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Using angular speed measurement with Hall effect sensors to observe grinding operation with flexible robot.

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Abstract:

Hydro-Quebec has developed and implemented a portable robotic technology to facilitate the maintenance of hydraulic turbines. To improve the quality of the grinding, it is thus necessary to reduce the vibrations caused by the flexibility of the portable robot «SCOMPI». Steady vibration responses of the dynamic model during grinding shows repeating and high frequency impacts between the wheel and workpiece. High speed camera observations confirm the existence of a vibro-impact process. From our experiments, it is shown that angular speed signal can be very useful for monitoring grinding, by detecting the exact location on the wheel and energy content of each impact. These detections can allow online modification of the commands of the robot, such as normal force or feed speed, so as to better control the material removal rate. A comparison between built in Hall effect sensors and added encoder shows too many differences, and even if the first results are promising, an improved encoder need to be designed.

Keywords: grinding, angular speed, angular sampling, flexible robot

I- Introduction

Lightweight robots are widely used in today's industrial automation field for the advantages they offer, such as increased maneuverability, transportability, and ability to work in restricted spaces. Most hydropower utilities perform in place interventions to address issues such as cavitation and cracking. These repair tasks involve processes such as welding and grinding. Hydro-Quebec has developed and implemented a portable robotic technology to facilitate the maintenance of hydraulic turbines [1]. The robot uses a controlled material removal rate strategy that relies on a good dynamic model of the grinding process to reconstruct surface profile with great accuracy. Despite the many proven advantages, issues such as motion inaccuracy and end-effector vibration, due to the lack of stiffness, which results in reduced withstanding to dynamic forces, have yet to be resolved [2, 3]. To improve the quality of the grinding, it is thus necessary to reduce the vibrations caused by the flexibility of the portable robot «SCOMPI». Steady vibration responses of the dynamic model during grinding shows repeating and high frequency impacts between the wheel and workpiece [4]. This behavior arises from the inherently lower structural stiffness of the robot compared to conventional machine tools [5-7]. High speed camera observations confirm the existence of a vibro-impact process. To avoid limitation in acquisition time caused by the use of the high speed camera, an alternative approach is proposed using another signal to check the

preliminary observation. For this technique, the phase of the wheel needs to be known, so as to detect the precise position of the impact. The grinder is composed of a wheel mounted directly on the shaft of a DC brushless motor. The signals from the motor's Hall effect sensors can thus be used for phase information. A signal is generated from these sensors, and acquired through a tachometer input. Since the signal from Hall effect sensors is of very poor quality, the angular speed acquired is very noisy with 50% variations around the mean value. A correction of this angular speed signal is done and the short term cyclic parts of the signals are computed in the angular domain. The analysis shows a relationship accelerometer's signals and the angular speed variation. The wheel impacts the surface once or twice per revolution. The results reveal that the angular speed suddenly decreases of about 2% of the mean value at each impact, as predicted by simulation of the dynamic model. To improve these observations, an optical encoder is added to the grinder, and angular sampling is used through another acquisition card. Nevertheless, previous results couldn't be confirmed, such as variations in angular speed are not the same if observed from Hall effect sensors or from external encoder. Conclusion is finally that a better encoder needs to be designed and built in the grinder, rather than externally fixed.

II- Set-up and pre-processing

The grinder situation is as shown in figure 1: the workpiece is vertical, fixed, and the grinding wheel is normal to the workpiece and also vertical. Feed displacement is horizontal, normal to the plate, with go and back passes.

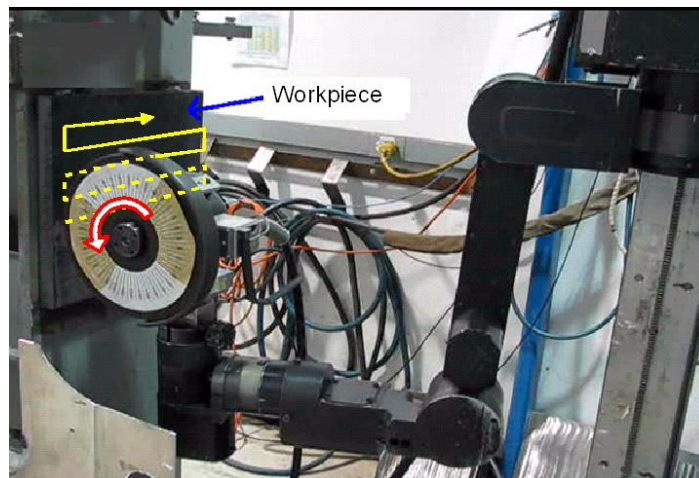


Figure 1: grinding configuration

A three axes accelerometer is fixed on the grinder, and the signals from Hall effect sensors are used to build a 36 pulses/turn signal:

