Inertial system for measurement of the dynamic response and status of the vehicle suspension elements

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Abstract: The current paper describes the information and communication system, based on micromechanical inertial sensors (MEMS) to measure the dynamic response and status of the vehicle suspension elements. It consists of an inertial sensor network from at least two sensors, which are situated on the moving elements of the vehicle suspension. The communication system part reads and stores the inertial sensor data while the information system part calculates the frequency response, attenuation time, resonance frequencies and distance between moving parts. The calculated distance is compared with the adjusted clearance and the system accuracy is shown. It is shown that the system is capable to measure the distances from 0.6 to 1.0mm with 0.1mm accuracy. The inertial data scanning is performed with a sampling frequency of 160Hz, according to the expected peak accelerations and translations.

Keywords: MEMS sensor, diagnosis, dynamic response

INTRODUCTION

The MEMS sensors are widely used to measure the frequency, amplitude (strength) and spectrum (signature) of vibrations [1,2] enabling the ability to perform active monitoring of moving objects such as unmanned autonomous vehicles [3,4]. Vibrations have an influence on vehicle constancy and convenience of use, they also can be very dangerous for users. Vibrations with too big amplitude or concrete frequency may cause discomfort, tireness and even loss of health. However the most of the systems studied the damping characteristic of the shock absorbers [5,6] while the dynamic response of other suspension elements are not well studied.

The current paper represents such type of system which is capable to measure the dynamic response of lots of suspension elements simultaneously based on the inertial network. The individual MEMS inertial sensor is mounted on each studied element and inertial data of all three axes are recorded and analyzed. The displacement and relative speed may be calculated using a numerical integration. The dynamic characteristics may be also calculated using the spectrum analysis and periodogram methods.

SYSTEM DESCRIPTION

The measurement system contains two main parts – communication and information system. The communication system consists of an inertial sensor network from at least two sensors, which are situated on the moving elements of the vehicle suspension. It is responsible for data reading, data synchronization and PC communication transfer. The used inertial sensor network topology is based on two inertial sensors as shown at Figure 1. The requested sensor power supply (+5V) is drawn by the USB bus because of the low sensor power consumption (less than 10mA).

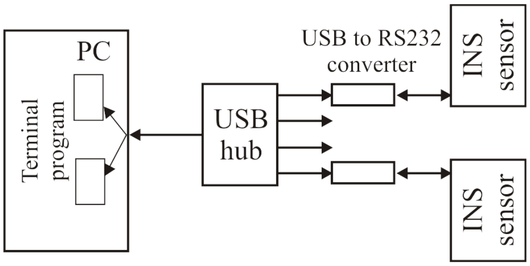


Figure 1. Sensor topology

The experimental car is lifted on the vibration stand type BOGE-AFIT ShockTester which generates vertical oscillations to measure the suspension characteristics (Figure 2). The third inertial sensor is located on the vibration stand and measure the vibration of the vehicle suspension response while the first two sensors measure the accelerations of the studied suspension elements. The test car is Fiat Bravo with installed Macpherson strut front suspension. The sensor positions are shown at Figure 3.

Figure 2. Fiat Bravo on the vibration stand

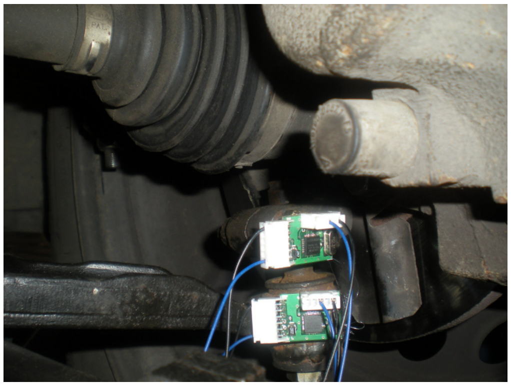


Figure 3. Sensor position on the studied elements

The inertial data from the vibration stand and inertial network are recorded on PC. The initial synchronization is provided by starting commands to all sensors.

