Compact Vibration Measuring System for In-Vehicle Applications

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Abstract. *Low frequency vibration occurs especially in ground transportation. It is of permanent interest in studies of driver's and passenger comfort issues and seating dynamics research. Piezoelectric accelerometers commonly used for vibration measurement are not suitable, hence other sensors capable of measuring accelerations down to sub-hertz region have to be used. Based on some previous experience with MEMS acceleration sensors a compact measuring system employing two three-axial MEMS accelerometers interfaced via a data acquisition unit to a light-weight notebook was designed and constructed. The digitised data were processed by scripts by Matlab® with the aim to analyse both the vibration influence on seated person and the dynamic properties of the seat. Some preliminary results from illustrative test runs with a passenger automobile are presented.*

Keywords*: vibration measurement, MEMS accelerometer, vibration measuring system, seating dynamics, human comfort*

1. Introduction

Low frequency vibrations occur, among others, in ground transportation; either as a cause in adjacent environment or within the vehicle itself. The frequency content may vary from well below 1 Hz up to, say, 20 Hz. Exposure to low frequency vibrations and shocks may affect comfort and in case of prolonged exposition, extending for many years, may impair health. Hence it is worthwhile to undertake technical efforts to minimize generation and/or propagation of low frequency vibrations. The comfort issues are of importance in design, development and marketing of vehicles, earth moving machinery and agricultural tractors.

To be able to assess the effectiveness of vibration attenuation by the seat during various field conditions a specific measuring apparatus is required. Various means are used, i.e. in-vehicle analogue data loggers, telemetry systems, instrumentation carried in an escort vehicle, etc.

In most cases the vibration transmission from the vehicle floor (seat base) to the seated driver via the driver's seat and the driver's buttocks is of interest. In general translatory and rotational vibration components are present; however, mostly the translatory components in mutually perpendicular coordinate axis are measured and evaluated. To facilitate their measurement the apparatus, described below, was developed in collaboration with the Institute of Measurement of the Slovak Academy of Sciences.

2. Fundamentals of vibration measurement in transport means

First of all it should be noted that in ground transportation the acting forces are of primary interest, followed by various vehicle parts relative movement. As a result the preferred measurand is the absolute acceleration followed by relative displacement measurement. Despite a well-defined physical relation between both characteristics experience shows (e.g. [1, 4, 6]) that the errors introduced by real measuring systems are of such magnitude that these exclude real application of this relation. In practical situations it is advisable to complement one measuring system by another one and use data fusion [1, 2].

From experience it is known that the *vibratory acceleration* a_v observed in ground transportation is smaller than the standard gravity acceleration $g_N \approx 9.81$ m.s^{-2}. It is also well known that the measured accelerations are of random nature with periodic components. The vehicles are in general subjected to traverse on arbitrary curvilinear trajectory with non-constant traversing velocity. Moreover the vehicle chassis plane may be inclined in respect to the horizontal plane. Both effects give rise to quasi-static acceleration, which is superimposed onto the mechanical vibrations due to road/track undulations and/or engine influence [3, 6].

The quasi-static *translatory acceleration* a_t frequency content extends down to sub Hertz frequencies. So measurement of the *total acceleration* $a_T = a_t + a_v$ poses some practical problems. The use of standard piezoelectric accelerometers with their well-known inherent low frequency limits [1, 2] is not feasible. Other accelerometers types have to be considered, capable measuring also quasi-static acceleration [1, 2, 5, 6]. The current approach is to employ sensors based on the so-called servo-accelerometer principle made using contemporary semiconductor manufacturing technologies which are called Micro-Electro-Mechanical Systems (MEMS) [1, 2, 5]. Further on the use of one type of MEMS type servo-accelerometer for this purpose will be illustrated. This is a continuation and extension of previous work on application of servo-accelerometers for measuring of mechanical and vibration quantities [4, 6].

3. Measurement system description

The compact vibration measuring system consists of following:

A/ Two identical three-axial MEMS accelerometers;

B/ Analogue acquisition unit with USB output/power supply;

C/ Standard notebook with acquisition program.

A/ Each of the used three-component MEMS accelerometer type CXL04LP3, made by Crossbow, San Jose, California USA is enclosed in a plastic box 19×47.6×25.4 mm of mass 46 g and delivered with a 244 cm long cable with a connector on the other end. The measuring range is ± 40 m.s^{-2} ($4 \times g_N$); output voltage is approx. 2.5 V for zero acceleration and sensitivity is ≈ 50 mV/m.s^{-2}. The accelerometers are factory calibrated. Accelerometer is fixed either to a 2 mm thick steel plate 120×100 mm (the base/floor sensor, denoted as “sensor A” (index “b”)) or on a steel disk of 70 mm dia., located in a rubber disc “sensor B” (index “s”). The rubber disc is made according to the requirements of ISO 10326/EN 30326 standard, pertinent to laboratory tests of professional drivers’ seats. This disc is located between the seated driver and the seat cushion. As described in the said standard, it is used to measure the vibratory input to the seated person. For comparable results the standard requirements was adhered to.

B/ The analogue acquisition unit with USB 2.0 communication interface consists of 8 input channels, each equipped with 24 bit sigma-delta convertors with sampling frequency of up to 50 kHz. The 8 channels are timed simultaneously, thus facilitating reliable phase/time delay estimation. The control is facilitated by a microcontroller. The unit draws some 250 mA from the 5 Volt power supply of the USB port. The acquisition software enables to sample either 32 thousand data points into a file or continuously much larger amount onto disk. For chosen sampling frequency of 200 Hz the first method facilitates measurement duration of 150 s, which suffices for foreseen application. Analogue anti-aliasing filtration is not implemented.

