Suitability of a Three-Axis Inclinometer to the Automated Blade Control System of Excavator

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Abstract –

Partly automated blade control of excavator has been studied. Main focus of the study were to find means to control one of the excavator's work cylinders automatically while machine operator controls the rest of non-automated work cylinders.

This article concentrates on the suitability of a certain inclinometer sensor for partly automated blade control of excavator. Test device was built where inclinometers output data controlled hydraulic cylinder and the statical and dynamical properties of the cylinder and the controlling sensor were studied. In statical tests the inclinometer was attached to the milling tools distributing board along with the reference sensor. The positioning accuracy and the positioning repeatability were studied with the statical tests. In dynamical tests the inclinometer was attached to the pendulum and the dynamical properties of the inclinometer were researched with the pendulum oscillation experiments. Test device contained angular potentiometer which purpose was to function as inclinometers reference sensor. The LVDT displacement transducer was attached to the side of the cylinder which functioned as cylinders integrated displacement sensors (VRVT) reference sensor. In dynamical tests the inclinometers and reference sensors data responses were measured with different pendulum rod lengths and attachment setups. Centripetal accelerations and angular frequencies were calculated from the measured data and their effects for angular error are introduced.

Results indicate that cylinders positioning accuracy was $\pm$ 1.5 millimetres and the inclinometers angle accuracy was $\pm$ 0.3 angle of degrees with delay of 600 ms. Accuracies are sufficient but the delay is too long for partly automated blade control.

Keywords -

Inclinometer, inclinometer sensor pendulum experiments, partly automated excavator

1 Introduction

Automated solutions for heavy construction equipment have increased a lot in recent years. Automated blade control for road-scrapers and dozers has been in commercial use for a while. The use of machine guidance systems in excavators is now day common in construction sites but the commercial solutions for the automated blade control of excavator has been lacking. Just recently the automated blade controlling solutions for excavators has been increased. Several studies and papers have been made of semi-automatic and automated excavators over the years.

An Autonomous excavator LUCIE was developed in Lanchaster University [1], [2]. An Autonomous truck loading excavator was developed in Carnegie Mellon University [3], scanners attached to the excavator recognizes surrounding environment and can locate the truck for loading procedure, Korean research consortium is developing automated excavation system [4] where surrounding environment can be recognized. Based on the environment and the site planning scheme the optimized digging plans are created. First experiences of automated dredging excavator have been reported [5]. Also fully automated excavator solutions have been developed for mini-excavator [6] and for 13 and 21 ton excavators ([7] [8]).

Semi-automatic excavator solutions for three degrees of freedom excavators have been introduced ([9] [10]).

Recently in Bauma trade fair 2013, Komatsu introduced prototype of an intelligent machine control system (iMC) for excavator. This prototype was fully automated excavator on which the operator digs normally and the iMC system prevents to dig below the design models grade [11]. Also machine control system company Idigbest has developed automatic digging system for excavator [12] based on IDigBest patented valve system where system prevents to dig below grade.

This article concentrates on the introduction of the measurement results regarding the tested inclinometer suitability for the partly automated blade control of excavator. Tested inclinometer were three axis CAN-bus interfaced tilt sensor, figure 1, which measures gravitational intensity towards sensor's inner axis. This particular sensor was very sensitive for external accelerations and it is in common use.

Interested inclinometer properties were the effect of the centripetal acceleration to the sensors output data and inclinometers output data delays compared to the reference sensors output.

The Aim of this research was to find out how these particular inclinometers apply to the partly automated blade controlling of excavators.

2 Methods

Research of inclinometers suitability for automated blade controlling was started by creating labview program. With the labview program together with the sensors CAN protocol provided by the sensors manufacturer, the inclinometers output data could be monitored. According to the monitored sensor output data, mathematics to convert output data to angle of degrees was created.

Figure 1. Tested inclinometer.

After the mathematics of the angle of degree conversion was found to be accurately enough, a test device was built, figure 2. Test device consisted of laptop, digital control valve with CANopen bus, a cylinder with an integrated displacement sensor (VRVT), labview graphical programming language, and the compactRIO with analog I/O module and CAN module. Test device was programmed in a way that the inclinometers output data controlled cylinders rod length.

