Condition based maintenance using MEMS accelerometers: For faster development of IoT in railways

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ABSTRACT: Internet of things (IoT) has grown as electronic circuits have become cheaper, more efficient, smaller in size and received benefits from open hardware & software and mobile technology. As a result, IoT has the potential to make condition monitoring significantly cheaper to install and operate, which in turn can reduce the need of manual inspection of track and rolling stock. Thus, possible effects include improved safety and cost of inspections, as well as improvements in detectability, data quality, analysis, decision-making and ultimately availability. In this project, MEMS accelerometers have been assessed and a data acquisition unit has been developed based on open hardware and tested in a heavy haul track. The tested accelerometers ranges from a few euros to hundreds of euros in cost. Practical implications of the study are believed to be increased awareness of the benefits of MEMS accelerometers over piezoelectric accelerometers, with reference to the current cost difference.

Keywords: Internet of things, IoT, MEMS, accelerometer, track, S&C, turnout, sleeper, track geometry, heavy haul, railway

1 INTRODUCTION

Rail transportation is in many cases the most sustainable mode of transportation (ETSC, 2003; IEA–UIC, 2017), which makes shifting road and air transports to rail an important sustainability goal (EC, 2011). Sustainable transportation is also one of the 17 global sustainable development goals of United Nations (UN, 2015). However, a shift in transportation requires that railways reliability is maintained or even improved, which can be achieved by expanded condition monitoring. Nevertheless, it requires that sensors, microcontroller and connectivity is cheap, especially in a large scale, as envisioned by the term Internet-of-things (IoT). As an example, a traditional piezoelectric transducer for measuring acceleration (vibration) costs €500–1 000; only the sensor. This would be a very large cost if one for example intend to monitor switches & crossings (S&Cs), e.g. the Swedish rail network includes 12 000 S&Cs. However, in the last decade, electronic circuits have become cheaper, more efficient, miniaturised and received benefits from open hardware & software and mobile technology. Especially micromechanical systems (MEMS) has led to price reduction on the sensor side. This development has been led by the smartphone and car industry. A MEMS accelerometer can cost one percent of a piezoelectric model, e.g. €5 instead of €500, but with some difference in specifications.

In this project, MEMS accelerometers have been assessed and a data acquisition unit has been developed based on open hardware and tested at Malmbanan, the Swedish Iron Ore Line. Accelerometers have the potential to be applied wherever there is a discontinuity in the railway track, such as S&Cs, rail joints, bridges, tunnels and culverts. In this study, the developed prototype is tested on a sleeper at an S&C’s frog (common crossing). The aim is to measure the vertical sleeper displacement as rail wagon axles pass the rail sleeper, to assess the substructure stiffness and geometry degradation.

Due to the low axle passage frequency, <10 Hz, which is the range of geophones, the requirements on the MEMS sensor and analogue to digital converter (ADC) are high. The application also has a higher power consumption and puts higher demand on connectivity, compared to simple data loggers that are common in an IoT setting. It is also wished that the measurement unit is battery powered so it in can be easily deployed by maintenance contracts, for example before and after failures.

In Section 2, the requirements for a data acquisition unit for measuring rail sleeper displacement is specified. Thereafter, a prototype is tested in lab and field, followed by results, discussion and conclusions.

2 REQUIREMENTS FOR THE DATA ACQUISITION UNIT

The main function of the data acquisition unit is to measure sleeper displacement from train wheel axle passages. The axle passage frequency of a train are often less than two hertz and even below one hertz, which puts high demands on the sensor and analogue to digital converter (ADC). The hardware requirements are gone through starting from the power source and end with the connectivity.

2.1 *Power source*

A battery powered solution is preferred, so as to have a mobile unit, e.g. for measuring before and after maintenance work. Many batteries becomes more or less inoperable at sub-zero temperatures. However, lithium batteries can withstand temperatures down to −20°C and even −40°C. Lead–acid, rechargeable Li-ion batteries and Li-Po batteries are not suitable due to poor low temperature performance or high discharge rate.

2.2 *Wake-up function*

Wake-up function based on a MEMS accelerometer has been demonstrated in track to be effective; see Figure 1. The figure shows a frame from a video filming three MEMS wake-on-shake units with ATTiny2313A (microcontroller) and ADXL362 (MEMS accelerometer) from Sparkfun. The video frame is at the point in time when the circuits are woke up by the train vibrations, and then turns on LEDs (blue pointing arrows).

