IDENTIFICATION OF PENDULUM OSCILLATION PARAMETERS USING MEMS ACCELEROMETER

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The article deals with analysis of problematic focused on identification of pendulum oscillation parameters. Theory is based on mathematical description of physical pendulum with real damping and kinematics theory. The article describes experimental laboratory model of physical pendulum with precise construction. Simultaneously it describes wireless sensor system with dual axis MEMS accelerometer, which is used for components accelerations measurement of free oscillating pendulum arm. The article presents methodology for solution which is based on expression of boundary conditions and follows prediction of actual angle displacement in next period of oscillation. Experimental measurement and its subsequent evaluation determine properties and usefulness of principles of measurement and evaluation in purposes of control and visualization. Final evaluation offers suggestions for future improvement of described method.

KEYWORDS

physical pendulum, damped oscillation, mems accelerometer, wireless sensor system

1 INTRODUCTION

In many cases of engineering practice we encounter with the problem of loosely hanging body manipulation such as load of gantry or tower crane. Manipulation parts can be except the conventional material also containers with molten metal used in metallurgical plant. In this case the manipulation has to be controlled by precise technological procedure.

In the process of handling is the crane's manipulation base (support) driven by motor acceleration. Angle displacement from base vertical position originates by virtue of load inertia. This displacement actuates the tangential component of gravitational acceleration, which keeps pendulum arm in permanent but damped swinging motion. So the amplitude of this motion is the dominant limiting factor for handling speed and its acceleration. And therefore measurement of pendulum oscillation, amplitude (and of course frequency) and all kinematical parameters can be used to ensure handling quality in the automation process. Manipulation requirements also include conditions for compliance of technological procedure or prevention of collision and emergency states.

Many relative principles of sensor operation have been created for measurement of angular displacement [Dado 1996] or body (robot) estimation orientation [Music 2010], [Bozek 2015a, 2015b]. Actual trend in the sensor technology is using of MEMS sensors. Application of absolute sensors on the oscillating object allows measurement of motion parameters by acceleration measuring. The parameter estimation of inertial sensors in related topics is well known and described in scientific papers [Saxena 2010], [Lai 2011], [Schuozhi 2012].

In an ideal case we can consider that all oscillation parameters lie in a vertical plane. Such measured system could require a biaxial accelerometer employment. The problem of mathematical explanation of acceleration components collides with the separation of dynamic and static components. Kurilla [2010] mentioned that such problem is insolvable in term of inertial navigation. And therefore the article deals with interdisciplinary analysis of pendulum oscillation parameters tolerating some degree of evaluation inaccuracy.

2 MATERIALS AND METHODS

The design of mathematical model is based on the analysis of dynamics and kinematics with respect to the inertial measuring system. Mathematical model serves for composition of computing algorithm that will be applied into specialised software for data acquisition and evaluation. A mathematical model of physical pendulum is a formula for expression of actual angle course ϕ directly from components of sensed acceleration a'_t and a'_n. The kinematic increments of these components carry information of actual motion parameters (velocity, acceleration, deviousness). Increments of gravitation acceleration carry information of actual declination angle that is the object of interest.

Many scientific articles are devoted to the problem of declination angle measuring by means of one-axial or biaxial MEMS accelerometer [Crescini 2010]. They use goniometric functions for angle derivation from decomposed triangle, whereby the most accurate method describes the angle by tangents or arctangents functions [Łuczak 2011] as

$$\varphi = \arctan\left(\frac{g_x}{g_y}\right) \tag{1}$$

The components of separated static acceleration g_x and g_y are defined by decomposition of gravitational acceleration into deflected axes of measuring system. Dynamics of moving pendulum causes the subtraction of kinematic and static acceleration components. Their back separation is fixed on the actual angle deviation ϕ that is the searched unknown quantity. Therefore we handle with a problem of kinematic accelerations elimination for follow-up application of (1) for formulation of the angle.

The value of actual angle of pendulum deviation can be directly determined only at two motion boundary conditions. The first case is the state when the pendulum is traversing the equilibrium position and the angle $\phi = 0$. Then the cosine component of acceleration has the value of g. Subsequently it is possible to calculate the actual value of angle velocity ω_m by

$$\omega_m = \sqrt{\frac{a'_n - g}{r}}_{(\varphi=0)} \tag{2}$$

The calculation problem is aimed on searching the maximum of acceleration normal component a'_n. At the same time the value of tangential acceleration is $a'_t = 0$. Described situation can serve for the detection of transition the zero position.

