Measurement and Analysis of Low Frequency Vibration

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Abstract. *Low frequency vibration occurs especially in ground transportation, either as a cause in adjacent environment or within the vehicle itself. The 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 three-axial MEMS accelerometer was interfaced to a data acquisition unit. The digitised data were processed by scripts by Matlab® with the aim to discriminate between low frequency translatory acceleration and vibration acceleration. Some preliminary results of this endeavour are presented.*

Keywords: vibration measurement, MEMS accelerometer, vibration measuring system

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. Excessive vibrations interfere with human activity and may cause malfunction of mechanical and/or electronic equipment on board of the vehicle. Prolonged exposure to low frequency vibrations and shocks may affect comfort and in case of prolonged exposition, extending during several years, may impair health. Hence it is worthwhile to undertake technical efforts to minimize generation and/or propagation of low frequency vibrations. To be able to assess the importance of vibration abatement measures and to assess their effectiveness means for reliable measurement are necessary. The paper will report on some preliminary results of application of a three-axial accelerometer for measurement of translatory acceleration and use of this information for evaluation of measuring head inclination in a stationary position and of acting vibration.

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. There is in principle a straightforward relation between both movement characteristics (and the vibratory energy as well) given by respective variables time integration or derivation. However experience shows (e.g. [2, 4]) that the errors introduced by real measuring systems are of such magnitude that errors exclude such an approach even on a short time scale. In practical situations it is advisable to complement one measuring system by another one and use data fusion [2].

In ground transportation the vehicles are in general subjected to traverse on 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 accelerations, which are superimposed onto the mechanical vibrations due to road/track undulations and/or engine influence. The vehicle chassis is subjected to the sum of both influences [3]:

i. Translatory acceleration a_t, caused either by traverse with non-constant velocity or traverse on a curvilinear trajectory with constant speed. In both cases forces acting on the vehicle chassis (considered in this context as a rigid body) are generated which are in general non-stationary.
ii. Vibratory acceleration a, which describes rigid body movement around some equilibrium. The relative displacement around the equilibrium point after some time is eventually zero.
iii. Inclination of the vehicle chassis plane in the Earth's gravitational field gives rise to additional horizontal acceleration components, which are indistinguishable from those due to straight traverse with a non-constant velocity or traverse on a curvilinear trajectory.

Any technical oscillatory system has limits on its relative displacement. Often it is implicitly assumed that the oscillation system equilibrium position is in the middle of the allowable travel and the extent of oscillations is such that no interference with the end stops, limiting the free travel (stroke), would occur. However translatory acceleration due to either straight traverse with non-constant velocity or inclination of vehicle chassis in respect to Earth's gravitational field would change the equilibrium position. The equilibrium may drift to the vicinity of the end stops. Hence the implicit condition would be violated and a more complicated approach has to be followed, accounting for possible non-linear effects. Hence it is important to be able to measure and discriminate between vibratory acceleration and translatory acceleration, in the way described above.

From experience (abstracting from impacts and crashes) it is known that the vibratory acceleration a observed in ground transportation is less than the standard gravity acceleration $g_n \approx 9.81$ m.s^{-2}. It is also well known that the practically measured accelerations are of random nature with harmonic components corresponding to some vehicle and/or engine characteristic features. The translatory acceleration frequency content extends down to sub Hertz frequencies, i.e. into the $1/f$ noise band of many sensors [1, 4, 5]. So measurement of the total acceleration a_T poses some practical problems. The use of standard piezoelectric accelerometers with their well-known inherent low frequency limit [1, 2] is not feasible. Hence other accelerometers types have to be considered, capable measuring also quasi-static acceleration. These can be classified, for example, in following way [1, 2, 7]:

i. Passive transducers, based on seismic mass displacement measurement, using capacitive, LVDT or piezoresistive transducing system, or alternatively, strain-gauges;
ii. Frequency compensated electrodynamic sensor, specially designed for measuring low intensity low frequency acceleration [8];
iii. So called servo accelerometers, working on force compensation principle.

Many of these sensors are nowadays made using contemporary semiconductor manufacturing technologies and are called Micro-Electro-Mechanical Systems (MEMS) [1-3]. Further on the use of one type of MEMS type servo-accelerometer for this purpose will be discussed and illustrated. This is a continuation and extension of previous work on application of servo-accelerometers for measuring of mechanical and vibrational quantities [4].