Figure 1: Test of three MEMS wake-up circuits of the same model (Lindqvist, 2017).

2.3 *Microcontroller*

The microcontroller of the hardware can be either a dedicated programmed microcontroller or a more generic microcontroller, such as Arduino-based microcontrollers or Raspberry Pi computers. Whichever chosen, the reliability of the system depends on how thoroughly the uploaded code have been tested (Schryen, 2011). Ampere consumption of some common microcontrollers is shown in Table 1.

Important microcontroller features for rail applications to consider includes power consumption, inputs/outputs (analog and digital), clock speed, flash memory, SRAM, EEPROM, parameter/firmware updates, ADC and reference voltage. The flash memory is the program/sketch space. The SRAM is where the sketch creates and manipulates variables when it runs. The EEPROM is a long-term memory that can be used by the programmer.

An ATmega2560 microcontroller is sufficient for a sleeper application as it can sample up to at least 1 000 samples per second (SPS) and can collect data for 20 seconds to a few minutes continuously, without

Table 1: Ampere consumption of some common microcontrollers.

	Arduino Uno	**Arduino Nano**	**Arduino Mega 2560**	**Raspberry Pi 3 B**	**Raspberry Pi 1 B+**	**Raspberry Zero**
Microcontroller	ATmega328p	ATmega328	ATmega2560	BCM2837	BCM2835	BCM2835
Ampere consumption [mA]	144[1]	19[2]	79[1]	340[3]	190[3]	100[4]
Ampere consumption – 2nd source	47[5]	35[1]	53[6]	400[4]	330[4]	
Operating voltage [V]	5	5	5	5	5	5
Clock speed [MHz]	16	16	16	4x1.2 GHz	4x1.2 GHz	1 GHz
Flash memory [kB]	32	32	256			
SRAM [kB]	2	2	8	1 GB	1 GB	512 MB
EEPROM [kB]	1	1	4			
Microcontroller	**ATmega328p**	**ATmega328**	**ATmega2560**	**ESP32**		
Ampere consumption [mA]	0.2 at 1 MHz, 1.8 V[7]	0.2 at 1 MHz, 1.8 V[7]	11 at 8 MHz, 5 V[7]	30-50 at 240 MHz[8]		
	5.2-9 at 8 MHz, 5 V[3]	5.2-12 at 8 MHz, 5V[7]	20 at 16 MHz, 5 V[7]	20-25 at 80 MHz[8]		

[1]tlextrait.svbtle.com, [2]arduino.cc, [3]Pi-Top at Youtube (no peripherals), [4]raspberrypi.org (no peripherals)
[5]gadgetmakersblog.com, [6]tpcdb.com, [7]Microship (datasheet), [9]Espressif Systems (datasheet)

the need to empty the SRAM to a microSD, which gives a few milliseconds interruption. Note that the internal reference voltage of the ATmega has low accuracy, so a voltage reference diode should be supplied if the ADC requires an external reference.

An advantage of having a dedicated microcontroller code is efficiency, while an advantage of an Arduino-based microcontroller can be coding simplicity; see advantages of open source in Pearce (2012). The choice of microcontroller strongly depends on the extent of implementation; a few sensors or thousands.

2.4 *MEMS-accelerometers*

Rail sleeper displacements can be represented with a simple harmonic motion. The acceleration is proportional to the displacement; $a = -\omega^2 x = -(2\pi f)^2 x$. A sleeper displacement amplitude of two millimetres at two hertz thus gives an acceleration of 3.2 m/s^2. Four hertz gives 12.6 m/s^2, or 1.3 g. In practice, it is a range of frequencies that are excited in mechanical systems. The acceleration can exceed 100 g when measuring directly on rails. From field measurements, it is found that in general, a few hundred hertz sampling rate and 10–20 g range is sufficient for measuring at the sleeper of a SC’s frog. However, some train axles at S&C frogs can result in vertical accelerations of more than 20 g..

In this study, a number of MEMS and piezoelectric accelerometers were tested; see Table 2. Dytran 7509A4 gives satisfactory results at frequencies down to 1 Hz. Another interesting MEMS accelerometer is ADXL354, considering the low noise density, but the sensor need to be tested further before performance and reliability can be evaluated properly. The results of this study is of ADXL326 and Dytran 7509A4.