The sensor packets are also numbered to synchronize all data packets. The distance between the studied parts is calculated according to the double numerical integration of the inertial data:

$$v_c(i) = v_c(i-1) + \frac{a(i) - a(i-1)}{2}\Delta t \qquad (1.1)$$

$$d_c(i) = d_c(i-1) + \frac{v_c(i) - v_c(i-1)}{2}\Delta t \qquad (1.2)$$

It is known that a harmonic vibration of frequency ω and displacement amplitude d_{max}, results in a maximum acceleration a_{max} calculated as follows [7]:

$$a_{\max} = d_{\max}.\omega^2 \qquad (2)$$

Therefore, if the expected maximum acceleration is equal to g and the displacement amplitude is equal to 1.0mm, the harmonic vibration frequency is equal to:

$$f_{\max} = \frac{\sqrt{\frac{a_{\max}}{d_{\max}}}}{2\pi} = 49.84Hz \approx 50Hz \qquad (3)$$

The sampling frequency has to be equal to $F_d \geq 2f_{max}$. The chosen sampling frequency from the LIS3LV02DQ datasheet is equal to 160Hz.

EXPERIMENTATION AND DATA ANALYSIS

The adjusted clearance between the studied elements varies from 0.0mm to 1.2mm with 0.4mm step. If the clearance is fixed to the desired value than three vibration tests are accomplished and the inertial data are recorded in a binary format and analyzed later by MATLAB routine. The spectrum analysis is realized on the basis of a Fourier transform periodogram. The window has a rectangular shape with *N*=192 samples and 180 overlapped samples. The typical spectrum response of the inertial sensor is shown at Figure 5. The spectrum peaks are clearly visible and the detailed look at the periodogram (Figure 5) shows the three main processes of the vibration cycle may be defined as follows:

1. vibration stand acceleration process
2. stationary vibration process
3. oscillation and attenuation process

The spectrum peaks are situated on the straight line which defines the attenuation speed. The line slope is equal to:

$$k = \frac{\Delta w}{\Delta f}, \qquad (4)$$

where $\Delta w = w_2 - w_1$ - the difference between the window numbers of two neighbor peaks;

$\Delta f = f_2 - f_1$ - the frequency difference between the neighbor peaks

The window sliding ($\Delta w = 1$) is equivalent to the time shifting $\Delta T = OV.T = OV.N.\Delta t$, where OV – window overlapping coefficient. Therefore the window difference is equal to:

$$\Delta w = w_2 - w_1 = \frac{t_2 - t_1}{OV.N\Delta t},$$

and the line slope may be expressed as:

$$k = \frac{(t_2 - t_1)F_d}{OV.N\Delta f}. \qquad (5)$$

The line slope of the attenuation process shown at Figure 5 is equal to 0.33Hz/s.

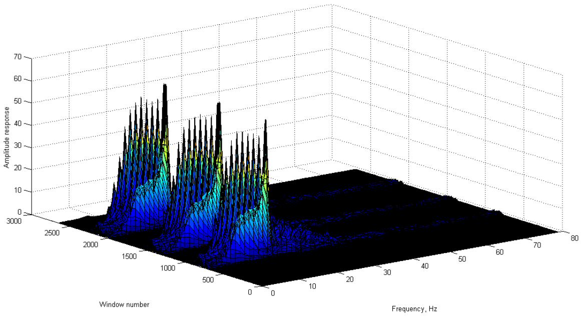


Figure 4. Typical spectrum response

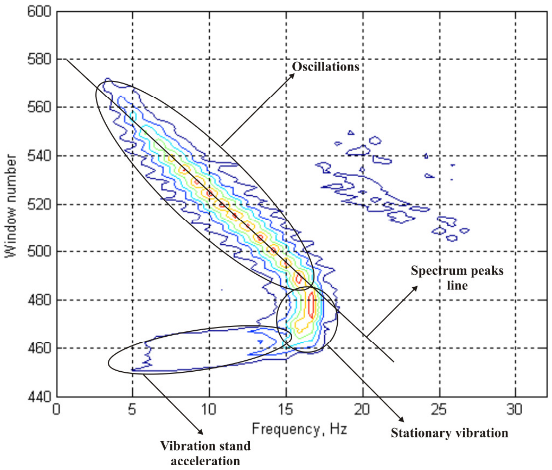


Figure 5. Detailed look of the spectrum response

The displacement between the both sensors is calculated according to the equations (1), where the acceleration value is substituted with the acceleration difference of both sensors: $\Delta d(t) = d_{c2}(t) - d_{c1}(t)$.