The second case occurs when the pendulum is traversing the extreme position (dead centre) and the deviation gets the local maximum (local amplitude) $\phi = \phi_m$. The pendulum stops in the extreme position for a short moment (ω = 0) and the value of tangential acceleration at gets the value of local amplitude (a_t = ±max). Hereby the output value a'_t is influenced by the static sinus component g_x, what excludes the use of arccosines function. The solution is to formulate the local deviation amplitude from using arccosines function

$$\varphi_m = \arccos\left(\frac{a'_n}{g}\right)_{(\omega=0)} \tag{3}$$

The base of computing solution is again aimed on searching the local extreme, rather the local minimum of normal acceleration resultant course a'_n. The direction of actual deviation with regard to zero position (±ϕ) is formulated by the polarity of resultant tangential acceleration a'_t. The negative value of a'_t means the counterclockwise pendulum deviation therefore the positive value of angle ϕ. This rule is similarly valid for the positive angle of resultant tangential acceleration. Described method is used for computing of values of immediate angle amplitudes ϕ_m.

The time course of deviation angle between identified extreme positions $\phi \in \langle +\phi_{max0}, +\phi_{max1} \rangle$ can be predicted by means of functional dependence $\phi = f(\phi_m, \delta, \omega_1 t)$; the ϕ_m value is the local amplitude of every following oscillation time period T. More accurately diagnostic can be started at the moment when the natural angle frequency ω_1 of damped oscillation is quantified in (4) and the damping coefficient δ in (5) from the value of first two identified amplitudes ϕ_{max1} and ϕ_{max2} at time 1T and 2T. T is the period of damped oscillations.

$$\omega_1 = 2\pi \frac{1}{t_{\varphi\max 2} - t_{\varphi\max 1}} = 2\pi \frac{1}{T} \tag{4}$$

$$\delta = \frac{\ln\left(1 - \frac{\varphi_{\max 1} - \varphi_{\max 2}}{\varphi_{\max 2}}\right)}{T} \tag{5}$$

So we get the formula for prediction of angle deviation course at time $t \in \langle 2T, 3T \rangle$, thus during the following period. At time 3T we can get the deviation amplitude that can be used for calculation of maximal absolute prediction error on given interval. Equation (6) can be used for calculation of maximal absolute prediction error on interval from (x – 1)T to xT.

$$\Delta\varphi_{(xT)} = \left(\varphi_{\max P} - \varphi_{\max S}\right)_{(xT)} \tag{6}$$

The maximal absolute prediction error Δϕ(xT) on X interval of oscillation period T is the difference between the predicted deviation amplitude ϕ_{maxP} and the measured amplitude at time xT. The prediction formula is used for angle computing at every following interval xT (for x = 2, 3, 4…). The damping coefficient and the natural angle frequency have to be updated at measuring process in order to better predict the actual position of pendulum. Similar result offers the solution from amplitudes of deviations at times (2x – 1)T/2 (for x = 1,2,3...), what is an evaluation realised only from right or left amplitudes ($\pm\phi_{max}$). Theoretically the evaluation can by realised from every detected amplitude (at time xT/2). From realised experiments it is known that the inaccuracy can appear by influence of sensor mounting deficiency or steering shaft directivity.

The angle predicted by this method allows follow-up derivation of motion angle parameters (ω, ε) in every oscillation moment. Together it serves input parameters for virtual model of physical pendulum adaptation. The accuracy of supposed application is limited by the inaccuracy of arccosines function (toleration range 0° to ±2°) and the sensor noise that can be estimated during sensor calibration [Dongkyu 2011]. Łuczak [2014] experimentally evaluated the accuracy within range of 0,18°–2°.

3 LABORATORY MODEL OF PHYSICAL PENDULUM

For simulation of hanging weight free oscillation the model of physical pendulum was created (Fig. 1) that besides the free oscillation offers a possibility to keep the constant amplitude of oscillation by deflexion using disc motor and electronic control circuit [Adamik 2011]. The precise rotary shaft support insures the planar kinematic parameters of pendulum. Micromechanical sensor system is mounted on the end of pendulum arm.

The experiment objective is to create a measuring system of oscillating motion kinematics variables of a physical pendulum model using a biaxial accelerometer that is an alternative to relative measuring principles.