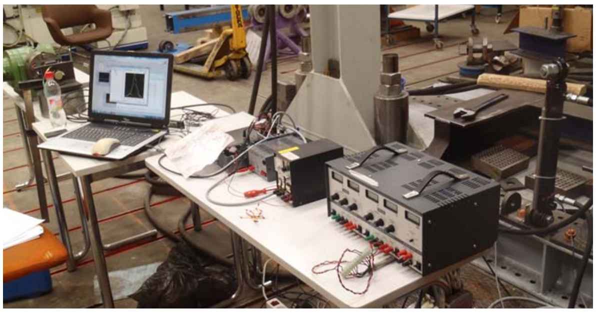

Figure 2. Test device.

In the statical tests inclinometer was attached to the milling tools distributing table with the potentiometer, figure 3. The distributing table was used to change inclination of the inclinometer sensor with different angle steps. On each measurement same angle steps were taken. Measured data were used to obtain the inclinometers angle of degrees accuracy and the cylinders positioning accuracy.

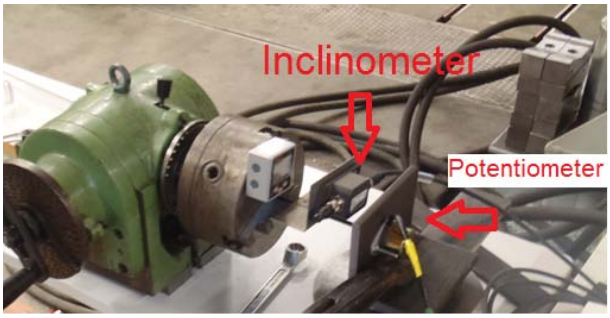

Figure 3. Milling tool's distributing table with the inclinometer and potentiometer.

In the dynamical tests, inclinometer was attached to the pendulum with the reference sensor. Dynamical tests were made with different pendulum rod lengths and counterweights. Two different attachment setups for the inclinometer to the pendulum were used, inclinometer attached to the pendulums bob, figure 4 and the inclinometer attached to the pendulums rotational axis, figure 5.

Reference sensor was attached to the backside of the pendulum in the axis of rotation, figure 6. Reference sensors angle range was ±20 angle of degrees and for that reason oscillation tests had to stay within this limit.

Figure 4. Inclinometer attached to the pendulum's bob.

Oscillation tests were made by deflecting the pendulums rod from its position of equilibrium about 20 degrees of angle and the sine wave form output data was then stored as tdms files for future analyse.

In the oscillation tests attachment setup 1, fig 4, the centripetal acceleration became so big that the inclinometer couldn't measure the angle changes effectively. With this kind of attachment setup, counterweight was attached to the pendulums rod to the upper side of the rotational axis. Counterweight enabled to measure inclinometers angle changes more effectively. Counterweight was also used with attachment setup 2 to increase the oscillations period time. Two counterweights of mass 1.42 kg and 2.04 kg were used.

On the sensor attachment setup 2 the centripetal acceleration can be assumed to be zero because of the attachment location. The angular frequency's effect to the error of the angle became the most important test result with this attachment setup.

Figure 5. Inclinometer attached to the pendulum's axis of rotation.

From the collected data several physical features were calculated with the mathematical pendulum and the simple harmonical motion equations. With calculated physical features the centripetal acceleration's effects to the inclinometers error of the angle and the angular frequency's effects to the error of the angle were the most important test results.

Figure 6. Potentiometer attached to the backside of pendulum.

3 Results

Statical tests gave information how digital control valve and used cylinder assort to the automated blade control and also the inclinometer angle accuracy and the positioning accuracy of the cylinder was obtained with statical tests. Example of statical tests recorded data is shown in figure 7.