- the rotor of the brushless DC motor provides 12 poles – 6 north and 6 south alternatively,
- each Hall effect sensor changes state 12 times per turn, that give three signals with 120° offset and 6 square pulses per turn (rising and falling on state changes),
- the 36 pulses/turn signal is built using filters and delays, considering each state change of the three *Hall effect signals*

The 36 pulses/turn is then sampled at 50 kHz through a tacho input, in the same time as others signal (accelerometer, force normal to the workpiece). The DT9837 card from DataTranslation is used. The tacho input gives the number of counts from a high frequency clock (12 MHz) between two rising edge of the signal, so angular speed can be obtained easily knowing number of pulses per turn. As angular resampling is expected, sampling frequency was set higher than pulses frequency (as big as possible in this case). Tacho input gives also the same value as long as no new value is available (next pulse has not occurred). The angular speed obtained like that can be seen in figure 2, purple dots, for a load free rotation case.

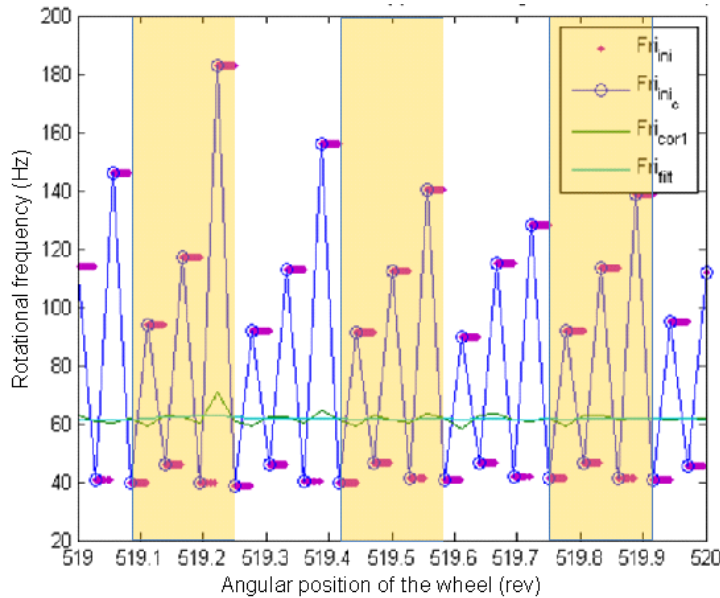


Figure 2: Temporal acquisition of signal from Hall effect sensors

As the angular speed varies a lot, only the first point of each local constant speed is considered for having the position of the wheel (blue line, circled points). Thirty-six positions per turn are thus obtained.

The variations of the angular speed are supposed to be from electronic and mechanical difficulties, such as:

1. Hall effect sensors, that are not mechanically spaced by 120° ,
2. Hall effect sensors, that have level for changing state which differs from each other, and are different for north and south pole detection,
3. Delays and filters used for building the 36 pulses signal,
4. Mechanical misalignment of rotor compared with rotational axis or other problems.

The first three points induce different variations during the generation of the signal, but the variations due to each Hall effect sensor and for each kind of pole (north or south) are quite constant. That results on the pattern emphasized with coloured and white zones in figure 2: rising angular speed values succeed low speed values, with a periodicity every six values. These six values correspond to a north pole and a south one passing in front of the three Hall effect sensors. A nice method to correct these variations is to compute a moving average on six points, using the positions chosen for angular resampling. All the variations will compensate each other. Point 4 concerns problems not due to Hall effect sensors. It results on a global shape that can be observed on each revolution. A solution to remove this shape is:

- computing the *cyclic mean*, based on many revolutions in the same conditions (free load rotation, constant speed),
- subtracting this *mean revolution* to every revolution of the signal
- using a low pass filter to reduce remaining noise.

Note that this correction make the moving average detailed previously unnecessary. Corrected and filtered signals can be seen in figure 2 and 3. They concern a characterisation of the cyclic mean on the first 150 revolutions, and a correction on the full signal (two passes: go [250-500] and back [500-750]).