The range, bandwidth (BW), sensitivity and noise are all connected to the mechanical design of the MEMS; see Table 3. Therefore, it may be advantageous to have two sensors with different range (±g) and/or several of the same to cancel out some of the noise.

2.5 *Analog to digital converter (ADC)*

The most important features of an ADC is the sampling rate (samples per seconds; SPS) and the resolution (bits). As an example, 10 bits equals 2^10 = 1024 divisions of the voltage signal on the y-axis. Low frequency measurements, like sleeper movement, requires a precision ADC, i.e. ≥14 bits, but less sample rate. In this study ADS1115 of 16 bit, 860 SPS, I2C interface and with an internal voltage reference, is used.

2.6 *Data storage*

The service life of a flash memory depends on whether it has wear levelling or not. The maximum number of erase cycles of a single memory segment is counted in thousands, and for a flash memory with wear levelling, it is from 100 000 to 1 000 000 cycles. The number of erase cycles of a flash memory with wear leveling depends on the size of it. An over-sized memory can therefore be used for extended life.

2.7 *Connectivity*

Mobile network enables infrastructure managers, supply chain and researchers to easily install an all-in-one data acquisition system for temporary or long-term monitoring in track.

GSM/GPRS is the most common mobile technology used today, with both advantages and disad-

Table 2: Tested accelerometers.

Modell	**Range [+/-g]**	**Noise**	**BW [Hz]**	**Impact [g]**	**Manufacturer**
ADXL326, MEMS	16	$300\ \mu g/\sqrt{Hz}$	0,5-550, z-axis	10000	Analog Devices
ADXL354, MEMS	8	$20\ \mu g/\sqrt{Hz}$	0–1500	5000	Analog Devices
7509A4-05, MEMS	25	$25\ \mu g/\sqrt{Hz}$	0–1500	5000	Dytran
8315A100, MEMS	100	$1.25\ mg/\sqrt{Hz}$, 0–100 Hz	0–1000	6000	Kistler
8703A50, Piezoelektrisk	50	–	–	–	Kistler

Table 3: Dytran datasheet 7509A4-xx.

Model	**Range [+/-g]**	**BW [Hz]**	**Sensitivity [mV/g]**	**Max impact [g]**	**Noise [$\mu g/\sqrt{Hz}$]**
7509A1-xx	2	0–400	200	2000	5
7509A2-xx	5	0–600	800	2000	7
7509A3-xx	10	0–1000	400	5000	10
7509A4-xx	25	0–1500	160	5000	25
7509A5-xx	50	0–2000	80	5000	50
7509A6-xx	100	0–2500	40	5000	100
7509A7-xx	200	0–3000	20	5000	200
7509A8-xx	400	0–4000	10	5000	400

vantages. A major limitations is its power consumption. When sending, current peaks can reach 2 amp. Therefore, cellular IoT technology has been introduced. Three such technologies are LTE-M (LTE Cat-M1), NB-IoT (LTE Cat-NB1) and EC-GSM-IoT. Liberg et al. (2017), authors at Ericsson company, describes LTE-M as '*intended to achieve low device cost, deep coverage, and long battery lifetime, while maintaining capacity for a large number of devices per cell, with performance and functionality suitable for both low-end and mid-range applications for the IoT*'. Further, they describe NB-IoT as '*intended to achieve deployment flexibility, ubiquitous coverage, ultra-low device cost, long battery lifetime, and capacity sufficient for supporting a massive number of devices in a cell*'. Thus, the technologies focus on two somewhat different areas within IoT. LTE-M has higher data rates than NB-IoT and has also the ability to shift without interruption between mobile stations. See Liberg et al. (2017) for a detailed description of the technologies. As the data rate determines the transmission time, and thus, the power consumption, the suggested wireless solution is LTE-M when applicable. In this study, the SIM900 GSM/GPRS shield from Seeed Studio is used. Typical power consumption for GPRS in Tx, such as SIM900 module, is 250–500 mA at 3.3 V; 0.83–1.65 W.