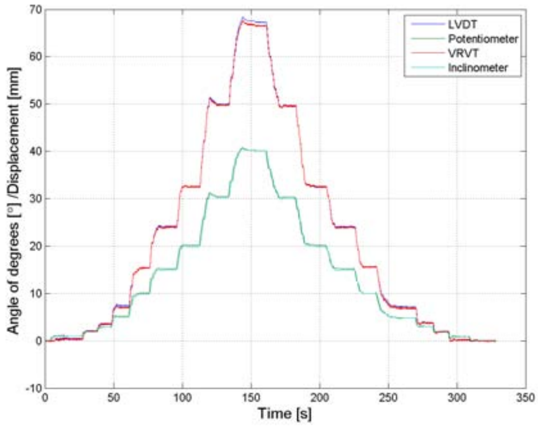

Figure 7. Example of collected data from statical tests.

From the statical tests positioning accuracy for cylinder was found to be ± 1.5 millimetres and inclinometer's angle accuracy was found to be ± 0.3 angle of degrees.

Pendulum oscillation tests introduced valuable information regarding sensors usability in partly automated blade controlling in excavators. Recorded data from oscillation tests were accordant with figure 8 and figure 9. Gathered tdms data were converted with matlab and the sine wave form figures were zoomed in for further analysing. Zoomed in figures data points were used to calculate physical features.

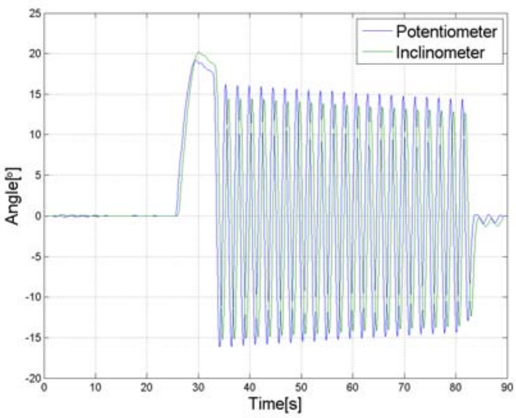

Figure 8. Example of collected data from dynamical tests, where inclinometer is attached to the rotational axis of the pendulum without counterweight.

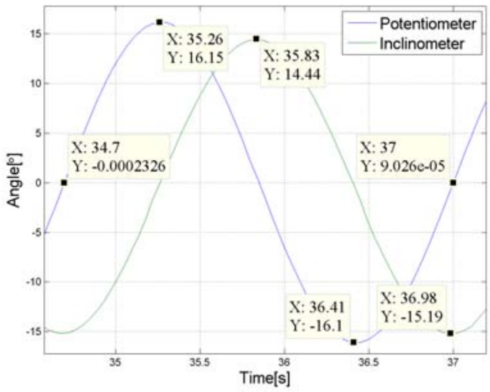

Figure 9. Figure 8th sine form data were zoomed in and several data points were added.

Delay behaviour between the reference sensor and the inclinometer data output is shown in figure 10. Same results were found on every oscillation tests. Delay was found to be almost 600 ms.

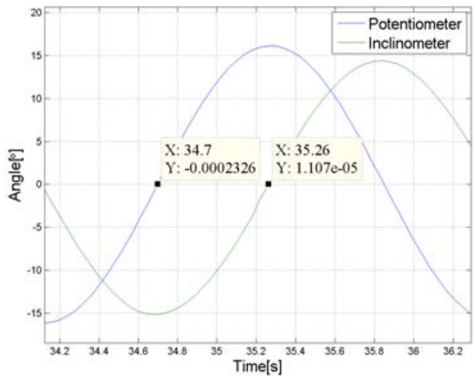

Figure 10. Output delay between reference sensor's and inclinometers output data.

Angular frequency's and centripetal acceleration's impact to the inclinometer's output data with different rod lengths and counterweights is gathered to the figures 11, 12 and 13. Figures 11 and 12 are from attachment setup 1. Figure 13 shows angular frequency's effect on the error of the angle when inclinometer is attached with attachment setup 2.