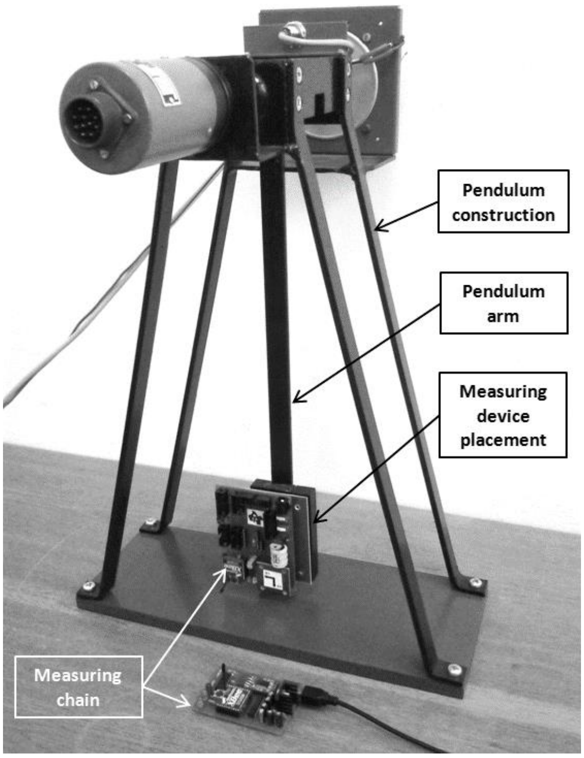

Figure 1. Construction of physical pendulum model

3.1 Wireless measuring system

The problem of kinematic parameters sensing using MEMS sensors is characterised by their mounting on individual parts of mechanical system. Thereby there originates the array of distributed smart sensors with defining type and start position. For acquisition and control of data sequence it is required to use the microcomputer technique with wireless low-power communication that eliminates interference and problems with cable connections [Lewis 2004], [Mozdik 2015]. Due to the extreme low energy consumption of recent electronic components, the battery-powered modules are able to action in long time. By means of energy harvesting directly from the environment, those components can operate fully autonomously [Beeby 2010].

The analysis of information acquisition from local distributed sensors on the stationary mechanism determined the network and modular structure of sensor network (Fig. 2) [Adamik 2011]. The principle using one sensor and one central module was preferred, whereby the modules are wireless connected by means of XBee communication modules based on the IEEE 802.15.4 standard.

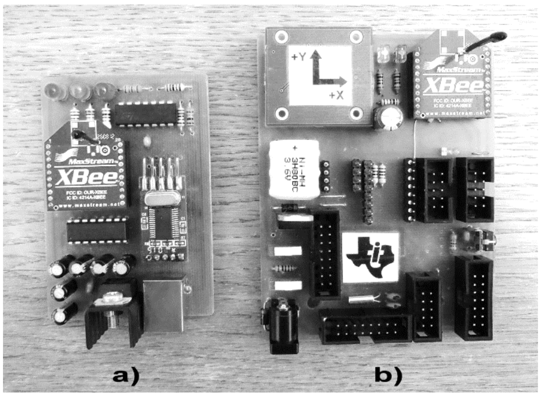

Figure 2. Sensor network modules a) central module, b) sensor module

The microcontroller MSP 430 is a main part of configured sensor module (Fig. 3). This microcontroller controls the sequence of acquisition data sensed by micromechanical sensor connected to SPI bus of its universal communication interface. The sensor module allows direct connection of biaxial accelerometer ADIS 16006 and wiring of communication and supply signals for alternative sensors. Read data formatted to suitable structure are transferred by XBee unit to central module (Fig. 4).

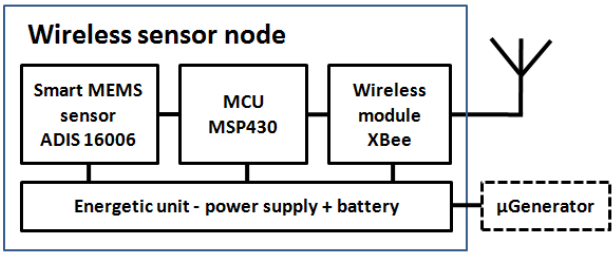

Figure 3. Structure of sensor module

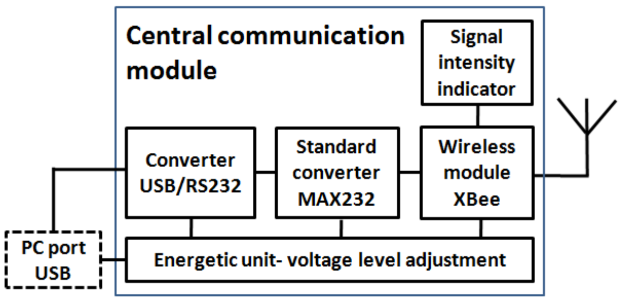

Figure 4. Structure of central module

3.2 Algorithm composition of physical pendulum model

The application of proposed mathematical model to computing software system requires the prescription of measuring initial conditions and measuring system limitations. So the prediction process of actual deviation angle during the damped oscillations is divided into three parts:

- parameters identification up to time 2T,
- course identification from time 2T to $\phi_{maxX} = 5°$,
- course identification from $\phi_{maxX} < 5°$ to 0°.

