. So, this paper target on reduce linear spectra with high magnitude.
Figure 2. A schematic diagram of the pipe-pump system.

Figure 3. Vibration level measured by acceleration sensor 3

3. Control System

Actuator applied in this paper is a kind of inertial actuator. Inertial actuator has been applied to many active vibration control systems. Researcher had done a lot of works to inertial actuators [7-13]. Control algorithm in this paper is mainly consisting of frequency analysis algorithm and adaptive algorithm. The reason to choose this kind of algorithm is to suppress vibration of linear spectra and do not change vibration at other frequencies. Kim, S. et al [14-16] had done some works in this area. Their simulation result revealed that this algorithm can reduce magnitude of linear spectra effectively.
3.1 Inertial Actuator

Inertial actuator of which being used in this paper shows in Fig. 4. Inertial actuator consists of voice coil motor and spring. Voice coil motor usually consists of ferromagnetic cylinder, permanent magnet, coil and coil support. Components of inertial actuator are present in Fig. 5. In this voice coil motor, coil and coil support is static, while ferromagnetic cylinder and permanent magnet moved vertically. Ferromagnetic cylinder and permanent magnet act as part of vibration absorber’s mass. The resonant frequency of the inertial actuator is 31Hz. Its parameters list in Table 1.

![Figure 4. Schematic of Inertial Actuator](image)

![Figure 5. Components of Inertial Actuator](image)

<table>
<thead>
<tr>
<th>parameter</th>
<th>sign</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>full thrust</td>
<td>( F_p )</td>
<td>105</td>
<td>N</td>
</tr>
<tr>
<td>continuous thrust</td>
<td>( F_c )</td>
<td>35.4</td>
<td>N</td>
</tr>
<tr>
<td>electrical time constant</td>
<td>( T_e )</td>
<td>0.98</td>
<td>ms</td>
</tr>
<tr>
<td>force constant</td>
<td>( K_f )</td>
<td>11.5</td>
<td>N/A</td>
</tr>
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</table>

3.2 Control Algorithm

![Figure 6. Block diagram of control algorithm](image)

Figure 6 shows the block diagram of the control algorithm. In this block diagram, \( W_i(z) \) is a controller filter; \( F(z) \) is a group of filters; \( H_i(z) \) is the pathway for the vibration in the pipe from the place of acceleration sensor 1 installed to the place of acceleration sensor 3 installed; \( H_2(z) \) is the inertial actuator. The \( d(k) \) is a reference signal, it is picked up by acceleration sensor 1 and sampled by analogy-to-digital converter in digital signal processing system. The \( p(k) \) is the signal of \( d(k) \) after transfer to the place where the inertial actuator installed. The \( g_i(k) \) is sine signal synthesised in digital signal processing system. The \( e(k) \) is error signal, it is picked up by acceleration sensor 3 and sampled by analogy-to-digital converter in digital signal processing system.
The first step in the control algorithm is implementing fast Fourier transform and get frequency spectrum of the reference signal. Then, pick out \( n \) frequencies of which have the highest magnitude. Secondly, construct digital filter group \( F(z) \) and synthesis sine signal \( g_1(k) \sim g_n(k) \) by using those frequencies got in the first step. Finally, use LMS algorithm update coefficients in adaptive filters.

4. Experiment

Experiment was carried out on the pipe system of which showed in Fig. 1. Figure 2 shows the configuration of inertial actuator and acceleration sensors on the pipe system. Figure 7 shows the instruments used in this experiment. Charge amplifier was used to transfer charge signal to voltage signal. Power amplifier was used to amplify signal output by digital signal processing system. All signals in this system were collected by B&K 3560D and saved in a computer at the same time. The sample frequency of PULSE is 2000Hz. Frequency resolution of PULSE 12 is 0.625Hz. The block of equipment used in this experiment shows in Fig. 7. The core of the digital signal processing (DSP) system used in this experiment is a TMS320F2812 processor. The sample frequency of analogy-to-digital converter in the digital signal processing system is 2000Hz. The fast Fourier transform in the digital signal processing system is 512 point.