C/ Compact integration of the above units was facilitated. Because the sensors rely on constant voltage supply of required stability a stabilisation circuit of type ADP 3607 was used. No temperature compensation as in [6] was used. To increase system reliability no connectors were used. All connections were thoroughly fixed to each other to avoid any failures during field measurements. The electronics is thoroughly fixed in a rugged box of size 260 × 120 × 40 mm. The sensors' cables and the USB cable are entering the box via rubber bushings, so facilitating partial dust-proofness and compactness: see Fig. 1.

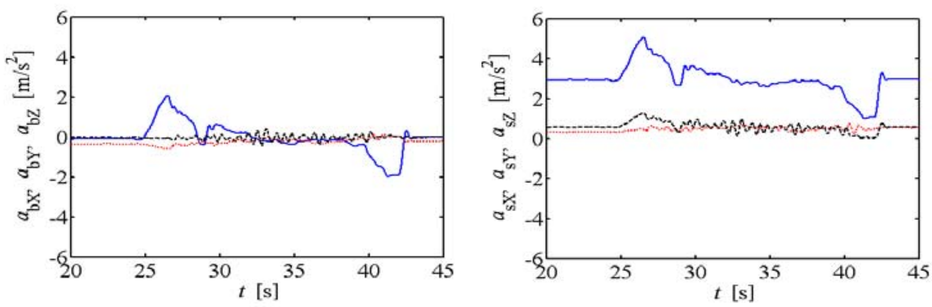
(a) (b)

Fig. 1. Photo of the sensors (a) and the box with the notebook (b).

To make the experimental conditions more transparent a straight traverse, including some original vehicle inclination, is assumed. This condition calls for a specific field measurement conduct: the vehicle stands for a while in standstill then accelerates to required velocity, maintains a straight course at this more-or-less constant velocity and then decelerates to standstill. This measurement organisation facilitates proper data analysis.

4. Measured signal processing in the laboratory

The data analysis program is written in the Matlab® environment. As indicated above the program first reads in raw data, containing a section on the beginning when the vehicle is in standstill. The signal is subjected to low-pass filtration by a FIR LP filter of 100th order with cut-off frequency 0.5 Hz. In this way the translatory acceleration a_t is obtained and displayed (Fig. 2 a, b). The program calculates the sensor inclination angles (in the illustrative example more pronounced for the sensor B on the seat; in this case some 14°, whereas the other ones are about 2° and hence negligible) and subtracts these, essentially DC components, from the time sequence to correct for sensor inclination. From Fig. 2 the operator can also assess when the vehicle was travelling with constant speed (a_t in the x-direction is approx. zero).



(a) (b)

Fig. 2. Pre-processing of acceleration signals for extraction of the translatory acceleration component a_t on seat base (a) and on seat surface (b): (——) fore-and-aft direction (x - direction); (• • • •) transversal direction y - direction); (— — —) upward direction (z - direction).

Then the time interval, wherein the signal is assumed to be stationary, is selected, in this illustrative example between 32nd s and 38th s. Signals from the selected time interval are further subjected to band-pass filtration by a FIR filter of 100th order to extract the vibratory acceleration a_v in the frequency band 0.5 Hz to 80 Hz in each of the three perpendicular sensors axes (Fig. 3). So pre-processed accelerations data are further subjected to calculation of power spectral densities (PSD), transfer function estimates (TFE) and respective coherence functions γ, root-mean-square values, etc., by Matlab® functions, which is a standard data analysis approach used in analysis of mechanical vibrations. Relative uncertainty of the measured acceleration is of the order of ± 5 % [7], as common in seating dynamics research.

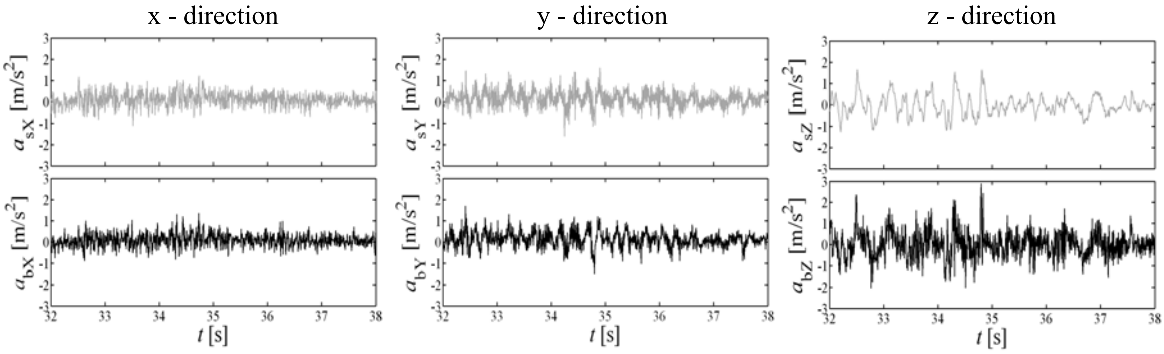


Fig. 3. Vibratory acceleration signals in mutually perpendicular axes: seat base (▬▬), seat (▬▬).

5. Results

The resultant PDFs and TFEs and coherence functions γ (to be shown in the presentation) are used by competent specialists for assessing seat dynamic properties and attenuation of vibration transmitted to the driver. This is the main purpose of the compact vibration measuring system for in-vehicle application. The illustrative results were gathered in test runs with voluntary test persons in a ŠKODA Fabia 1.2 HTP passenger car in academy premises.

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