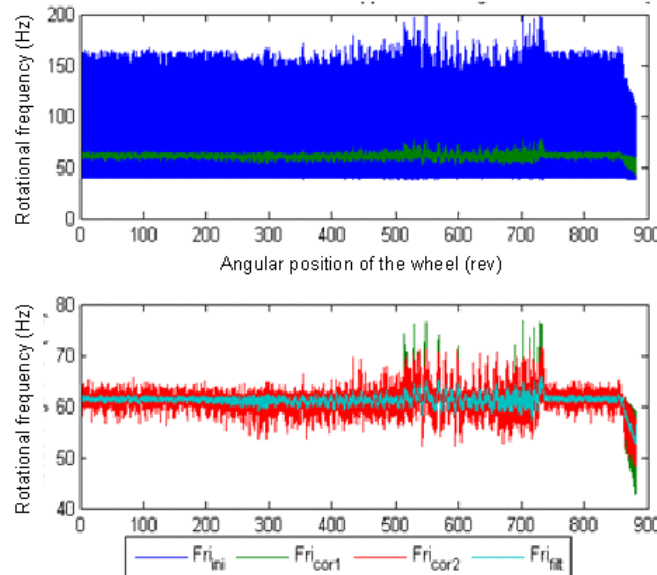


Figure 3: Correction of angular speed, two passes signal

III- Comparing with acceleration

The signal of angular speed – corrected and filtered – is compared with the acceleration in feed direction (figure 4). Moreover, the cyclic part of the acceleration is computed, in order to see the repetitiveness of the moves. This cyclic part is computed continuously, based on twenty consecutive revolutions. The function is easily programmable since the signal is in the angular domain and a revolution of the wheel corresponds to an entire number of samples. The cyclic part (in red) presents amplitudes a bit lower than the original signal (in blue), but the shape is very similar.

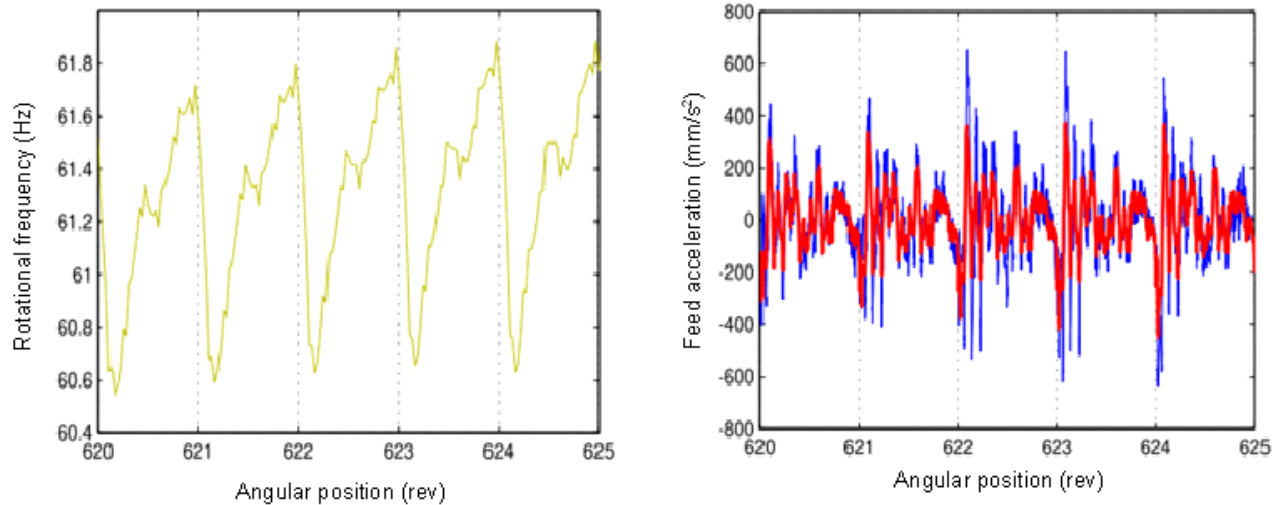


Figure 4: Comparison between angular speed and acceleration in feed direction during grinding

The angular speed is very repetitive, with sudden fall and smoother acceleration for every revolution. A small slowing-down can be seen during the acceleration. On the acceleration signal, a wide edge corresponds to each fall in angular speed. Contact between the grinding wheel and the workpiece is suspected at these instants, with duration similar to the duration of the fall in angular speed – about 30° . The little slowing down can be seen as a small edge in the acceleration signal, and may correspond to a second impact of the grinding wheel on the workpiece. These first observations are very hopeful, but the compatibility of the signal based on Hall effect sensor is difficult to obtain. Tests were thus performed at a rotational frequency of 60 Hz instead of 100 Hz. Moreover, a correction needs to be performed on the angular speed signal so as to reduce the consequences of the difference between the three Hall effect sensors. The angular precision is also only 36 points per turn that is a low. An optical encoder is thus added to the grinder, and another acquisition card is used to improve performances.

