Analysis of the dynamic response of the car suspension based on inertial MEMS sensors

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Abstract - The current paper discusses the measurement and analysis of the dynamic response of the car suspension based on the inertial micromechanical inertial sensors (MEMS). This paper reviews the state of the art, describes the methodology and presents experimental validation of a concept of determination of the dynamic response of the car suspension. The inertial data are analyzed in time and frequency domain and the time attenuation period and damping frequency variation are estimated.

Key-Words: MEMS sensor, diagnosis, dynamic response

1 Introduction
The optimal driving behavior and the driving safety is the result of an optimal dynamic response of the suspension. The acceleration of the body is an obvious quantity for the motion and vibration of the car body and can be used for determining a quantitative value for driving comfort. To be useful in a repair shop, the test systems generally must be very quick and reliable. There are several systems in use by repair shops to evaluate the condition of the suspension as a whole, and these infer the condition of the damper. One main method for suspension performance analysis is to excite the suspension through the tire via a shaking platform. The platform performs a sinusoidal sweep to observe the conditions for wheel hop resonance. Generally, they look for the resonance frequency, amplitude, and phase shift. There are two popular suspension testing systems that utilize the sine swept tire shaker. They each characterize the damper condition in slightly different manners [1-3]. Regardless of some shortcomings (damper fluid temperature [4] and tire pressure dependence [5]), if care is taken these methods may be effective.

The proposed instrumentation for calculation of the suspension dynamic response is made with MEMS technology that is less expensive and more accurate than the technology used in the noted suspension testers. Another feature is that the system is portable and easy to use. Also the elaborated MATLAB routine for data analysis allows developing a quick and time efficient test to assess the performance of the suspension.

2 Experiment study
A common approach for Suspension Parameter Testing (SPT) systems is to take the vehicle in static positions, and apply forces in specific ways to record the deflection of the component to be characterized, i.e. the tire, the springs, or the various linkages. These quasi-static tests are great for suspension diagnosis or further developing the models that have helped advance the automotive design process.

The experimental car is lifted on the vibration stand type BOGE-AFIT ShockTester (Figure 1), which excites the platform to 16 Hertz, and then shuts off. The ensuing platform vibrations decay at a rate that infers the performance of damper. The data acquisition system based on inertial MEMS sensor is located on the vibration stand and measure the vehicle suspension response. The vibration amplitude and frequency depend from the suspension design and condition.

Figure 1. Experimental car on the vibration stand
The test car is Fiat Bravo with installed Macpherson strut front suspension and its position on the vibration stand is shown at Figure 2.

The vibration stand generates a vertical force $G_z$ which is decomposed to one force $G$ to the direction of the steering knuckle and another force $G_x$ which is directed to the horizontal axis of the vibration stand. The amplitude of the horizontal force and suspension carrier depends from the slope of the steering knuckle axis $\gamma$ and the vibration stand inclination angle $\gamma'$ according to the equation:

$$G_x = G_z \sin(\gamma + \gamma').$$

The used data acquisition system is based on the MEMS accelerometer sensor LIS3LV02DQ – a three axes digital output linear accelerometer, produced by ST. This sensor includes a sensing element and an IC interface able to take the information from the sensing element and to provide the measured acceleration signals to the external world through an I2C/SPI serial interface. The integrated $\Sigma A$ converters are tightly coupled with dedicated reconstruction filters which remove the high frequency components of the quantization noise and provide low rate and high resolution digital words. The LIS3LV02DQ has a user selectable full scale of ±2g, ±6g and it is capable of measuring acceleration over a bandwidth of 640 Hz for all axes [6]. The inertial MEMS sensor reads the data with a sampling frequency of 40Hz to satisfy the Nyquist criteria.

### 3 Data analysis

During the experiments every vibration attempt is accomplished three times (Figure 3). The time domain analysis clearly shows the three main processes of the vibration cycle which may be defined as (Figure 4):

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

Vibration process can be analyze with time-frequency analysis. The most popular analysis are:

- a) Short Fast Fourier Transform (SFFT) [7,8]
- b) Wigner-Villes Transform (WVD) [8]
- c) Wavelet Transform [9]
- d) Linear decimation [10]
- e) Frequency Response Functions (FRF) [11]
- f) Power spectrum density (PSD) [12]
- g) Auto-Regressive Model [13].

The spectrum analysis is realized on the basis of a Short Fast Fourier Transform. The window has a rectangular shape with $N=192$ samples and 180 overlapped samples. The total periodogram is
shown at Figure 5, while the single periodogram from the second attempt is shown at Figure 6.

![Figure 5. Total periodogram of the oscillations](image)

It is clearly visible the above mentioned three stages of the vibration process (Figure 7) also in the frequency domain. The spectrum peaks are situated on the straight line which defines the attenuation speed (Figure 8).

![Figure 6. Single periodogram of the oscillations](image)

![Figure 7. Vibration stages in the frequency domain](image)

![Figure 8. Definition of the spectrum peak lines](image)

The line slope is equal to:

$$ k = \frac{\Delta w}{\Delta f}, \quad (2) $$

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 $\Delta t = OV \cdot T = OV \cdot N \cdot \Delta t$, where $OV$ - window overlapping coefficient. Therefore the window difference is equal to:

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

and the line slope may be expressed as:

$$ k = \frac{(t_2 - t_1)F_d}{OV \cdot N \Delta f}. \quad (3) $$

The data analysis shows the following conclusions:

1. The calculated attenuation coefficient is equal to 0.33Hz/s according to equation (3) and the data represented at Figure 8;

2. The attenuation defines two main frequencies which difference remains constant all the time and it’s equal to $\Delta f = 2f_d/N = 1.25$Hz;

3. The maximum amplitude of the spectrum peaks appears at the frequency $f_0 = 8$Hz;

4. The spectrum peaks appear in the frequency range from 6 to 10Hz.

5. The total frequency range of the oscillations is equal to 14Hz (from 3Hz to 17Hz).
According to the total frequency range, the passband filter may be designed to reject the bias offset and the low frequency components of the inertial data. These components are source of the integration errors while the suspension speed and displacement are calculated.

4 Conclusion
The paper discusses the measurement and data analysis of the suspension vibrations based on micromechanical inertial sensors (MEMS) to measure the dynamic response and status of the vehicle suspension elements.

The system allows real-time calculation of:
- Total attenuation time;
- Resonant frequency according to the maximum amplitude of the spectrum peaks;
- The total frequency range of the oscillations;
- The calculated attenuation coefficient which represents the system dynamic response;
- The suspension speed and displacement of the car body according of the numerical integration of the inertial data.

In the same time the proposed system is less expensive and more accurate due to the low cost and high sensitive MEMS inertial sensor (1mg resolution). The combined time and frequency domain analysis allows fast and user friendly calculation of the suspension dynamic response, detection of suspension problems and prevention of the suspension element failures.

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References