24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

EXPERIMENTAL STUDY ON LINEAR QUADRATIC ALGORITHMS IN ACTIVE VIBRATION ISOLATION SYSTEM

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This paper presents a research on dynamic characteristics and effectiveness of active pneumatic vibration isolator subjected to harmonic oscillatory excitation. The study covers an investigation of a pressure pulsation within a pneumatic system guided with linear quadratic regulator (LQR) algorithm. The dynamic behaviour of the passive vibration isolator and the controlled one are compared using spectral analysis. The experimental data illustrates the effectiveness of a LQR-controlled system. For a hertz-level excitation signal the amplitude of pressure oscillations within a pneumatic bellows of an automated system was consistently decreased in comparison with pulsation amplitude in the passive system. The further analysis of the system features and control algorithm will be used to further improve the system effectiveness and expand its working frequency range.
Keywords: Vibration isolator, active system, control valve, pressure pulsations

1. Introduction

The subject of vibration isolation in industrial machinery, power plants and constructions has been widely discussed in the literature. At first, the passive vibration isolators [1-5] were implemented. Structurally simple units acted as spring-damper elements, effectively reducing the high-frequency vibrations. On the downside, the operation of these systems was defined by the fixed properties of isolator elements: resonant frequency, general stiffness, damping characteristic. As a result, any passive vibration isolation system would suffer a reduction in effectiveness in the low-frequency range.

The growing demand for precise vibration isolators forced the evolution of semi-active systems, where the key element is usually represented by elastic member, which parameters can be tuned during the operation. In case of pneumatic bellows, the controlled object modal frequency may be tuned by adjusting the chamber pressure, thus providing the necessary offset from main frequency of excitation signal. For these purposes researchers from the University of Castille-La Manche (UCLM) have developed a control algorithm [6, 7] which changes the resonant frequency of pneumatic system through switching between two connector tubes of various diameter and length between the bellows and additional gas vessel with rigid walls. An integrated team of researchers from the University of Ulsan (Korea) and Novosibirsk State Technical University [8] developed a control algorithm of pneumatic vibroinsulator stiffness minimization. However, semi-active system parameters cannot be changed indefinitely due to construction parameters and sensor limitations.

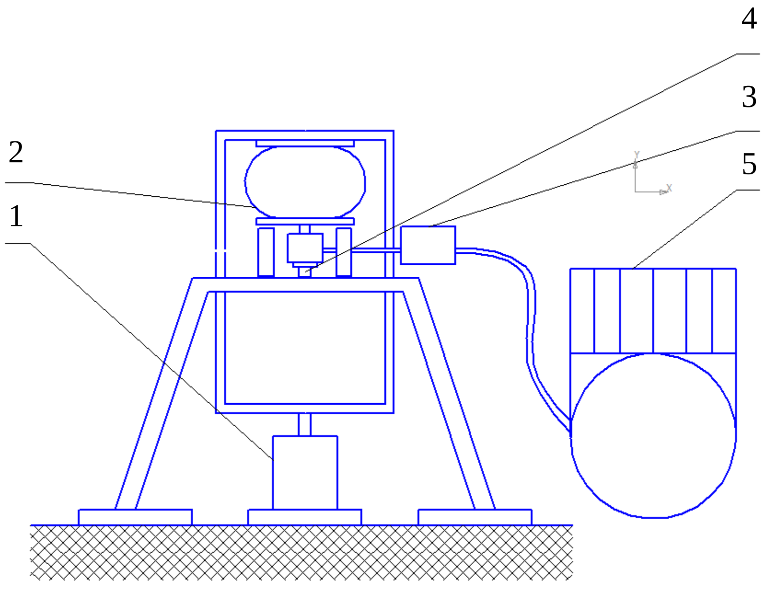
The active vibration isolation method demonstrates another approach to the problem, since the active system aims to provide the active counteraction to the disturbing force. For example, Maciejewski *et al.* [9, 10] used the proportional control algorithm with vibration, relative vibration speed and relative vibration displacement as regulated parameters. The resulting system proved its effectiveness in the low-frequency range of excitation signal and pointed out the weakness of any feedback loop system: any element, adding the delay to control output would undermine its efficiency.

This article is a further development of our research [11] on a single-coordinate vibration isolation. The research aims to decrease the control output delay by providing the overcritical flow through control valve. In this case, linear quadratic regulator (LQR) was used to control both the mean pressure level in pneumatic chamber and pressure pulsations amplitude.