3 DESIGN OF PROTOTYPE

Following the requirements, a prototype has been designed as per Table 4 and Figs 2 and 3. Its function is as follows: The voltage regulator powers the wake-on-shake unit, which turns on the relay to the Mega 2560. The Mega 2560 collects data from the accelerometer via the ADC. The accelerometers have analogue outputs, and thus, a 2nd order low-pass filter is applied, of 33 kΩ and 100 nF (Milne et al., 2016). The sampling speed is 630–650 Hz. The data is temporarily stored in the SRAM, and saved to a txt-file on a mircoSD card after a specified number of seconds. After the data collection is completed, the stored txt-file is uploaded to an ftp-server. When the file has been uploaded, the unit turns off itself through a signal cable to the wake-on-shake. With a 9 Volts standard battery, the unit can be in standby mode for about 200–300 days. The Arduino Mega 2560 microcontroller was selected over Uno as the Mega has a flash memory of 256 kB and a SRAM memory of 8 kB, compared to Uno that has 32 kB and 2 kB. The clock DS1307 is used to give the data a time stamp. However, since the ftp-server gives the txt-file a time stamp, the clock could be removed. Similarly, the microSD could also be removed. The SRAM is sufficient for about 40 seconds at 600 Hz; 128 Hz is enough for sleeper monitoring (Stenström et al., 2018).

A corresponding printed circuit board (PCB) has also been designed for robustness; see Figs 4 and 5.

Table 4: Specification of prototype.

Subsystem	**Product**
Power source	Lithium battery
Wake-up function	Wake-on-shake: ATTiny2313A and ADXL362
Microcontroller	Arduino ATmega2560
Accelerometer	Dytran 7509A4 and ADXL326
ADC	ADS1115, 16 bit, 860 SPS and internal V_{Ref}
Data storage	MicroSD
Connectivity	SIMCom SIM900 GPRS module
Clock	DS1307 RTC Module
Voltage regulator	MP1584

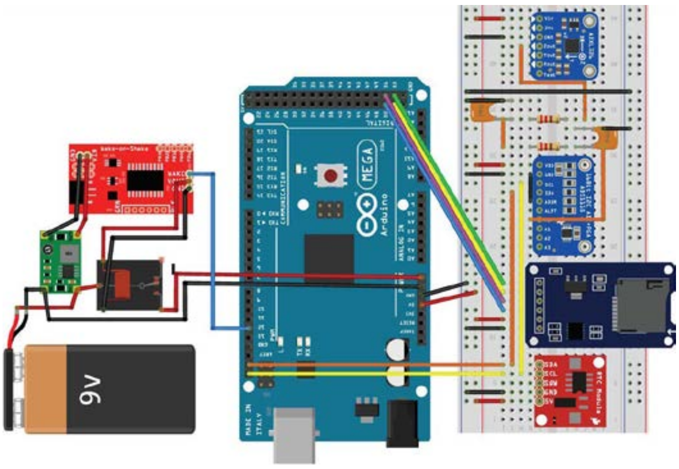

Figure 2: Breadboard schematic. The SIM900 shield is not added. Designed in Fritzing.

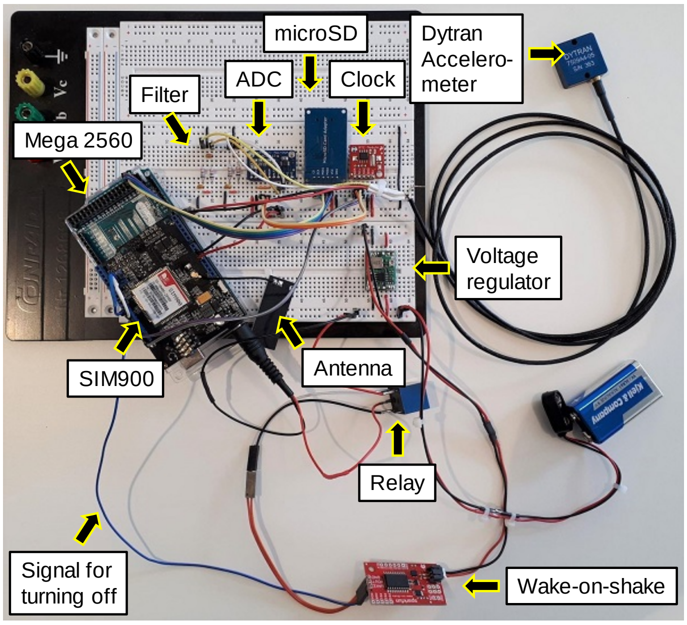

Figure 3: Breadboard prototype with Dytran accelerometer.

