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REFINER DISC GAP AND WEAR MEASUREMENT METHOD

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DYNAMETRIX CORPORATION

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Project summary

This project began in 1995 as the first recipient of the Agenda 2020 program under the sensors and controls category. The project plan was to establish the feasibility of making this kind of measurement, to introduce the technology into the production environment at a paper mill, and to establish the commercialization of the system as a product for the paper industry. Based upon a brief mill trial in 1986 where a simple inductive proximity sensor was mounted into a refiner at an Oregon paper mill, along with the fact that the Pulp and Paper Research Institute of Canada used a similar inductive proximity sensor in their research refiner, we elected to incorporate this basic measurement technology into our project. This assumption on the basic technology for this application was born out in the early project work in the DynaMetrix laboratory.

As part of the feasibility component of the project, DynaMetrix constructed two simulator systems. The first would reproduce the environment where a metal target plate, with grooves mimicking the refiner plate, was driven by a variable speed electric motor. The second simulator was designed to allow testing the dependence that plate wear had on the overall calibration process.

The Oregon Graduate Institute (OGI) was subcontracted to perform materials testing to determine the optimal material to use in the construction of the sensor. Based upon the recommendations of that research, the housing of the sensor was designed and fabricated.

The sensor and the simulator equipment provided the expected voltage pulse signal. The computer equipment was programmed to acquire this signal and convert it from analog to digital. The algorithms for interpreting these pulse signals were devised and implemented in the lab system. We ran numerous designed experiments with this apparatus which lead to the completion of the software for the basic operation of the measurement. The essential preliminary interaction between the operators and the system were devised.

In the original plan, two designed experiments were to be conducted at research facilities. The first was the trial at the Herty Foundation on their small stock refiner. The second was to be at the Institute of Paper Sciences and Technology on their small TMP refiner. The DOE, upon the recommendation of the AF&PA technical committee, cancelled the second experimental design at the IPST TMP refiner, as the two were fundamentally similar except for the nature of the machine being monitored. This accomplished shaving on the order of \$250K from the project budget. The results of the trial at the Herty Foundation were very encouraging. We gathered the necessary data with the portable data acquisition system. This data was reduced at the laboratory and confirmed the measurement. During this trial, a detail that was missed both by DynaMetrix and the J&L Fiber Services company (the plate manufacturer) was that the sensor was mounted at the same radius as the mounting bolts. This resulted in additional pulses during each revolution.

Based upon the progress to date, the system for the Willamette mill was prepared. The plates were modified and the mill made the mounting holes in the refiner casing. The installation went well and the field trials began. When we viewed the signal at the field trial, we first noticed that a previously unseen condition was present. The basis of this was residual magnetism in the plate segments. Up until this time, the rotating plates have been single units. With the large refiner, the plates come in six segments. We were seeing six additional voltage spikes that were positioned in time to correspond with the segment to segment interface. The residual magnetic properties were not uniform from segment to segment, causing the magnetic coils of the sensor to pick up the discontinuities. We went through various steps to reduce this residual magnetism to a minimal level without eliminating the confounding spikes to a degree that the algorithms would operate in a robust manner.

At this point, DynaMetrix understood that they needed to alter the basic sensing element to a methodology that was non-magnetic. A natural choice was to use the ultrasonic mechanical pressure wave for sensing the field. We did some quick experiments and zeroed in on a 100 kilo-Hertz transducer for this task. We designed the processing electronics and tested the technique in the laboratory. This required the fabrication of a third simulator to provide the rotating disk in a fluid suspension. This delay in the project caused us to come to the end of the 3 1/2 year period without providing the end customer mill with a fully functional system. DynaMetrix has submitted

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a proposal for a minimal extension of the program to cover the field trial of the new sensor technology approach, and then, upon successful demonstration of the sensor, to rewrite the front-end software to accommodate the altered signal. The majority of the current software functionality will continue to function. The estimated federal cost is \$150,000 with a like amount of shared non-federal funding needed to bring this to completion as a commercial product.