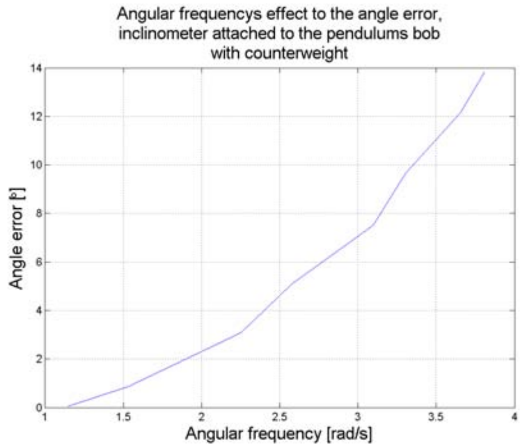

Figure 11. Angular frequency's effect to the angle error.

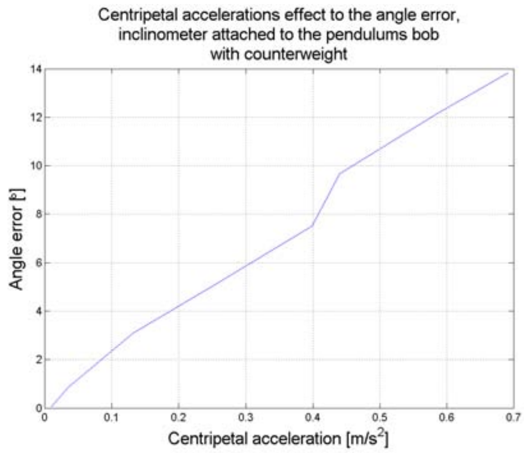

Figure 12. Centripetal accelerations effect to the angle error.

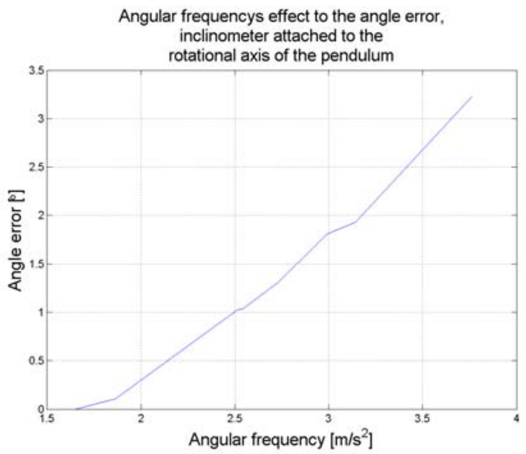

Figure 13. Angular frequency's effect to the angle error.

4 Conclusion

Partly automated blade controlling solutions for excavator holds potential and it might be very effective when used along with machine guidance systems. Over all excavator operators work can be monotony and machine operator's concentration changes during the workday and the operator might even get bored time to times. Co-operative use of automated blade controlling and machine guidance systems might provide the needed boost for operator's work.

Valuable information about usability of tested devices and sensors on automated blade controlling was gained from statical and dynamical tests. Statical tests provided information about the accuracy of chosen equipment. Oscillation tests provided information how a different sensor location attachments on the real excavator's boom and arm effects on sensors output data. Attachment setup 1, fig 4 simulates situation where sensor is attached off-set from the joint angle. Attachment setup2, fig 5 simulates situation where sensor is attached to the joint angle of excavator.

Most accurate sensor output data are gained when sensor is attached to the joint angle of the excavator or as nearest as possible. This way the centripetal acceleration remains minimal, especially when using sensors which are sensitive for external accelerations this is very important.

Angle accuracy of inclinometer is small enough for partly automated blade control and with the optimization of the inclinometer output data conversion to angle of degrees it can be acquired even smaller. Inclinometer dynamics works decently enough when digging speed stays slow. However the inclinometers delay is too long for partly automated blade control and for that reason this particular inclinometer seems to be unsuitable for partly automated blade control on excavator.

For future work prototype of mini-excavator with partly automated blade control combined with machine guidance system should be developed. Prototype would provide information what kind of benefits can be achieved with these systems together. Also benefits of partly automated blade controlling for excavator with infra-bim model, where all the grade information comes from infra-bim model should be studied. Once partly automated blade controlling has been studied next natural step would be to automate more than one work cylinder.

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