In the first time interval from oscillation start (releasing from side displacement) up to time 2T it is not possible to predict the oscillation course but the extreme positions, what is caused by abstention of oscillations parameters such as the natural angle frequency and damping. From the values of first two amplitudes ϕmax0 and ϕmax1 at time 2T, these parameters can be calculated. They are used for prediction of angle deviation course during following periods at time 2T and 3T. The course prediction by (6) has to be modified for estimation from amplitudes by the cosine function. At time 3T we can get the accurate data of deviation amplitude that can be used for computing of maximal absolute prediction error on the interval. The estimation of oscillation course on the third interval – at time when $\phi_{maxX} < 5°$ to the equilibrium state (0°), is influenced by the natural sensor noise and inertia responses of oscillating system. Therefore the exact detection of osculation amplitudes is practically not possible. Moreover the acceleration a'_n in (13) includes the dynamic component that disables the calculation of deviation angle in stationary position by (15). So the angle course of oscillating pendulum in the third interval is predicted in (6) from average values of natural angle frequency and damping, calculated during measuring. Generally the need of exact deviation determination at this interval has to be considered. From realised analyse, the flowchart (Fig. 5) outputting into a text file can be configured for continuous computing of actual deviation angle.

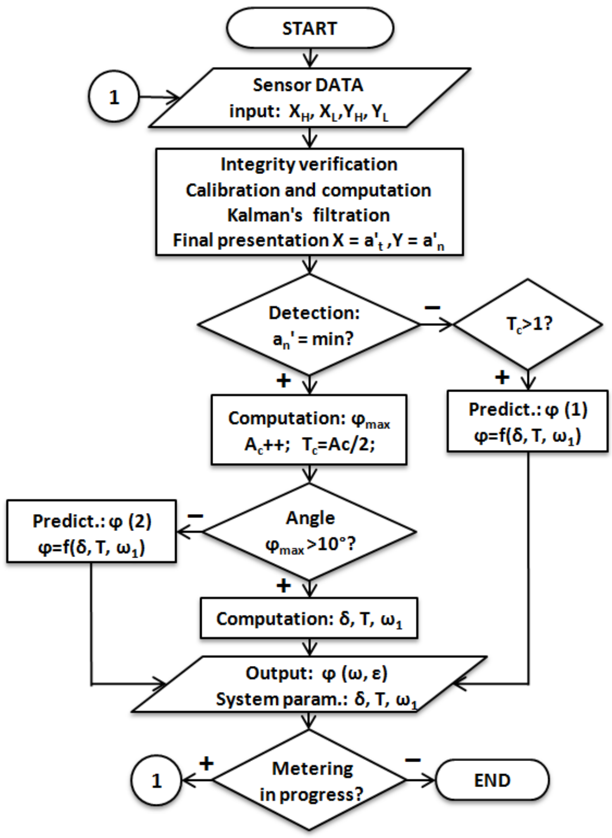

Figure 5. Flowchart for calculation of pendulum actual angle deviation

The acceleration measurement by sensor module initiates the program execution. The oscillating motion is synchronised by means of maximal deviation ($\pm\phi_{max}$) and releasing of pendulum weight. Received velocity data from accelerometer in X and Y axes are converted to acceleration value and filtered by Kalman filter. Filter source code in C language is used in inertial navigation [vBulletin Solutions 2016]. This code was modified

for C++ language and its input parameters are real sensed signal and filtration parameters.
Filtered data are considered as accelerations in system of tangent-normal line (a'_t, a'_n). The base of received data analyse is the detection of local minimum of signal a'_n, what is the extreme deviation position. At every extreme position the local amplitude value $\pm\phi_{max}$ and time of it occurrence are calculated for corrective coefficients estimation. If the angle is greater than 5° and oscillation time is smaller than 2T, the amplitude values are transferred to the output. At time 2T the prediction of angular displacement course is initiated what is a direct graphical output. At oscillation damping, when the angle of extreme positions is smaller than 5° and their detection is inaccurate, the total prediction is used up to the equilibrium state. This algorithm includes the detection of unpredictable larger vibrations during the motion as well as the evaluation of static angle displacement. User command or stop of accelerometer data transfer quit the programme.

3.3 Experimental measuring on the model

The experimental measuring of acceleration components was realized on the physical pendulum arm whose motion was initiated by its releasing from the right maximal displacement (negative angle). Simultaneously the data processing by means of software application VR Manager was executed with the computing of designed mathematical model and interactive visualization of virtual reality environment of pendulum model.
Acceleration components of pendulum damped oscillation were measured by wireless sensor module and processed in a specialized VR Manager application. First, the information of accelerometer acceleration were received and computed by means of calibration coefficients into acceleration dimensions at the output samples frequency of 501,476 Hz. On the acceleration samples in X and Y axes the double-channel Kalman filter was applied with experimental estimated parameters: X and Y noise parameter: 0,022; X process dynamic: 0,617; Y process dynamic: 0,238. Results were saved into text file that had 63 448 samples of XY acceleration after measuring finishing. In the pendulum environment the samples XY mean the tangential a'_t and normal a'_n acceleration measured on the oscillation perimeter of 42 cm. Graphical visualization of measured accelerations course is in the Fig. 6.

