POSSIBILITY OF USE A LOW-COST MEMS TECHNOLOGY FOR MONITORING STRUCTURAL ELEMENTS OF BUILDINGS

Bartłomiej Ćmielewski [1]

Abstract

In modern world when building are bigger and bigger there is necessity to monitoring such objects and adjacencies area during the construction process. In a very close range to them, a deep trenches cause often movements of a water level. This movements can induce a subsidence of a close range old buildings which may lead to cracking walls or in the worst case scenario to collapse it. Other thing is a disregard a force of nature (snow, wind, rain). There were several building disasters in past few years. The most famous is collapsed roof in Katowice Trade Hall at the time of 56th National Exhibition of Carrier Pigeons in January 2006. At the time of the disaster there was 700 people inside, 65 of them was dead as well as more than 170 injured.

So there is necessity to create cheap, accuracy, and reliable system to monitor and warning the building manager in case of crossing alarm thresholds. In last few years the MEMS technology become very popular, dimensions and cost is attractive. In this paper author will test such devices for use in the warning systems.

Keywords

MEMS, monitoring, building construction, beam

1 INTRODUCTION

At the time of writing this article in press had appeared an article about "Evacuation in Torun school. Gym started to collapse". 65 people were evacuated from the School of Engineering and the Environment in Torun. Cracks appeared at morning on the object beams. At a time when the small parts of gym ceiling began to fall off from the concrete elements on the floor, the teachers ordered the evacuation.

For buildings where there is a long distances between the columns supporting the roof structure, the object monitoring should be obligatory. Construction of these elements may be made of wood, steel or reinforced concrete.

Classic monitoring systems are expensive. Therefore, in the article author will check a possibility of use a MEMS to monitor those structures [6,8]

For such objects interact environmental conditions, the most important are four of them: sun, wind, snow, temperature (in and outside). Each of these factors make an effects on the facility and it deflection (Figure 1). Especially dangerous is snow - causing additional load of the structure and high changes of temperature between day and night. The thermal stress can sometimes cause a bigger displacement of the beam than mechanical.

In European construction law, depending on the type of construction are different acceptable beam deflection.

In case of steal construction elements the maximum deflection is in standard: EN 1993-1-1:2005 "Eurocode 3. Design of steel structures. General rules and rules for buildings", there is written that it should not exceed equation 1.

$$\Delta f < L/250 \tag{1}$$

where: L is a span of an element.

In case of concrete elements the deflection of reinforced concrete elements is affected by many factors, most of which is not included into calculation, for the ceiling beams with a span of less than 6.0 m, permissible deflection is:

$$\Delta f < L/200 \tag{2}$$

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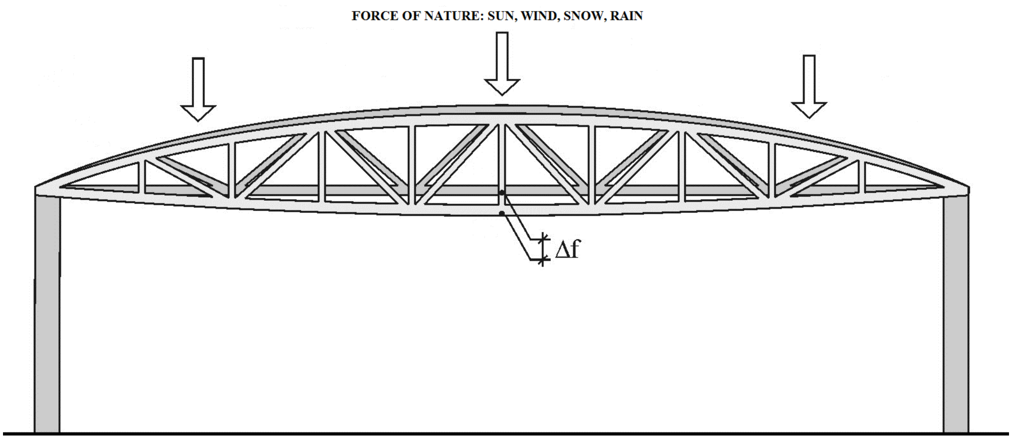

Fig. 1. *Simple vertical cross section of a hall, and force of nature interacting on construction (based on Kowalski 2007)*

The cost of classic geodetic monitoring installation often exceeds the project budget. In this paper an author want to pay attention to the possibility of use a small three-axis low-g MEMS accelerometers. It allows on calculating the direction in each direction from the vertical line.
Using several measuring devices, it is possible to create an active control-measurement network. To investigate in real-time all construction building elements by placing devices for example on beams and columns.
To check a possibility of use a MEMS, were conducted two experiments: on tachymeter and beam.