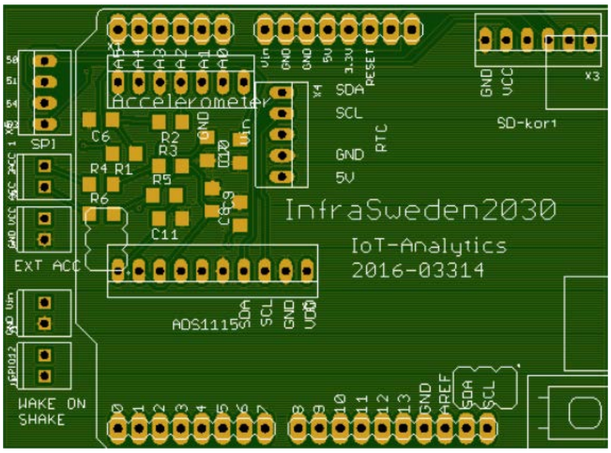

Figure 4: PCB.

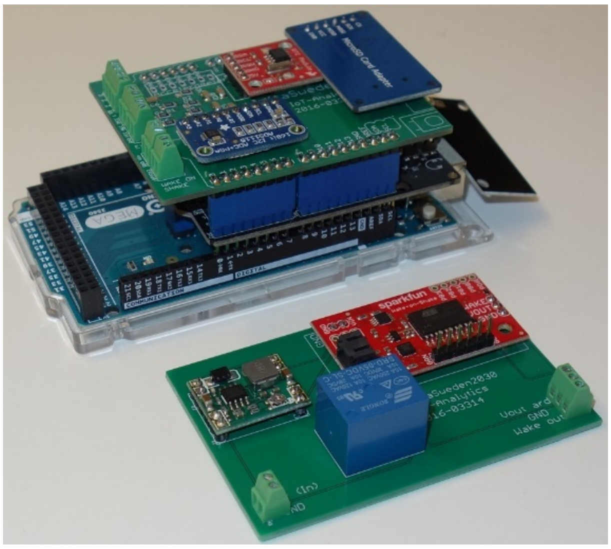

Figure 5: Mega 2560, SIM900, PCB with components and wake-on-shake unit.

4 RESULTS AND DISCUSSION

The prototype has been tested with accelerometers ADXL326, costing about €5, and Dytran 7509A4, costing about €700. The tests begin with measuring the noise of the transducers by measuring static 1 g. Both the sensors are within specification as seen in Table 5. The sensors are then calibrated by measuring 1 g and –1 g, and thereafter lab and field tests are carried out.

Table 5: Measured noise.

Model	BW in Hz	Specified $\mu g/\sqrt{Hz}$ rms	Calculated g	Measured g_{rms}
ADXL326	550	300	.007 ≈ .01	.0067 ≈ .01
Dytran 7509A4	1500	25	.00097 ≈ .001	.00063 ≈ .001

4.1 *Laboratory test*

Lab tests have been performed on a sine wave generator consisting of the sensor mounted on a cantilever beam, which in turn rest on an eccentric tap of a rotating cylinder. See Fig. 6 for the principle. The amplitude of the sine wave generator is about 1.8 mm.

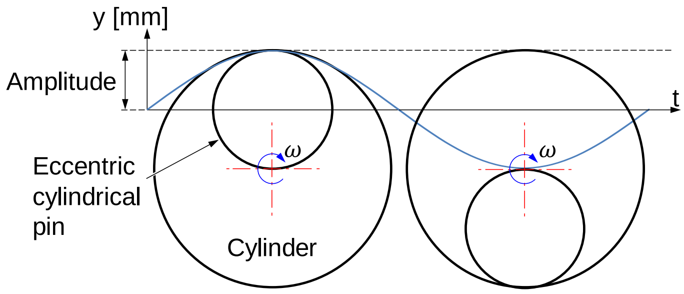

Figure 6: Principle of the sine wave generator

Measurement results are given in Figure 7. The results are based on the min and max amplitude of 20 seconds data collection. The acceleration data has been integrated two times to attain displacement (Fig. 8) using a second order digital Butterworth filter with a band-pass of 1–8 Hz. It is seen that the mean value are quite similar between the two sensors, but the spread in the data is larger for the cheaper sensor.