Technical accounting of entire project

Basis of the Measurement

This section will detail each component of the project. The basis of the measurement is when the distance is sensed from the probe to a surface that wears, coupled with the distance measurement to a surface that remains constant (no wear). Then the equations for the gap between the refining plates and the plate wear can be written as:

$$\text{GAP} = 2X_1 - X_2 + X_T - X_S$$

and

$$\text{WEAR} = X_T - (X_2 - X_1).$$

Where the individual terms are defined in Figure 1.

Figure 1. Measurement Term Definition

The initial sensor technology used, as mentioned in the summary above, was the inductive proximity style device. This consists of a set of coils mounted in a suitable housing. These coils are connected to a signal conditioning module that converts the 1 megahertz oscillation to a zero to one volt analog signal that is proportional to the distance from the sensor to the target. The geometry of our configuration with the target holes mounted in the rotating plate causes the signal conditioning module to put out a signal that looks like what is seen in Figure 2. Note that the baseline of the signal in real systems may have a sinusoidal appearance. This is caused by the fact that the rotating disk is not always mounted perfectly. There is often a mechanical runout and this sinusoidal disturbance to the ideal signal is a direct measure of the runout. The voltages represented by V_1 and V_2 are proportional to the distance measurements X_1 and X_2 referenced in the equations above for GAP and WEAR.

The Simulators

DynaMetrix fabricated two simulation test apparatus in order to obtain dynamic measurements from the sensor. The first unit was designed to simulate the rotating refiner disk and the sensor embedded into a metallic surrounding. The sensor and disk can be moved relative to each other

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to simulate the refiner disks opening and closing the operating GAP. The movement is controlled by a positioning table that has a position accuracy of 0.0001" in three axes of movement.

Figure 2. Postulated nature of the sensor signal

The sensor mount is moved relative to the rotating disk to simulate the actual measurement. The signal obtained from the simulator is shown in Figure 3. We used disks made from aluminum and mild steel. Eventually we modified one of the 16" disks from the Herty trial and mounted that onto the simulator. This gave us a real plate with the metallic alloy typical for use in the paper industry. One short coming of the inductive proximity sensing technique is that the bridge circuit in the signal conditioning module has a strong material dependence in the latest electronics package from the vendor. The simulator can be viewed in Photo 1 at the end of the report. Photo 2 shows the sensor diameter test fixtures used to evaluate diameter change on sensor response.

Figure 3. Actual signal from the refiner simulator

This setup allows us to have a spinning disk in the sensing range of the inductive proximity probe. This disk had two target holes to provide the non-wearing reference surface for the measurement. Early in the testing, we determined that having two target holes offered us the ability to adopt a calibration strategy allowing the measurement to confirm the calibration during each revolution of the disk. The computer algorithms would adjust the necessary gain terms to maintain the appropriate calibration.

Normal refiner plates experience approximately 1/8" of wear during their useful service life, and this needed to be taken into account. The technology embodied in the DynaMetrix approach

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allowed the first direct on-line measurement of the plate wear for the paper industry. Photo 3 indicates the second simulator configuration that tests for the dependence of the calibration as the target disk wears. This simulator has two adjacent ganged sets of metal plates that are moved in relation to each other through a 0.250" range. The sensor views the end of the segment of ganged plates and sees what is like the view of the grooves in a refiner plate. By varying the position of the alternate metal pieces, the sensor sees what is equivalent to a refiner disk that goes from new to worn condition in a controlled manner.

Figure 4 is an example of the data taken from one of the trials on the simulator. This data demonstrates that the voltage increases with increasing gap spacing. The successive curves are from a series of tests taken at increasing gap openings. The two target pulses are seen with the different amplitudes corresponding to the known different depths.

Figure 4. Pulse signal from two different GAP settings.