2 LABORATORY TESTS

To test a low-cost MEMS elements was developed a prototype of a testing stand and a device using a digital three-axis accelerometer [2]. To calculate from it a angle value we need to use simple equation 3, 4, 5 [1,4,7]. The visualization of a device angles are presented on Figure 2,vertical inclination ϕ can be decomposed into two component angles θ, ψ (pitch and roll).

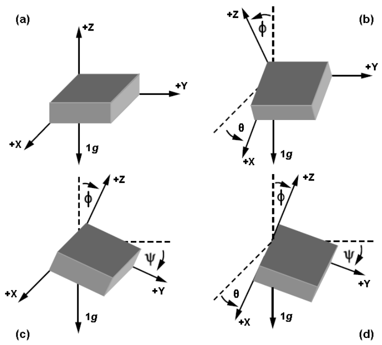

Fig. 2. *Angles of independent inclination sensing: g – gravity acceleration,*
ϕ - deviation from zenith, θ - deviation from X axis, Ψ - deviation from Y axis (Fisher Ch.J.)

$$\theta = \arctan\left(\frac{A_{xOUT}}{\sqrt{A_{yOUT}^2 + A_{zOUT}^2}}\right) \qquad (3)$$

$$\Psi = \arctan\left(\frac{A_{yOUT}}{\sqrt{A_{xOUT}^2 + A_{zOUT}^2}}\right) \qquad (4)$$

$$\phi = \arctan\left(\frac{\sqrt{A_{xOUT}^2 + A_{yOUT}^2}}{A_{zOUT}}\right) \qquad (5)$$

where: A_{xOUT}, A_{yOUT}, A_{zOUT} – raw acceleration reading obtained from the accelerometer

Used accelerometers should be first calibrated for elimination of 0 offset and non-linearity. For this purpose, a 12 parameters calibration was performed.

2.1 Tests with tachymeter

To test the accuracy, repeatability, stability readings was used Lecia TCRP1203 motorized total station (Figure 3). For his operating, the author developed a program based on protocol GeoCOM. This allowed it to remotely adjust the angle in a given interval of time.The aim was to verify that a slow movement can also be read and interpreted correctly. The first test was to check the stability of the reading. By 4 months, was left the device in more or less invariant environmental conditions. This allowed for a check a stability of readings which are at the level of +-0.15mrad.

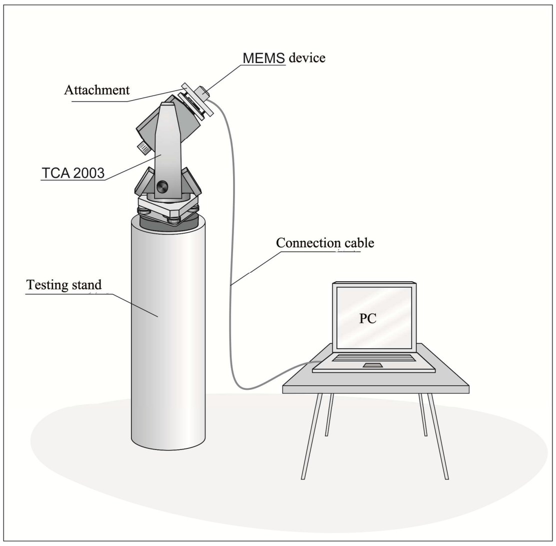

Fig. 3. *Laboratory experimental stand (Ćmielewski B. et al. 2011)*

The second test was to check the accuracy. In the program were setup the following parameters:

- the range of $\pm 1^g$;
- move 0.0010^g / 1.5h.

The results is presented in Figure 4. It can be seen the test range is characterized by a linear course.