The calculated acceleration difference in a time domain is shown at Figure 6 depending of the clearance. The results show that the maximum acceleration difference increases when the clearance is increased. The calculated acceleration difference has to be integrated to calculate the speed difference between both sensors, but the numerical integration leads to the error accumulation if the bias is not removed. Bias offset drift exhibited in the acceleration signal is accumulative and the accuracy of the distance measurement could degrade with time due to the integration. The low frequency components are also a source of integration errors. Due to these reasons the spectrum response has to be accomplished to define the frequency band of the inertial data and to construct the bandpass filter to reduce the noise and to remove the bias.

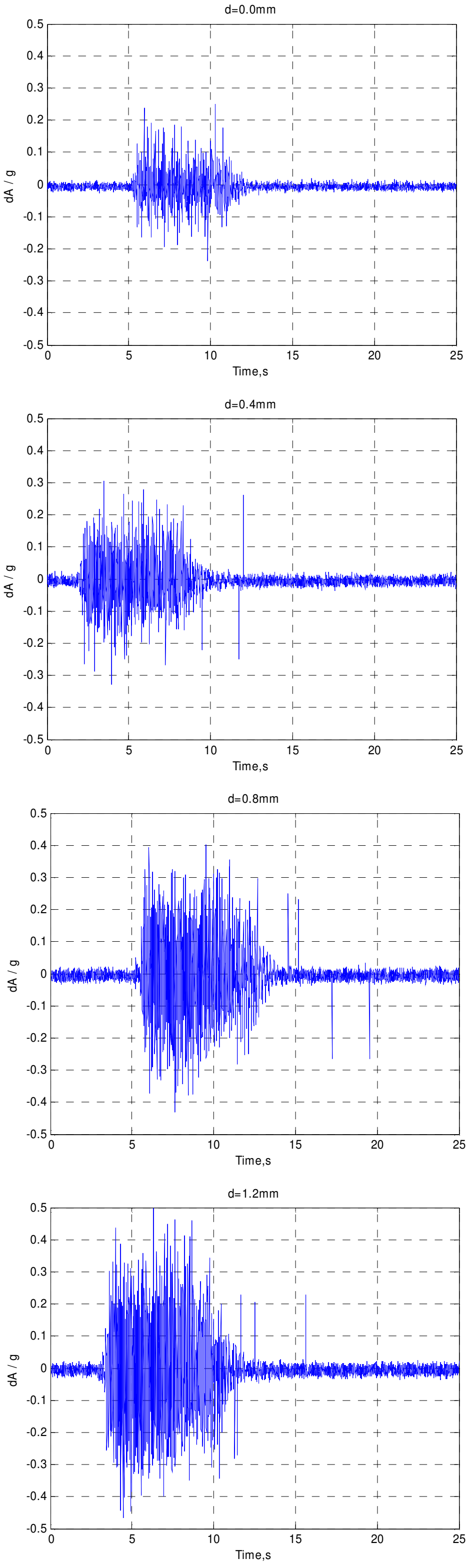


Figure 6. Calculated acceleration difference in a time domain

The spectrum response of the acceleration difference at d=0.4mm is shown at Figure 7. The spectrum responses at the other clearances are similar. According to the calculated spectrum response the following filter properties are defined:

- filter passband - 6÷24Hz
- stopband cut-off frequencies – f_1=3Hz; f_2=32Hz
- maximum passband ripple – 1dB
- Minimum stopband attenuation – 40dB
- Approximation – IIR, Butterworth

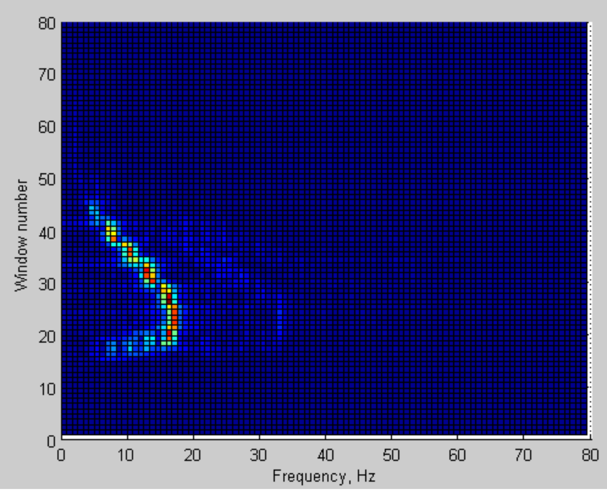


Figure 7. Spectrum response of differential signal

On this bases MATLAB buttord() function generates 11-th order Butterworth digital filter. The spectrum response of this digital band-pass filter is shown Figure 8.