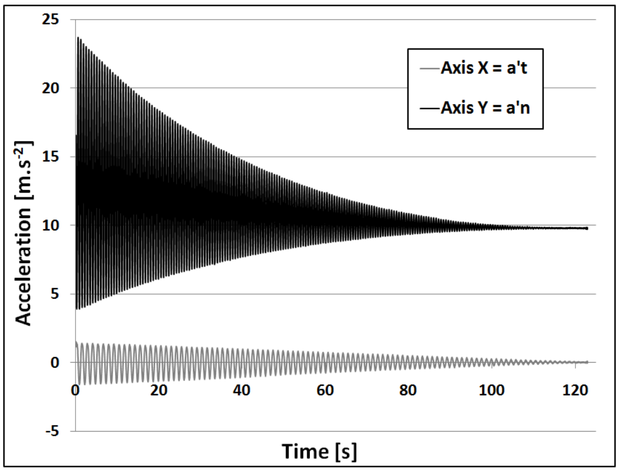

Figure 6. Measured courses of pendulum acceleration compounds

There can be deduced that the upper flowline of normal acceleration amplitudes represents the equilibrium position transitions that include the additive gravitational acceleration increments. The lower flowline of normal acceleration amplitudes ($\pm\phi_{max}$) represents the extreme pendulum positions that occur at time T/2. All measuring of normal acceleration is influenced by cosine component of gravitational acceleration of 9,81 m.s^{-2}.
The course of tangential acceleration a'_t has the half frequency regarding to the a'_n course, what confirms that two amplitudes of partial oscillations at equilibrium position transition originate during one oscillation. The values of tangential acceleration are in the interval of ±2 m.s^{-2}, what, regarding to sensor parasite noise, presents low sensitivity at motion damping ($\phi < 5°$). The a'_t value carries the information of actual pendulum displacement direction (polarity) and all exact computations are realized from the a'_n values. After pendulum stopping the acceleration a'_t has stationary value of 0 m.s^{-2}.
Filtered values of acceleration input to the algorithm for mathematical model computation. The sample frequency of 500 Hz is reduced by 10 for increasing calculation of speed. Every tenth sample inputs the pendulum algorithm, which outputs the actual value of angle ϕ whose course is displayed in the Fig. 7.

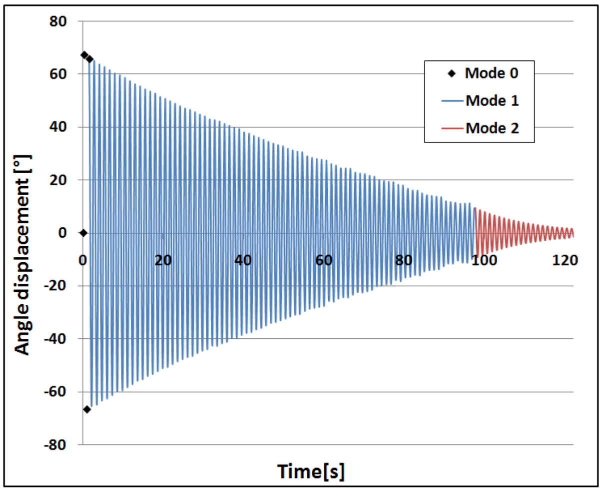

Figure 7. Course of computed angle displacement of physical pendulum

The algorithm is initiated for calculation in mode 0 when the prediction parameters are unknown. The particular amplitude points show this situation in the graph. At the moment when the first two amplitudes of the same polarity (positive) are known, the prediction parameters (T, ω_1, δ) are computed and the algorithm switches to the mode 1 (prediction in every next oscillation period). For elimination of the sensor mounting error the identification of prediction parameters is executed from the negative deviations amplitudes. The routine counts the amplitudes since the motion beginning. Therefore the angles have a sign as

- positive angle – left direction – even amplitude,
- negative angle – right direction – uneven amplitude.

The prediction in the first mode is dependent on correct evaluation of amplitudes from detected local minima of normal acceleration course. As the output acceleration signal at extreme positions is influenced by sensor noise and small vibrations of mechanical system, the detection of local minima is ambiguous (several extremes). The calculation is performed after the first extreme detection in actual deviation direction that has to have the opposite polarity than the previous extreme. By reason of previously described calculation inaccuracy, the lower prediction limit in mode 1 was specified at the amplitude value of ±10°.
Simultaneously with extreme detection of pendulum angle $\pm\phi_{maxS}$ the calculation of predicted amplitude in the next antinode $\pm\phi_{maxP}$ is executed. The flowline of predicted and

correct deviation amplitude in the Fig. 8 creates the cover of damped oscillation course.