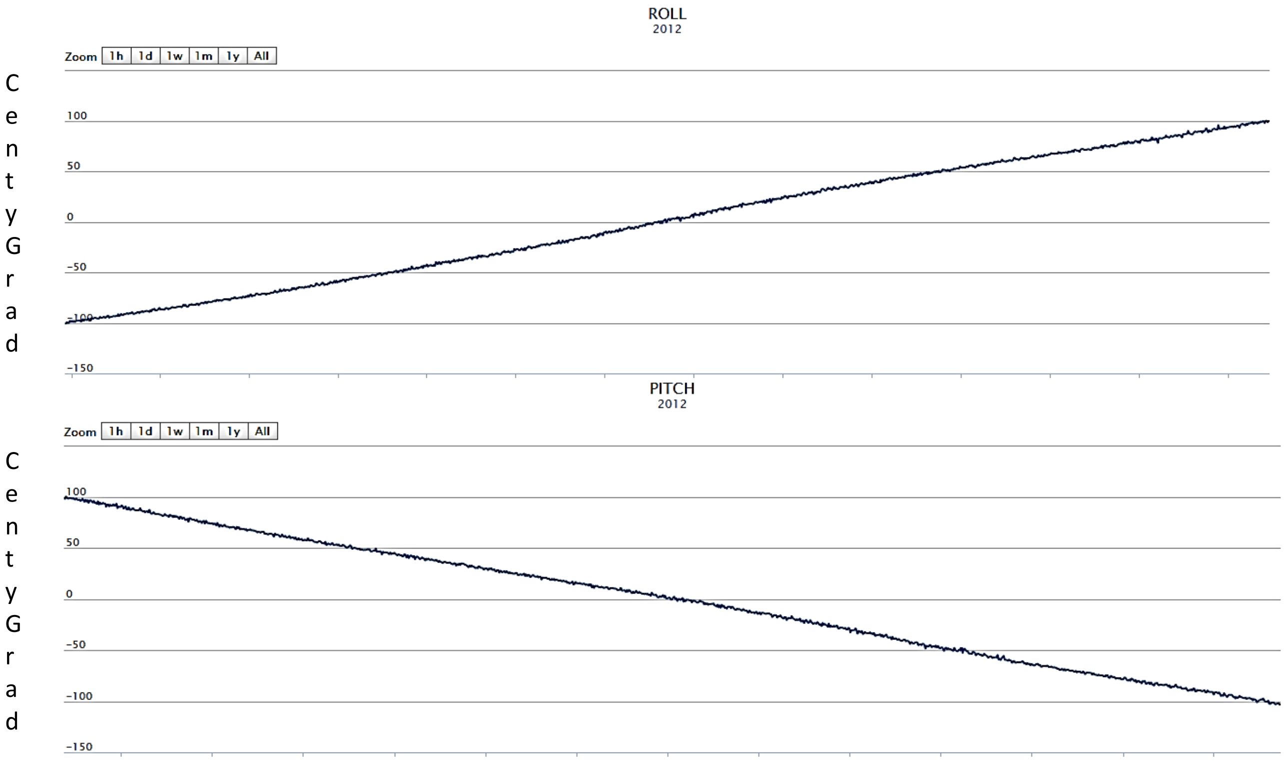

Fig. 4. *Accuracy $\pm 1^g$ with calibration in slow motion (duration 2 month, changes 0,0010g/1,5h)*

The last thing was test of the repeatability.

The total station was setup vertically, and in the sample of 1000 times, had been tilted in one side by the angle of 25^{g}, then returned to vertical position, and then moved again on the other direction by the same angle. The test was performed in both axes. The result are presented in the table 1.

	$-25^{g}0000$		$0^{g}0000$		$+25^{g}0000$	
Series of n = 1000	Angle X axis [^{g}]	Angle Y axis [^{g}]	Angle X axis [^{g}]	Angle Y axis [^{g}]	Angle X axis [^{g}]	Angle Y axis [^{g}]
Minimum	-24.9975	-24.9988	-0.0032	-0.0051	24.9962	24.9941
Maximum	-25.0053	-25.0084	0.0045	0.0017	25.0026	25.0018
Average	-25.0014	-25.0036	0.0007	-0.0017	24.9994	24.9980
(Max-Min)	-0.0078	-0.0096	0.0077	0.0068	0.0064	0.0077
Standard deviation	0.0045	0.0053	0.0038	0.0044	0.0036	0.0041

Tab. 1. *Repeatability test readings obtained.*

2.2 Tests on beam

Next test was performed on a beam under the press. On both side of beam, was installed two inclinometers and MEMS devices. Under the beam were prepared a five points to control by the precision leveling. Also were used two linear displacement transducers connected with press.

Fig. 5. *Experimental stand with beam.*

The press was setup to make a linear displacement on the following steps: 1, 2, 3, 4, 5, 10, 20, 40, 60, 0 mm. In Figure 6 is shown the relationship between the applied force and the displacement from the PTX sensor.