3. Measurement system description

The acceleration sensor is based on Analog Devices ADXL05EM3 sensor module, consisting of a three-axial MEMS accelerometer with measurement range ± 40 m.s^{-2}, whose output voltage is approx. 2.5 V for zero acceleration and its sensitivity is ≈ 50 mV/m.s^{-2}. The sensor module temperature is measured by a constant current source LM 334Z, whose output current has linear dependence on temperature and by appropriate adjustment can be made to correspond to 10 mV/°K. The acceleration module is mounted on a metal disk, which can be fixed into a rubber test disk for tests in field environment or in an enclosure for laboratory tests. The output signals are fed to an analogue conditioning unit amplifying the generated signals to fully utilize the ADC range of 0 V to + 5 V and 10 bit resolution. In line with above it is assumed, that in practical applications the acceleration would not surpass ± 10 m.s^{-2}, i.e. ± 0.5 V. Hence the input signals were amplified four-times for the x and y axis respectively, while two times for the z-axis, to be able to measure the gravitational acceleration. The sensor's DC bias was compensated by a DC compensating voltage in such a way that the conditioned signal DC component would remain at 2.5 V. No DC filtration is introduced; however a second order low-pass filter with cut-off frequency 100 Hz is implemented. It is fitted to the input connector of acquisition unit wherefrom the supply voltage is also drawn (see Fig. 1).

The acquisition unit is a specially build one, consisting of a micro controller and facilitating sampling of up to 16 channels at sampling frequency of 100 Hz and communicating the digitized data via standard RS 232C interface to the adjacent PC or a notebook at a rate of 56 kBaud [6]. This approach circumvents using a data acquisition board mounted in a PC and still facilitates the required data rate. Obviously nowadays a USB data acquisition unit with higher ADC resolution would be preferable; however essentially the same results would be obtained. Such unit is currently under development.

The four signals (three accelerations and the temperature sensor voltage) were sampled by a proprietary program and displayed in graphical form for check of consistency. These data were then subjected to analysis by scripts written in Matlab®. In Fig. 2 a typical measurement record is depicted, showing for clarity data for two axes only – z-axis and x-axis.

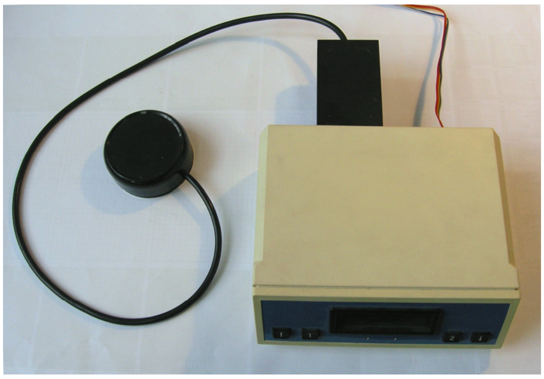


Fig. 1. Photo of the laboratory set-up.

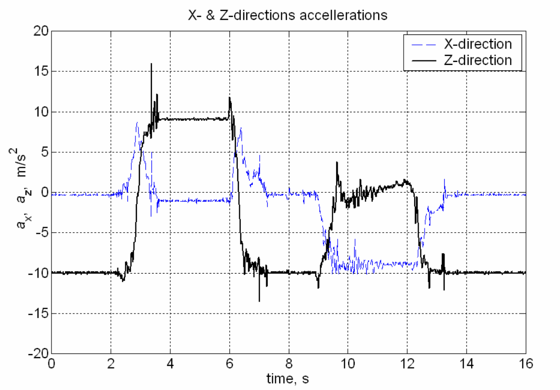


Fig. 2. Reproduction of the two acceleration signals for specific sensor movements.