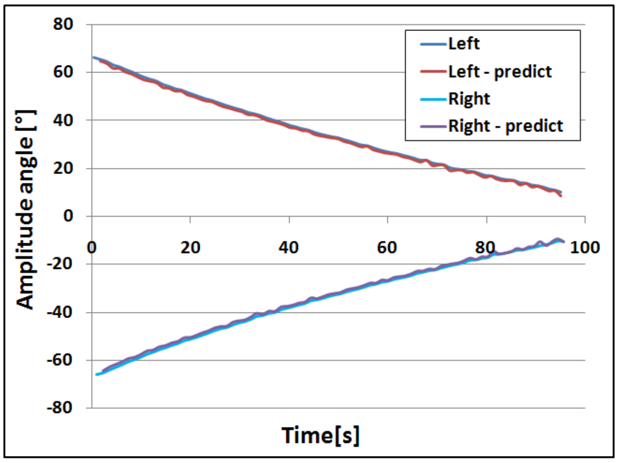

Figure 8. Angle amplitude flowlines in first measurement mode

From the chart it is visible that the flowlines of measured and predicted deviation angle at time of amplitude achievement are almost overlapped. Therefore the accuracy evaluation is more visual by means of the maximal absolute prediction error computed in (6) at time of even or uneven amplitudes. The prediction error on given interval xT culminates in the end point, what is the beginning of the next interval (x + 1)T. The chart of maximal prediction error dependent on the time in the first measurement mode is shown in the Fig. 9.

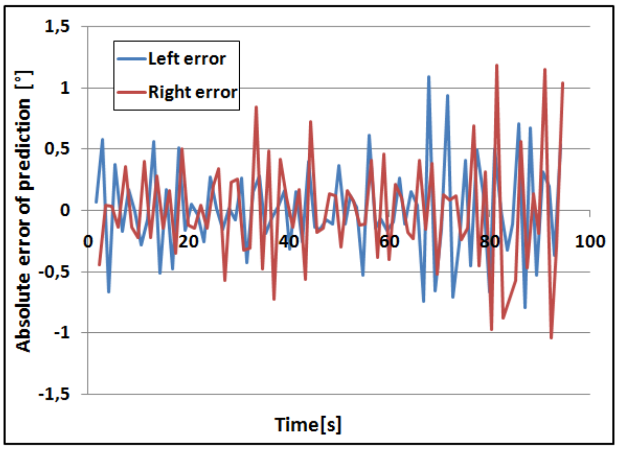

Figure 9. Maximal absolute error of angle prediction in first measurement mode

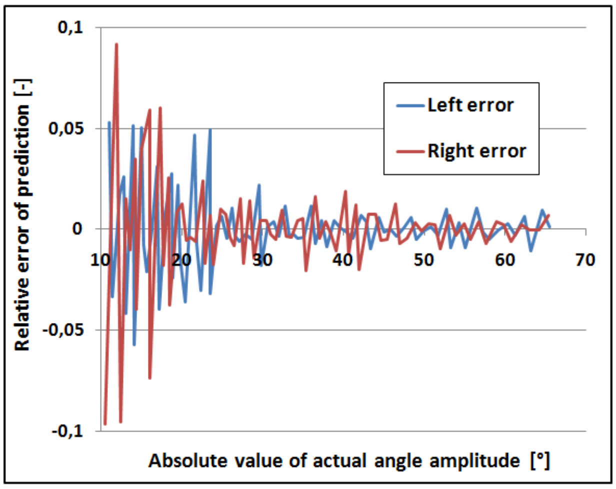

Figure 10. Relative error of actual angle prediction in first measurement mode

There is no difference in evaluation of prediction parameters and actual angle deviation. The absolute prediction error lies in the tolerant band ±1,2° and its dispersion increases with animation time and therefore with decreasing of oscillation amplitude. Fig. 10 displays the course of prediction error related to the value of actual correct amplitude angle.

From the course it can be seen that the relative prediction error is getting greater with decreasing amplitude angle. Reason could be the ambiguity of extreme positions detection due the natural accelerometer noise and small vibrations of mechanical construction. Likewise the influence has the inaccuracy of function arcsines formulation within the range of 0-15° [Lewis 2004]. This fact influences the values of prediction parameters and therefore the prediction accuracy. It can be deduced that the prediction accuracy from left amplitudes is greater.

At time when the pendulum amplitude exceeds the range of ±10°, the second program mode of pendulum angle calculation is initiated. For this second mode the last value of amplitude and average values of period, damping and natural angle frequency, computed during the measuring in the first mode, are adapted. The output course of deviation angle (Fig. 10) in the second mode is predicted from the last amplitude value and from moving averages of parameters in the Tab. 1 till measuring stops.