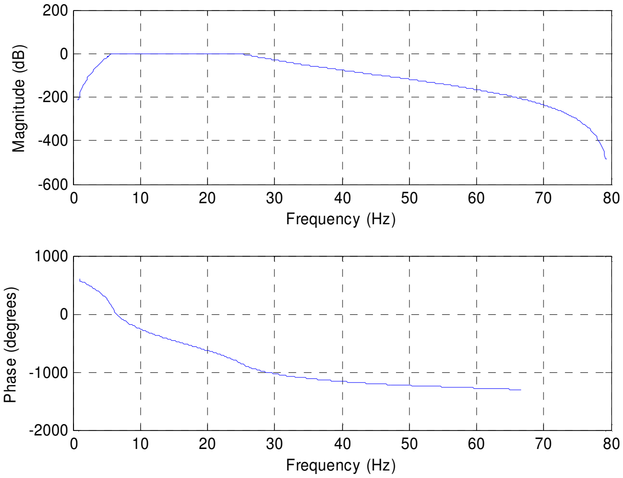
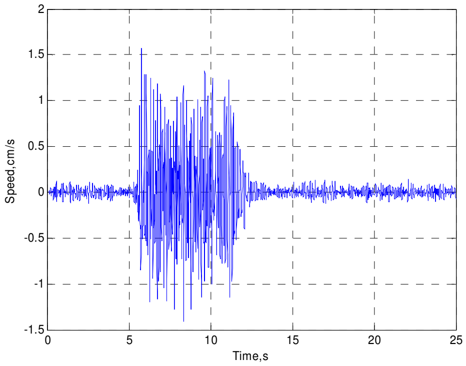
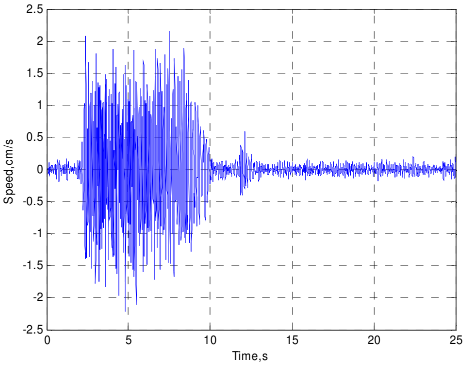


Figure 8. Spectrum response of the band-pass filter

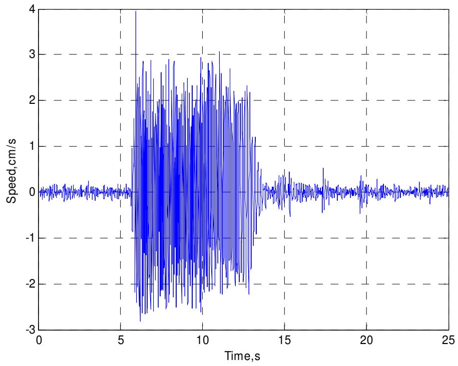
The filtered data are numerically integrated to calculate the element relative speed according to equation (1.1) and results are shown at Figure 9.