IV- (mis)improvement : encoder and angular sampling

An optical encoder with integrated bearings is added to the grinder. The screw of the fans is replaced with a homemade one so as to provide an axis for the encoder, fixed on the grid in the back of the grinder. The encoder gives 1000 pulses/turn, and a frequency divider is used to have only 250 pulses/turn. The acquisition card changes from the DT9837 to the DT9836, which provides the ability to use external clock, and a higher clock frequency for tachometer input (36 MHz instead of 12MHz). Signal from the encoder is connected to the external clock, so as to perform angular sampling, and to a counter/timer input (tachometer), to obtain angular speed. Signal from Hall effect sensors is connected to another counter/timer, also sampled according to external clock. As Hall effect signal provides 36 pulses/turn and is sampled 250 times/turn, corresponding file gives 36 values for counting each time a new value is available, and zero when a value is already read. A moving average on six non-zero consecutive value is performed, so as to avoid variations due to Hall effect sensors. The values are then interpolated on the 250 samples/turn to compare with encoder signal (low pass filtered). Results can be seen on figure 5.

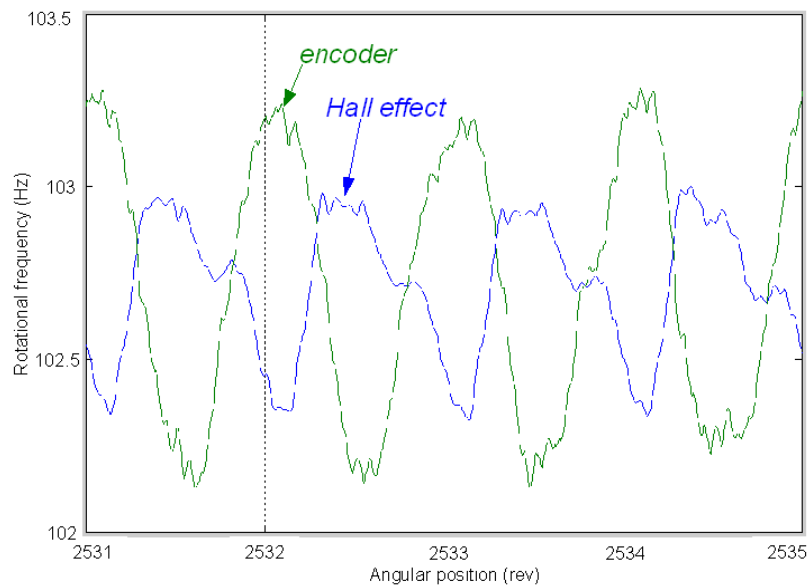


Figure 5: Comparison between Hall effect sensor and encoder signals (after moving average on 6 samples)

Only filtering/moving averages have been performed on the signals, so the characteristics of the coders are still presents on the signals in figure 5. Signal from encoder was expected to be a reference one, so as to know if the signal from Hall effect was goodly corrected. It is very surprising that the signals are in exact phase opposition, whereas the test is a free load rotation. A constant angular speed was supposed in order to correct the Hall effect signal, that cannot be confirmed by the encoder signal. The encoder is not fixed very well, as the added screw is not well aligned. The encoder frame moves according to the rotation of the grinder axis, so the encoder signal shape (~ sinusoidal) could be from this mechanical problem. Thus, previous results cannot be certified, as the reference speed cannot be defined, only supposed constant.

A. Grinding test

A grinding test has been performed, using encoder signal for wheel speed observation. The test concerns the whole grinding of a plate, with 42 passes (21 go and back). Angular sampling is considered. The same displacement has also been tested, with grinding wheel rotation but without grinding (no contact between wheel and workpiece). A time frequency representation is then performed (STFT, figure 6). As the signals are in the angular domain, the frequency axis is not in Hertz, but in event/revolution. As the rotational frequency is about 100 Hz, one event/rev corresponds to about 100 Hz and could be the consequence of one impact per turn, for example.