Table 1. Parameters for angle prediction in the second computation interval

Last angle ϕ_{max} [°]	Period T [s]	Damping δ [rad.s^{-1}]	Frequency [rad.s^{-1}]
9,84703	1,219109	-0,034866	5,156486

From the output angle course (Fig. 10) the equivalence of motion stop can be evaluated by means of comparison with time of tangential acceleration fixation (Fig. 9). Equivalence of motion states determines the correctness of prediction parameters. From the comparison there can be considered that predicted course has not reached the zero level at pendulum stop time 123,16 sec. This inaccuracy is caused by the noise component of average values of period, damping and natural angle frequency as well as the error of computation of last adapted amplitude from the values of relatively noised signal.

From performed measurement of actual displacement angle of damped pendulum oscillation for the VR model adaptation the average parameters of oscillating system can be calculated, that are specified in the Tab. 2.

Table 2. Average parameters of oscillating system (prediction parameters)

Parameter	Left	Right	Average
Period T [s]	1,251039	1,250385	1,250712
Freq. ω_1 [rad.s^{-1}]	5,026211	5,028435	5,027323
Damping δ [s^{-1}]	-0,01813	-0,02035	-0,01924

From the evaluation there can be considered that the accuracy of calculation or generation of pendulum position parameter reached satisfactory level. The use of a reference incremental angle sensor is advisable.

Multitude parameters influence the whole measurement by described conception. One of them is the wireless transfer, whose interference can cause fluctuation of the natural sample frequency of 500 Hz for error samples elimination. The calculation accuracy is influenced also by setting up of Kalman filter parameters determined experimentally. The correct setting of average noise parameter can have positive impact on the evaluation of extremes.

Proper determination of average noise value can positively influence the extreme evaluation. The determination of process dynamic parameter is especially important. Its high value causes a phase shift of filtered course what complicates the related evaluation of XY acceleration realised at the evaluation of size and polarity of deviation angle. Mechanical influences include the technical deficiency of arm rotary mounting (friction) as well as the deficiency of motion inertial forces elimination (body vibrations).

The limitation of designed evaluation method bases on the calculation of actual deviation amplitude using goniometric function arccosines that has enhanced inaccuracy in the angle interval of (0, ±5°). Presented method is suitable for harmonic oscillations with the stationary angle frequency. For oscillations with random vibrations of changing frequency (stochastic signal) this method affords incorrect results and requires further analysis.

In the term of biaxial MEMS sensor use for measuring of pendulum dynamic angle, there can be defined several inaccuracy factors. One of them is the determination of sampling frequency consistent with sampling theorem. Another is the level of sensor parasitic noise that identified random displacement up to 8° at pendulum stationary state. In the term of inertial measurement system, the disability of stationary gravitational acceleration elimination complicates the evaluation. For this purpose it should be considered use of MEMS inclinometer or gyroscope that are able to calculate actual displacement angle at every time of motion [Kang 2009], [Bogue 2007]. Designed principle could serve for verification or calibration of integral computing of angle in oscillation amplitudes.

4 DISCUSSION

The goal of investigation was to create a wireless measurement system of pendulum kinematic parameters using available micromechanical sensors. The result is the wireless sensor network consisted of sensor and central modules with mounted XBee communication modules.

Acceleration sensing using biaxial accelerometer ADIS16006 coordinated by microcontroller MSP430 of sensor module has a stationary sampling frequency of 500 Hz with satisfactory wireless transfer. Mainly in motion measurement systems the use of wireless communication is necessary because of problems with additional power supply wiring of sensor module and therefore inference of acceleration measuring.

Result of mathematical model of physical pendulum was the method of boundary conditions and prediction of angular displacement course that is an alternative to the relative measurement by means of incremental sensor or integral evaluation using inertial gyroscope. Described method can be used for verification or calibration of integral computing of angle in oscillation amplitudes.

The average absolute prediction error 0,0023°, which values lay in the interval ±1,2°, was achieved during damping oscillation measurement and angular displacement prediction. Designed method can be improved by more precise local extreme detection, related evaluation of sensed courses as well as expression of signal actual frequency.

5 CONCLUSION

From laboratory experiments it can be deduced that for the purpose of dynamic pendulum parameters analysis the described method can be used in the field of control and regulation. The accuracy is influenced by many error parameters. The reached accuracy of angle amplitude prediction was ϕ = ±0,3°. For adequate quantification of accuracy the implementation of reference sensor system based on relative measurement principle should by advisable. More accurate methods of kinematic parameters analysis using MEMS inclinometer or gyroscope have to be considered what allows calculating the actual displacement angle at every moment without prediction.