2. Test rig

The test rig layout is presented of Fig. 1. An electrodynamic vibration exciter (1) serves as a source of disturbing force and transmits the sine load to the upper surface of the pneumatic chamber through rigid frame. The valve assembly asserts the gas flow control at the inlet of the pneumatic chamber (2). The pressure pulsations in the pneumatic bellows were measured using the high-frequency dynamic pressure sensor PCB M101 A0, whereas the mean pressure level was monitored using the sensor PSE 550-02-28. The National Instruments real-time controller NI RIO 9023 served as a key component of an automatic regulator. LabView software package was used to develop a program to adjust test run conditions, perform the actual pressure control and conduct the telemetry recording and analysis.

The test rig housed two types of control valves for different designs: the disc valves AP-7211-NR2-4711 Camozzi unit with 2 mm bore diameter and the proportional spool valve LRWA2-34-3-A-00 Camozzi unit with 6 mm bore diameter. Both types of valves were controlled using the PWM signal, generated by NI RIO controller. The first solution incorporated two parallel feedback loops, controlling the mean pressure level using coupled AP valves and pressure pulsations amplitude by means of servo valve respectively (Fig. 2a). The second design housed a single LRWA servo valve, controlling the total pressure level using either LQR or a proportional-velocity-acceleration (PVA) control (Fig. 2b)

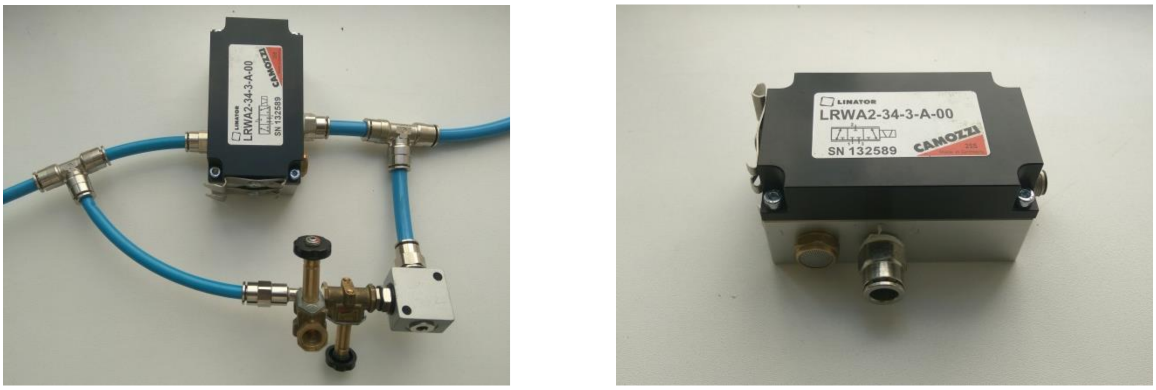


1 - electrodynamic vibration exciter; 2 - pneumatic belloaw; 3 - control valve;
4- pressure pulsation sensors; 5 - air compressor.
Figure 1. Test rig layout.

Table 1: Physical properties of the test rig.

Test rig parameter	Value
Load mass, kg	1.5
Available excitation frequency band, Hz	1-200
Maximum shaft stroke length, mm	50
Overall test rig mass, kg	37
Overall dimensions, m	1 x 1 x 1.5
PCB pressure sensor sensitivity, V/Pa	1.43×10^{-6}
PSE pressure sensor sensitivity, V/Pa	1.6×10^{-8}
AP-7211-NR2-4711 response time, s	0.013
LRWA2-34-3-A-00 response time, s	0.006

The response time in table 1 was defined through series of tests as a time interval between the input signal change and valve opening, followed by a vibration spike. A vibration sensor at the valve outlet was used to record the corresponding shock vibrations.



a) b)

Figure 2. Valve assembly options

In order to provide the authentic input from pressure sensors we had to set up their refresh rate – 40Hz for PSE sensor and 2KHz for PCB pressure pulsations sensor. Effectively, 2Khz refresh rate is the highest available to be run smoothly without exceeding the controller RAM, and 40Hz was enough to maintain the set pressure level with minimal aberrations. In order to provide the operation smoothness at the setpoint pressure level, the signal of PSE sensor was filtered using mean level filter, and the pressure pulsations signal from PCB sensor was processed using the Butterworth filter (4^{th} order, 40Hz cutoff frequency). As a result, we've obtained two almost independent pressure signals describing the overall pressure level in pneumatic bellows.

The LQR control design was specifically used to take into account both input signals to generate the single control output. In our case, the input matrix included input aberrations for mean pressure level and pressure pulsations amplitude.

Series of test runs were conducted for both control designs. The disturbance signal frequency varied from 1 through 5 Hz, and for each condition the optimal coefficients were set. A single test run took 5s to perform.