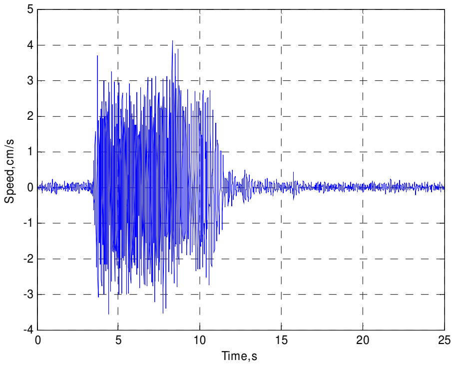
d=0.0mm



d=0.4mm

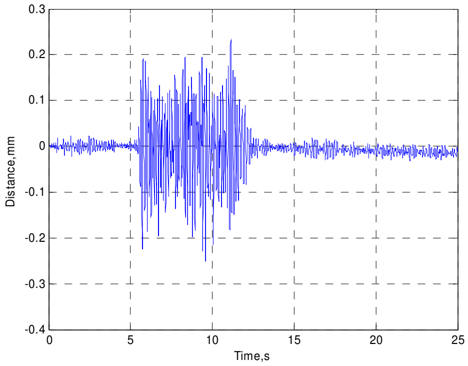


d=0.8mm

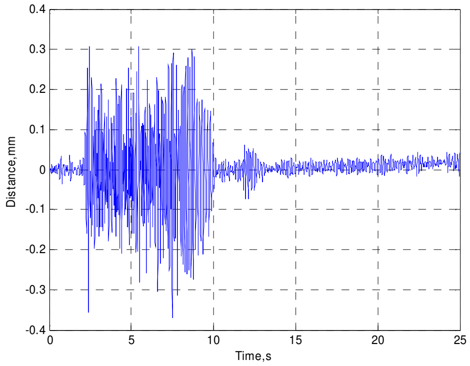


d=1.2mm

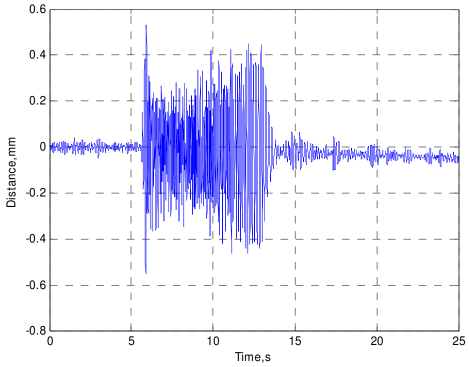
Figure 9. Calculated relative speed



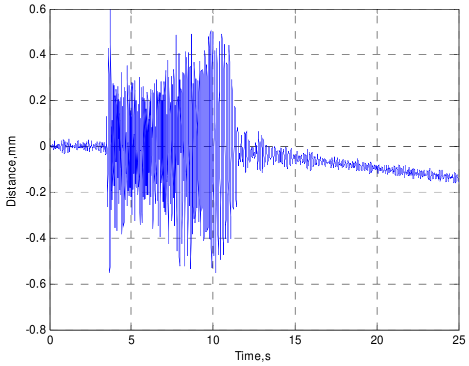
d=0.0mm



d=0.4mm



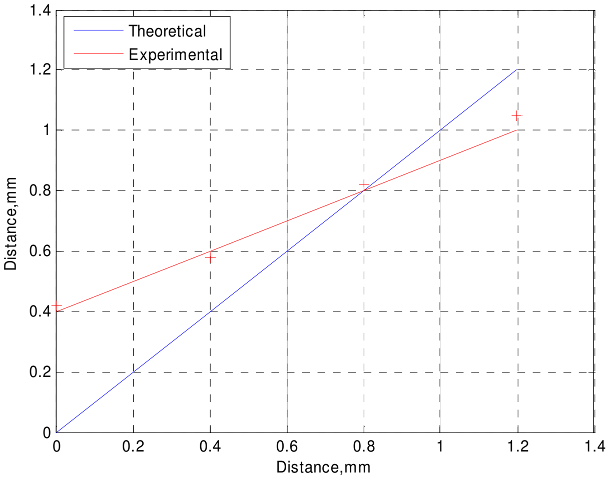
d=0.8mm



d=1.2mm

Figure 10. Calculated displacement

The second data integration is accomplished on the basis of the equation (1.2). The distance between the studied parts is shown at Figure 10 depends from the adjusted clearance. The calculated results are compared with the adjusted clearance and the comparison analysis is shown at Figure 11.



Theoretical = adjusted clearance
Experimental = Calculated displacement

Figure 11. Comparison graph between the adjusted clearance and measured distance

This analysis shows that the proposed system may accurately calculate the clearance between the studied parts. The accuracy is better then 0.1mm as the clearance is changed from 0.6mm to 1.0mm. The error at d≤0.6mm may be explained with the integration errors. In the same time if the clearance is bigger than 1.2mm then the calculated distance is lower then the adjusted clearance due to the fact that the element displacement may be less then the adjusted clearance.

CONCLUSION

The current paper discusses the information and communication system, based on micromechanical inertial sensors (MEMS) to measure the dynamic response and status of the vehicle suspension elements. It is shown that the system is capable to measure the distances from 0.6 to 1.0mm with 0.1mm accuracy. The dynamic characteristics of the studied elements are also defined according to the spectrum analysis of the inertial data. The problem with the integration error is also overcome with the designed IIR bandpass filter. The filter properties are also based on the spectrum response of the inertial data to ensure that the information criteria are not affected.

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