The designed experiments described later have three factors to examine during the trials. The GAP, the wear and the temperature of the field signal conditioning modules are the key elements to pay attention to. A temperature controlled incubator was installed in the laboratory. This factor posed the greatest potential difficulty to us, although it is common practice in the gauging industry to understand the temperature of specific elements in order to compensate for the thermal drift associated with analog electronics components. During our testing work, we discovered that by having two target holes in the rotating refiner plate, with known different depths, we could eliminate the need to track the temperature and allow our algorithms to recalibrate for each revolution of the disk. This is a significant breakthrough in measurement applications for this field. The few attempts at providing the gap measurement all suffer from frequent drift that renders the measurement of minimal value to the end user. Our self-calibrating methodology is a tremendous feature.

The Oregon Graduate Institute Testing

The internal operating environment of the stock refiner machinery is severely abrasive. The sensor is intended to last for at least 18 months of operation before something is replaced. The sensor would then go through several plate changes. The inductive proximity principle requires a non-metallic "window" between the internal coils in the sensor and the harsh pulp environment. The project plan had allocations for subcontracting some materials research to the Oregon Graduate Institute (OGI) because they have the facility to simulate the particular environment within the refiner processing cavity. This equipment was assembled for earlier work with a consortium of paper industry members interested in the properties of refiner plate wear for various surface conditioning treatments. Their task was to evaluate over 30 different candidate materials for their ability to withstand the conditions for the maximum amount of time. The results

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of the OGI research yielded the optimal material for the end protection of the sensor to be Ultra-High-Molecular-Weight (UHMW) polyethylene plastic. This particular material has over 10 times the abrasion resistance as stainless steel. This UHMW material can be machined as well. The remainder of the sensor body is fabricated out of 317 stainless steel.

With the results of the work at OGI, DynaMetrix then designed the housing configuration for the sensor. Part of the trial work in the laboratory included exploring the diameter of the sensor housing. We needed to find the minimum diameter that could still give us the measurement range of interest. Our trials examined diameters from 1 1/8" through 2", as seen in Photo 2. Our final diameter selection was for 1 1/4" OD. We used 1 1/4" threaded 317 stainless steel rod and had the internal and tip configurations machined to accommodate the UHMW end cap and the vibration connector plug which had to be laser welded in the final stages of assembly. This provided a rugged configuration that has lasted during all of the field trials without any noticeable wear.

System Architecture

During this time, the configuration of the support electronics was established and the software engineering effort was launched. Figure 5 describes the final configuration of the system components. The heart of the system consists of two high-speed Motorola microprocessor boards configured in the VME architecture. One of these CPU boards does the high-speed data

Figure 5. Block diagram of the system electronics.

acquisition on multiple input channels. The second board then takes the resultant linearized data stream and processes the algorithms to extract the gap and wear signals. Interaction with the operator interface on the field panel is controlled from the second CPU. This VME environment allows the inclusion of a third computer component. This is an embedded Pentium PC loaded with Microsoft NT Server and the Microsoft SQL Server software. This then forms a database engine that records the readings and provides the higher-level functions that add value for the end user. The initial components of a web server are included to act as a tutorial mechanism for teaching the end user community within the mill environment how to use the measurements. This promises to be a powerful element in the spread of this technology within the customer mills that are joined with an enterprise Wide-Area-Network, an element that is common for the major paper companies.

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The Herty Foundation Design of Experiment

With the basic feasibility testing and system design behind us, the next step in the research program was the design of experiments at the Herty Foundation research facility. They have a 16" Beloit double-disk stock refiner that was suitable for the initial trials inside of a functioning refiner with pulp present in the material flow. J & L Fiber Services prepared the plates and shipped the five sets to Herty. The refiner was prepared for receiving the sensors. Photo 4 shows the open refiner with the millwright inspecting the installation. Note what was mentioned in the project summary above that the sensor was mounted at the same radius as the mounting bolts. The signal that we collected for analysis then not only had the target measurements, but also contained the additional signals from the target holes. The measurement system algorithm would not be able to use this data stream. The data acquisition system taken to the field recorded the raw data and then the extraction of the information relative to the peak and baseline values needed was done manually. Figure 6 shows the raw data signal with the mounting bolt spikes.