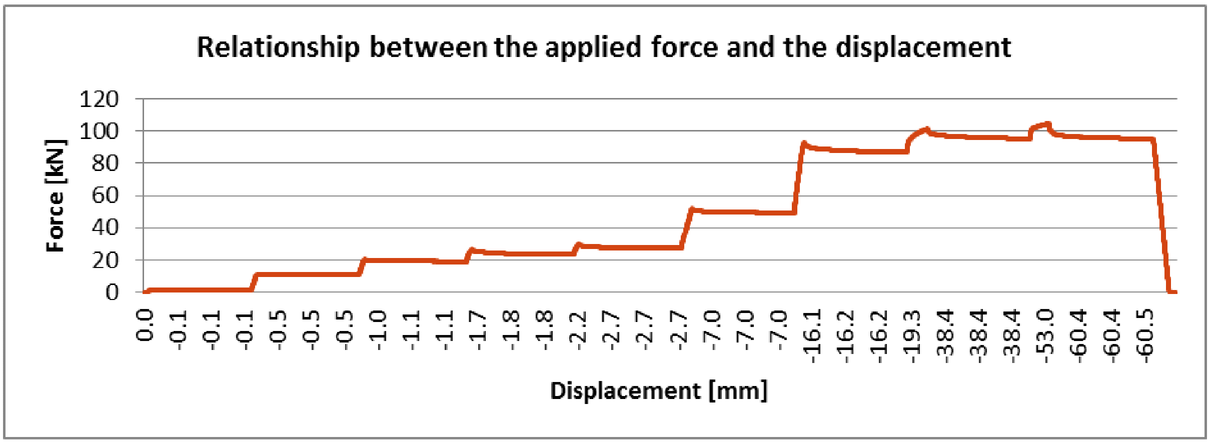

Fig. 6. *Relationship between the applied force and the displacement.*

The cracks suggesting exceeded load capacity of concrete appeared at a step 6, a further load is taken over by a reinforcement inside the beam. Complete destruction of the beam, in the penultimate step, when the displacement was about 60mm.

The results obtained by the prototype MEMS device is presented in Figure 7 and in Table 2.

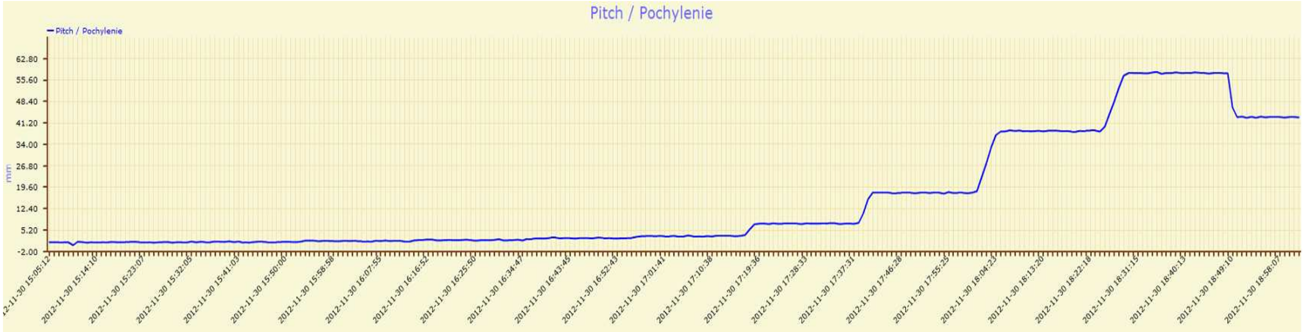

Fig. 7. *Calculated displacement in mm in the center of beam.*

In the early stages of the investigation when the displacement is to gradually and slowly 1-5mm, it's hard to notice changes in the graph. When there have been significant increases in the value of displacement 5-10-20-40-60mm, sudden changes can be seen on the chart. However, when we look the first stage of the study closely we can see slow changes. When we look at the Table 2, it is easier to analyze it.

3 SUMMARY

Table 2 shows the measurement data. The results of the techniques gave a similar results.