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REFERENCES

[Adamik 2011] Adamik, M. and Suriansky, J. Wireless sensor system for dynamic pendulum movement sensing. Acta facultatis technicae, 2011, Vol. 16, pp 7-16. ISSN 1336-4472

[Beeby, 2010] Beeby, S. and White, N. Energy Harvesting for Autonomous Systems. London: Artech House, 2010. ISBN: 978-1-59693-718-5

[Bodnar, 2001] Bodnar, F. Mechanics I, Statics and kinematics. Zvolen: Publisher of Technical University in Zvolen, 2001. ISBN 80-228-0986-1

[Bogue, 2007] Bogue, R. MEMS sensors: past, present and future. Sensors Review, 2007, Vol. 2007, pp 7-13. ISSN 0260-2288

[Bozek, 2015a] Bozek, P., Pivarciova, E. Inertial Navigate System Application in Manufacturing Technique. In: Technological Forum 2015 - 6th International Technical Conference, Kouty, Czech Republic 23.-25.6.2015. Praha: Czech Technical University in Prague, pp 163-165. ISBN 978-80-87583-13-5

[Bozek, 2015b] Bozek, P., Pivarciova, E., Korshunov, A. I. Reverse validation in the robots control. Applied Mechanics and Materials, 2015, Vol. 816. pp 125-131. ISSN 1660-9336

[Crescini, 2010] Crescini, D., Bau, M. And Ferrari, V. MEMS tilt sensor with improved resolution and low thermal drift. In: Proc. book of the conf. AISEM 2009 – Sensors and Microsystems, Pavia, 2010. pp 225-228. ISBN 978-90-481-3606-3

[Dado, 1996] Dado, S., Kreidl M. Sensors and measuring circuits. Prague: CVUT, 1996. ISBN 80-01-01500-9

[Dongkyu, 2011] Dongkyu, L. And Sangchul L. Test and error parameter estimation for MEMS – based low cost IMU calibration. Int. Journal of Precision Engineering and Manufacturing, 2011, Vol. 12, No. 4. pp 597-603. ISSN: 2005-4602

[Kang, 2009] Kang, J., et. al. Study of drill measuring system based on MEMS accelerative and mangetoresisitive sensor. In: Proc. book of the 9th International conf. on Electronic Measurement and Instruments. Beijing, 2009. pp 112-116. DOI: 10.1109/ICEMI.2009.5273991

[Kurilla, 2010] Kurilla, J. Using of MEMS accelerometer for weight oscillation parameter identification of travelling gantry crane. Posterus.sk, 2010, vol. 3, pp. 1-12. ISSN 1338-0087

[Lai, 2011] Lai, D., et al. Regression models for estimating gait parameters using inertial sensors. In: Proc. book of the 7th Int. conf. on Intelligent Sensors, Sensor Network and Information. Adelaide, 2011. pp 46-51. ISBN 78-1-4577-0675-2

[Lewis, 2004] Lewis, F. L. Wireless Sensor Networks [online]. Smart Environments, Automation and Robotics Research Institute, University of Texas Arlington, 2004 [2016-04-30]. Available from <http:arri.uta.edu, 2004>.

[Łuczak, 2011] Łuczak, S. Single-axis tilt measurements realized by means of MEMS accelerometers. Engineering mechanics, 2011, Vol. 18., pp 341-351. ISSN 1805-4633

[Łuczak, 2014] Łuczak, S. Guidelines for tilt measurements realized by MEMS accelerometers. Int. Journal of Precision Engineering and Manufacturing, 2014, Vol. 154, No. 3.,pp 489-496. ISSN 2005-4602

[Mozdik, 2015] Mozdik, R., Nascak, L., 2015. Measuring of quality of Wi-Fi network for wireless control models and processes. Acta facultatis technicae, 2015, Vol. 1, pp 55-64. ISSN 1336-4472

[Music, 2010] Music, J., Cecic, M., Zanchi, V. Real-time body orientation estimation based on two-layer stochastic filter architecture. Automatika, 2010, Vol. 51. pp 267-274. ISSN: 1848-3380

[Saxena, 2010] Saxena, A. et. al. In use parameter estimation of inertial sensors by detecting multilevel quasi-static states. In: Proc. of 9th Int. conf. KES 2005 – Knowledge-Based Intelligent Information and Engineering Systems. Melbourne, 2010. pp 595-601. ISSN 0302-9743

[Shuozhi, 2012] Shuozhi, Y., Qingguo, L. Inertial sensor-based methods in walking speed estimation: a systematic review. Sensors, 2012, Vol. 12, pp 6102-16. ISSN 1424-8220

[vBulletin, 2016] vBulletin Solutions, Inc. CProgramming Kalman Filter for XY Streams, Salem, 2016 [online]. [2016-05-30]. Available from <http://cboard.cprogramming.com>.

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