From Fig. 2 following can be concluded:

i. On the beginning, when the measuring head is idle the measured values correspond to the assumed axis orientation;

ii. In the time interval between the 2nd s and 8th s the measuring head was rotated by 180 deg around the x-axis (turned upside-down), which is seen on the z-signal. In the x-axis record the starting and stopping jerks are observable. In both signals some higher frequency vibrations are observable, notably in the z-axis signal when hitting support at approx. 3.5 s;

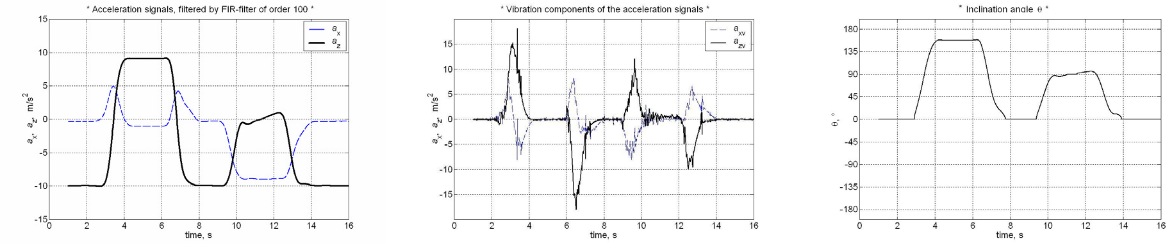
iii. In the time interval between the 8th s and 13th s the system was rotated by approx. 90 deg along the y-axis, the proper position attained at approx. 12th s, while the original position was at the 8th s.

iv. Afterwards the system was returned to the initial position.

4. Measured signal processing

From Fig. 2 it is seen that the position (rotation) can be easily detected, as well as the vibrations associated with the movement, however these two pieces of information have to be clearly discriminated. Further on some imprecision in head orientation is observable – in the time interval 4 s to 6 s the x-axis signal is not exactly zero, as is not the z-axis signal at 12 s. This also calls for some remedy – using an index head to align the sensor and measuring head axis beforehand. By precise rotation in Earth's gravitational field the measurement system calibration can be furnished [1, 2, 7].

Discrimination of the two pieces of information is furnished by digital signal filtration – the vibratory acceleration is the high frequency component, while the position information (rotation in the Earth's gravitational field in this demonstrative case) is the low-frequency component. A non-recursive digital filter with 100 coefficients was implemented; the filter cut-off frequency was chosen arbitrary at 0.50 Hz. The high frequency vibratory component is obtained by subtracting the low frequency component from the total acceleration. This is illustrated in Fig. 3.



a) The position information (Low frequency component)

b) The vibration information (High frequency component)

c) The angular information (Inclination θ)

Fig. 3. Result of decomposition of the measured signal, depicted in Fig. 2.

There is a correlation between Fig. 3a and 3c as expected. Fig. 3b illustrates the vibratory acceleration transients (jerks) due to accelerating and braking of the measuring head while rotating. Further measurements are needed to align the sensor/head combination, because, as seen from Fig. 3c, the full rotation did not furnish the expected value of 180 deg.

5. Results

The example illustrates the viability of use of a MEMS three-axis acceleration sensor with respective interface and a specific programme for measurement of low frequency low intensity acceleration. Analysis of gathered time data shows that from the time history the vibratory acceleration itself and inclination information (rotation in Earth's gravitational field) can be extracted. Further experiments are needed to test reliability of proposed measurement system in assumed harsh operating conditions.

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References

[1] Doebelin E. O.: Measurement Systems, Application and Design. 5th Ed., McGraw Hill, New York, USA, 2003.

[2] Ďado S., Kreidl M.: Senzory a měříci obvody. Vyd. ČVUT, Prague, Czech Republic, 1996.

[3] Anon.: Acceleration measurement, In Wiley Encyclopedia of Electrical and Electronic Engineering, Vol. 1 (2001). Webster JG, Editor. John Wiley & Sons, Inc., New York, USA 2001.

[4] Stein G. J., Šperka M.: Position measurement by micro-electronic accelerometer. In proceedings of IMEKO 2000*,* Vienna, Austria, ASMA, 2000, 385-388.

[5] Stein G. J.: Some recent developments in acceleration sensors. *Measurement Science Review*, 2001, 1: 183-186.

[6] Stein J., Chmúrny R., Koudelka M., Klán M., Dušek F.: Low cost data acquisition system for a mobile biological object. In proceedings of ADC Modelling - International IMEKO Workshop*,* Bratislava, SMS, 1996, 97-99.

[7] Stein J.: Microelectronic acceleration sensors. In proceedings of Measurement '95, Bratislava, Slovakia, Institute of Measurement of SAS, 1995, 44.

[8] Brincker R., Lagö T. L., Andersen P., Ventura C.: Improving the Classical Geophone Sensor Element by Digital Correction. Pinocchio Data Systems, Falkenber, Sweden, 2006.