Load phase	Displacement [mm]				
	Setup on press	DNA03	PTX	Nivel	MEMS
0	0.00	0.00	0.00	0.00	0.00
1	1.00	0.30	0.07	0.56	0.13
2	2.00	0.73	0.55	1.05	0.41
3	3.00	1.27	1.05	1.60	1.21
4	4.00	2.06	1.75	2.32	1.94
5	5.00	2.94	2.63	3.29	2.83
6	10.00	7.74	7.03	6.77	6.87
7	20.00	17.69	16.18		18.23
8	40.00	41.63	38.36		40.70
9	60.00	65.55	60.42		61.40
10	0.00	47.31	43.92		46.35

Tab. 2*. Comparison of obtained results.*

Inclinometer used in the study, in the seventh-step of test, exceeded its range, which resulted in the lack of further data.

In the first phase of the study, none of the measurement techniques corresponds to the movements of the press. This is due to the individual elements of the press - joint, and a part of the load transfer changing force from focused on the spread, in these parts in the first stages of squeezing has been the clearances elimination.

Measurements made by precise leveling, differ a little bit from the other techniques. When the beam was squeezed noticeable also was twist in readings from Nivel as well as with MEMS. Since sensors PTX and MEMS devices are aligned on the same side of the beam, it can be seen better results correlation. However, result from the precise leveling, due to the opposite location of measurement points on beam, are differ, because of the rotation of the test object.

Figure 8 shows the graphical interpretation of Table 2.

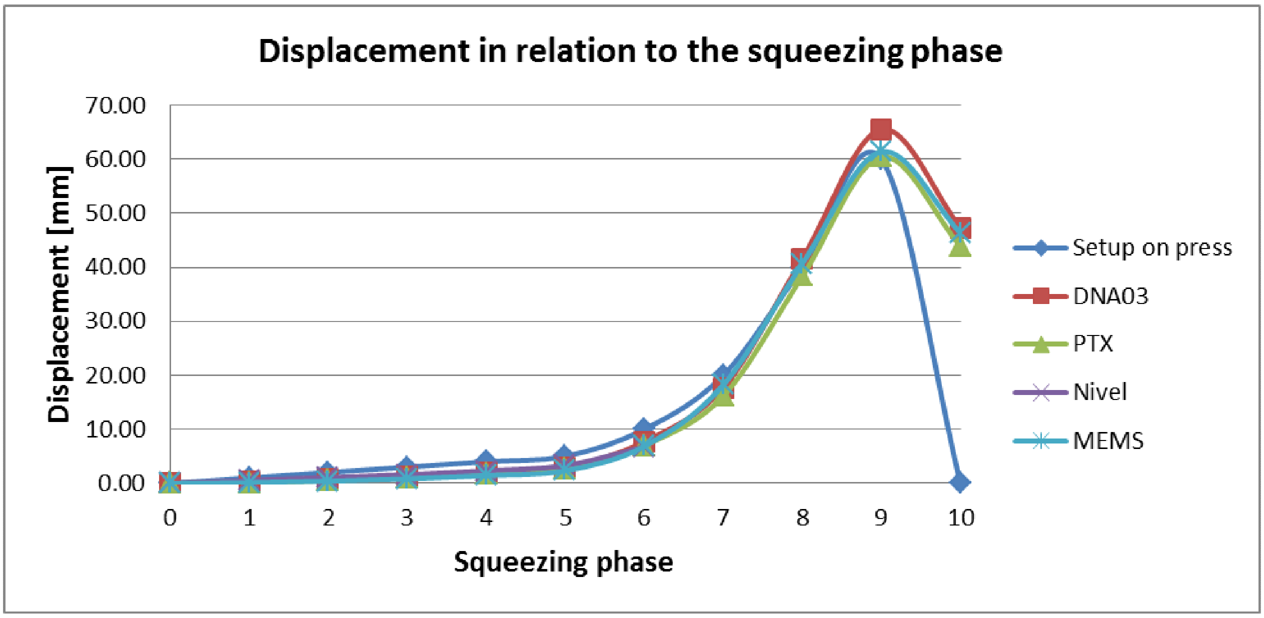

Fig. 8. *Comparison of results*

We can notice that the low cost MEMS accelerometers can be used in early warning systems, but for higher precision the classic geodetic survey must be performed.

4 CONCLUSION

Components used in the prototype produced the following results:
- 0.15mrad stability of readings
- repeatability of readings better then 1^c,
- accuracy 0,3mm/m.

All techniques give a similar result, which suggest that MEMS technology can find a place in engineer surveying. Installation costs are relatively low (one set of device cost about 6€) compared to traditional real-time monitoring techniques it is very cheap. System to visualization data from devices need only server with free SQL database. If the SMS warning messages module is necessary also modem GSM with SIM card is required.

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