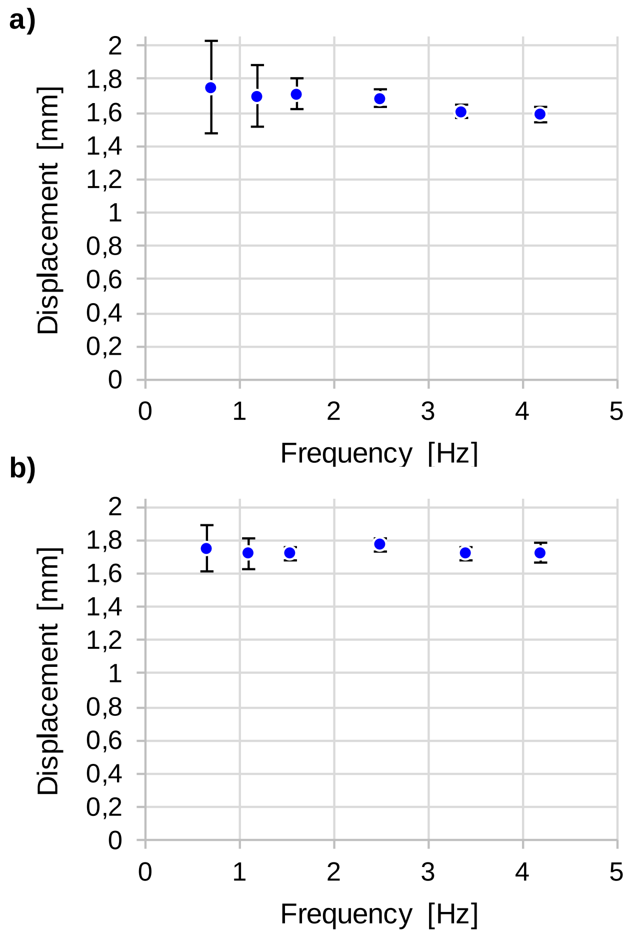

Figure 7: Arithmetic mean and standard deviation of max and min amplitudes on sine wave generator. a) ADXL326 and b) Dytran 7509A4-05.