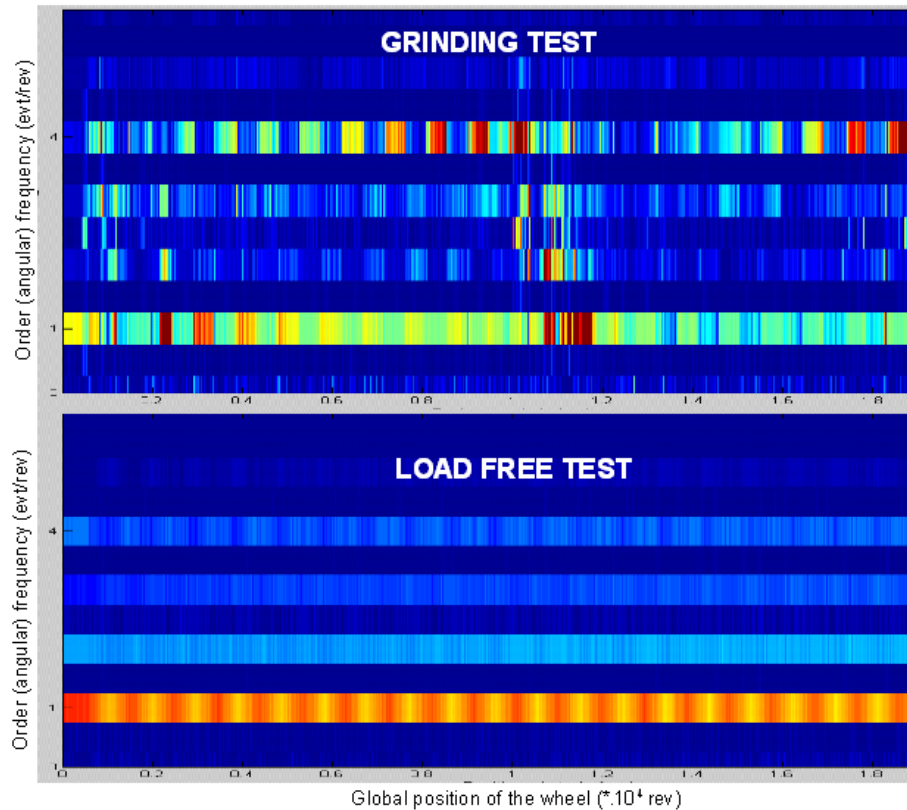


Figure 6: Time frequency representation of angular speed, full plate grinding / full plate move without grinding

Concerning the grinding test (upper part of figure 6), frequency contents for order 1 and 4 are alternatively high (orange/red) and low (green/blue). This periodicity corresponds to go and back passes. In the middle of the test (~11.000 revolutions), orders 2 and 3 can be observed. This zone is also observed on the plate with a surface that is a bit more burned and wavier. On the load free test, the STFT was expected to be constant, that is quite true for order 2-4, but not for order 1 that is different for go and back passes. This is very strange that the amplitude of angular speed variations could change with the direction of the displacement. Is it due to a change in the power consumption of the drives? Is it because the robot vibrations are higher in the back pass, which induces more vibrations of the encoder and parasites angular speed modulations? This test confirms that the use of the added encoder needs to take lot of precautions for interpretation of the results. Even if beautiful figures can be obtained, more care should be considered to add to the grinder or build in a reference encoder, to certify the results.

V- Conclusion

In this paper, the use of angular speed has been tested for monitoring robotic grinding. Many problems have been detected. The signal from Hall effect sensors is not well spaced in the angular domain, and a correction of the angular speed is needed. Considering that the angular speed is constant in a free load rotation, a characteristic of the Hall effect sensors can be defined and used for the correction. That reduces a lot the amplitude of angular speed variations. Some sudden drop in the angular speed can be detected, and are identified as impact between the wheel and the workpiece. An optical encoder has been added to the grinder, in order to have a reference

signal for angular speed, but variations are observed in free load cases. As the encoder is not well fixed to the grinder, these variations can be due to the fixation or can be real ones. Finally, the problem is to know which signal should be trusted, Hall effect sensors, external encoder, or another encoder that could be better designed. Observing angular speed for monitoring the impacts of a grinding wheel with the workpiece are promising, since variations in angular speed can be observed according to accelerations' signal, but the encoder needs to be improved.

VI. Acknowledgments

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