The oscillogram of pressure pulsation within the pneumatic bellows was recorded. Then, the display program performed an FFT analysis to point out the main frequencies of recorded signal and their corresponding amplitudes. After that, recordings of «active» and «passive» systems were compared. The overall efficiency was measured using two parameters. The first one was defined by the correlation between the tone components at the same frequency of disturbing force in both systems :

$$E_t = \left. \frac{Ap_{pas}}{Ap_{act}} \right|_{f=f_{in}}, \tag{1}$$

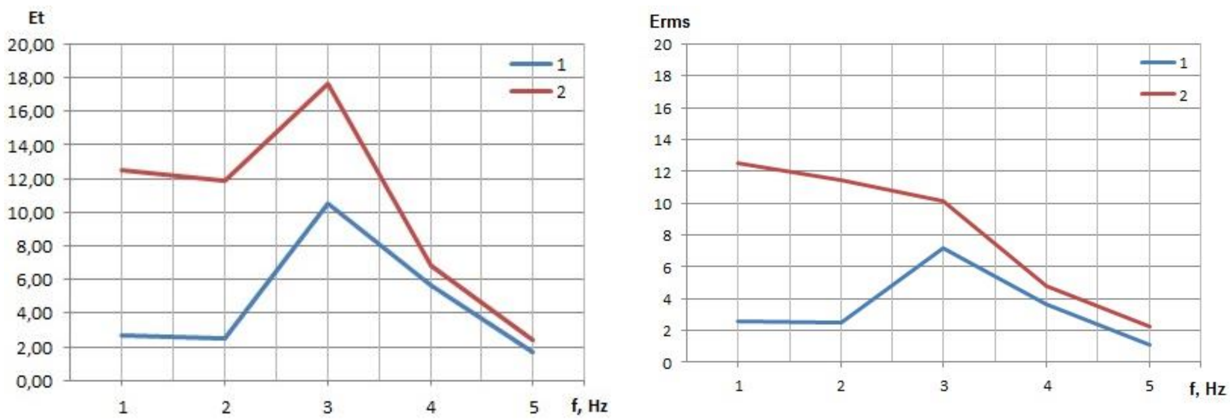
where Ap_{pas} is a tone component of the passive system pressure pulsation amplitude, Ap_{act} is a tone component of the active system pressure pulsation amplitude, f_{in} is a disturbing force frequency. The second parameter was defined by the correlation of the oscillogram RMS of the passive and active systems:

$$E_{RMS} = \frac{\sqrt{\frac{1}{2}\sum_{i=1}^{n}\left(Ap_{pas}\right)_i}}{\sqrt{\frac{1}{2}\sum_{i=1}^{n}\left(Ap_{act}\right)_i}}, \tag{2}$$

where n is the line count in the pressure pulsation spectrum of a pneumatic bellows pressure.

3. Experimental results

The first stage of experimental study was dedicated to adjustment of the parallel feedback loops system. In some cases, it is theoretically possible to obtain a specific set of coefficients and achieve a stable operation at certain working modes. In our case, the system was unstable with any set of controller coefficients and the idea was rejected.



a) b)

a – tone efficiency parameter; b – RMS efficiency parameter.
1 – PVA control algorithm; 2 – LQR control algorithm.
Figure 4. Vibration isolation system efficiency

The second stage was focused on control algorithms for a single LRWA valve. As previously described, the control algoritms are PVA regulator, using the signal of pressure puslation sensor as input, and LQR regulator, which used both signals of mean pressure level and pressure pulsation. The Fig.4 illustrates their efficiency evaluation through comparison with passive system using the tonal component measurement and RMS value of the pressure signal spectrum.

LQR-controlled system demonstrated a sizeable increase in efficiency for a low frequency excitation signal. In comparison with a simple PVA controller, a sixfold decrease in the pressure pulsation amplitude was achieved for 1Hz and 2 Hz pulsatons. The efficiency difference diminishes with the increase of excitation signal frequency, and both systems tend to efficiency level of a passive one at approximately 6 Hz.

4. Conclusion

The conducted experimental study of an active pneumatic vibration isolator system allowed us to draw the following conclusion:

The vibration isolation system efficiency heavily depends on the overall response time of the control valves system, which is affected by construction parameters, gas flow parameters and complexity of related calculations. In our case only the 6-mm bore diameter valves allowed us to achieve at least twofold efficiency advantage over the passive vibration isolator in the frequency range, including the pneumatic bellow modal frequency.

The practical efficiency of LQR control algorithm with gas flow control output in term of active pneumatic vibration isolator was found out.

5. Acknowledgements

The study was concluded by virtue of financial support from Ministry of Education and Science of the Russian Federation.

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