![Figure 7. Instruments used in this experiment.](image)

In this experiment, we choose to suppress vibration of two linear spectra with largest magnitude. Speed of pump turned to 2500 rotation per minute. The digital signal processing system gets two target frequencies and suppresses them. They are shaft frequency and its second order harmonic. The frequency spectrum of vibration measured by acceleration sensor 3 and acceleration sensor 8 was plotted in Fig. 8. The solid red line is the signal without control and the dashed green line is the signal with control. In Fig. 8(a), the vibration level at shaft frequency and its second order harmonic decreased about 7.4 dB and 12.7dB respectively. In Fig. 8(b), the vibration level at shaft frequency and its second order harmonic decreased about 5.1 dB and 11.4 dB respectively. The control effect on the foundation is less significant than on the pipe. Vibration signals measured by acceleration sensor 6 and 7 changed a little, while signals measured by the other seven acceleration sensors at shaft frequency and second-order frequency decreased significantly.

Experiment result was also recorded when the speed of pump is 2600, 2700, 2800 and 2900 rotation per minute. The results at the shaft frequency list in table 2. The results at the second-order harmonic of shaft frequency list in table 3. In table 2 and table 3, we can find, the vibration on the pipe decreased more than on the foundation. In the experiment, vibration at controlling point decreased about 6-20dB and 7-13dB at shaft frequency and second-order frequency of pump. Vibration at foundation decreased about 3-5dB and 3-11dB on the closest foundation near the inertial actuator.
Figure 8. Frequency spectrum of experiment result: rotation speed at 2500 rpm
Table 2. Results at shaft frequency.

<table>
<thead>
<tr>
<th>RPM</th>
<th>Acc3 Off</th>
<th>Acc3 On</th>
<th>Drop</th>
<th>Acc8 Off</th>
<th>Acc8 On</th>
<th>Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>109</td>
<td>101.6</td>
<td>7.4</td>
<td>100.7</td>
<td>95.6</td>
<td>5.1</td>
</tr>
<tr>
<td>2600</td>
<td>108.5</td>
<td>89</td>
<td>19.5</td>
<td>103</td>
<td>99.6</td>
<td>3.4</td>
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<tr>
<td>2700</td>
<td>108.6</td>
<td>102.7</td>
<td>5.9</td>
<td>104.3</td>
<td>99.8</td>
<td>4.5</td>
</tr>
<tr>
<td>2800</td>
<td>105.7</td>
<td>92.2</td>
<td>13.5</td>
<td>102.4</td>
<td>100.8</td>
<td>1.6</td>
</tr>
<tr>
<td>2900</td>
<td>105.1</td>
<td>99.3</td>
<td>5.8</td>
<td>101.9</td>
<td>98.9</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3. Result at second order harmonic of shaft frequency.

<table>
<thead>
<tr>
<th>RPM</th>
<th>Acc3 Off</th>
<th>Acc3 On</th>
<th>Drop</th>
<th>Acc8 Off</th>
<th>Acc8 On</th>
<th>Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>113.4</td>
<td>100.7</td>
<td>12.7</td>
<td>98</td>
<td>86.6</td>
<td>11.4</td>
</tr>
<tr>
<td>2600</td>
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<td>99</td>
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<td>101.3</td>
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<td>2900</td>
<td>104.5</td>
<td>97.5</td>
<td>7</td>
<td>101.5</td>
<td>98.6</td>
<td>2.9</td>
</tr>
</tbody>
</table>

5. Conclusion

An experiment was carried out on a closed pipe-pump system to suppress linear spectra of vibration in this pipe-pump system. An inertial actuator and control algorithm based on frequency analysis corporative to work as a control system. Vibration on the control point reduced more than 6dB at shaft frequencies and its second order harmonic, and vibration on the foundation mentioned in this paper reduced more than 3dB. It can be concluded that the active control system is able to reduce linear spectra vibration of pipe significantly.

The current system cannot suppress vibration of three and more linear spectra currently. To improve its performance and suppress vibration of more linear spectra, a redesign has to be made for the digital control systems and control algorithms. More work and experiments have to be performed too.

REFERENCES