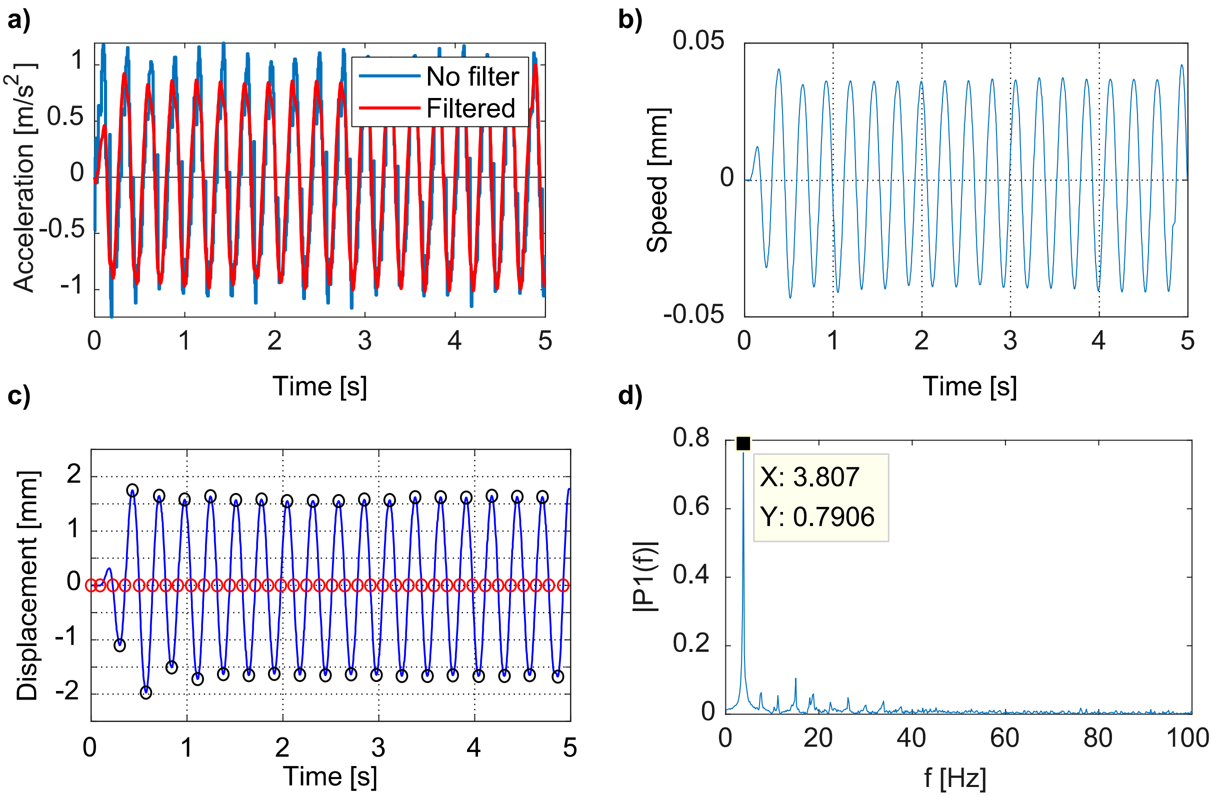

Figure 8: Example data of Dytran 7509A4-05 collected at 3.8 Hz from the sine wave generator, with integration to displacement. In c), the red circles are crossings of the x-axis and the black circles are min and max values.

4.2 *Field test*

Field tests were carried out at Malmbanan at a sleeper of a common crossing (frog); see Figs 9 and 10. The results shown in Fig. 10 is for a train consisting of 30 tonne iron ore wagons. It is seen that the spread in the results are larger than that of the lab tests, which likely is due to the larger spectrum of frequencies excited. The high g-forces of the iron ore train is not seen in the signal due to the analogue filter. The results are in line with Milne et al (2016). However, it is not clear what type of ADC Milne et al. used, and their study was from 2 Hz and higher.

Detailed results and Arduino code are given in Stenström et al. (2018). Parallel measurement at Trafikverket is also found in Nissen (2018).

Figure 9: Sensor mounting.

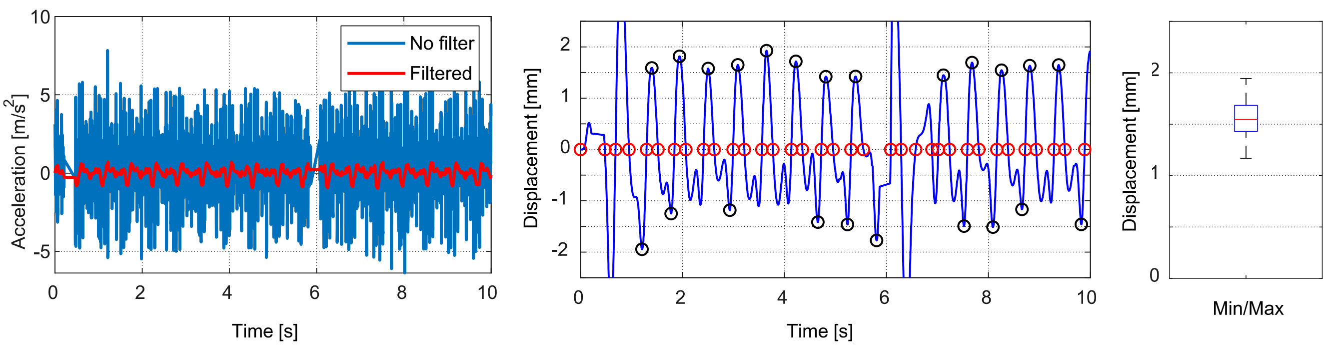

Figure 10: Measurement results of iron ore train wagons. The median displacement is abot 1.6 mm.

5 CONCLUSIONS

In the lab environment, the absolute relative measurement error of Dytran 7509A4 and ADXL326 were 1.7–4.4 % and 2.8–11.7 %, respectively (Fig. 7). Field test results show significantly larger spread in the data. In the boxplot of Fig. 10, 50 % of the max/min values are found within 1.36–1.69 mm. This can be compared with the lab measuremnet, where 50 % of the min/max values are found within 1,58–1,65 mm (values of Fig. 8c).

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