Figure 6. Example of Herty data with bolt hole interference.

We used both an electronic and a mechanical dial indicator on the refiner for reference in setting the gap conditions for the trial. We took data at 600 RPM, 1200 RPM and 1800 RPM, and the signal was repeatable across the entire speed range. We learned that great care needed to be exercised in the selection of the location for the sensor mount.

Mill Trial

The next activity on the project plan was for the mill trial. The measurement computer system had been programmed and the enclosures constructed. Photo 5 is a view of the field panel mounted near the sensors at the refiner. Photo 6 is a view inside the field panel. This is where the user interacts with the system for either calibration parameter entry or to view the operating measurements of the gap and wear. The sensors are connected to the field conditioning modules inside the field panel through flexible electrical conduit. The vibration and splash-proof connector on the sensor allows the easy removal and reconnection to the sensor. Photo 7 is a view of the main computer enclosure that has the system overview CRT screen. This is where the user can view the overall operation of multiple sensors, consider statistical quality control analysis of the recorded information, and review the online tutorial on the use of this measurement technology. Several electronic circuit boards needed to be designed and fabricated where off-the-shelf components were not available. Photo 8 shows an engineering testing the software in the field. Photos 9 and 10 are internal views of the main cabinet. Photo 11 shows the refiner with the field panel and tail end sensor.

The mill did an excellent job at installing the system components. When DynaMetrix arrived on the mill site, the equipment was connected and ready for the final inspection prior to activating the main power breaker. All of the components are rated at the NEMA 4 level for the ability to operate in harsh, wet environments. We had J & L Fiber Services (plate manufacturer) as well as

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Beloit Corporation (refiner manufacturer) consult on the placement of the sensor within the refiner in order to avoid damaging any of the structural integrity of the machine. The location was selected and a template was made for the mill to use in locating the position to bore the necessary holes. Willamette Industries did the machine modifications with the refiner in place during the normal monthly maintenance shutdown. This was good evidence that the technology can be retrofit on existing machines in the industry as opposed to requiring difficult mounting procedures that could only be done at the factory. J & L then prepared the two sets of refiner plates for the trial. These plates were specially treated with the degaussing equipment to remove the residual magnetism. The mill was anxious to start the system up and also had a local machine shop prepare the mounting holes in a set of partially-worn disks just in case that the factory was slow in delivery. This was typical risk-avoidance strategy on the part of the mill and was encouraging that they were eager for the trial to begin. On the other hand, J & L had difficulty with this first set of modified plates. Part of the work was subcontracted and a misinterpretation of the blueprints occurred rendering these new plates unusable for the trial. The mill was justified in having the used plates prepared, and those were mounted in the refiner.

Product Commercialization

From the beginning of the project, DynaMetrix has had a working relationship with the J & L Fiber Services Company and its' affiliation with the Beloit Corporation Pulping Systems group. J & L Fiber Services has the largest share of the market in North America for refiner plates. They view our association as a strategic advantage and have been joint participants with us in pursuing the objective of forming a marketing partnership for introducing this technology into the marketplace. Their existing sales channels and staff are in place and already calling on the potential customers for this technology. Numerous discussions have occurred over the last four years concerning the marketing rights. They have expressed their intent to participate, pending the successful demonstration at the Willamette mill trial.

When the project started, there was a third entity in the corporate affiliation with J&L and Beloit. That was the Measurex Corporation, one of the major players in the paper machine computer control community. Sometime after the project was under way, Measurex purchased their stock back and left that association. Sometime after gaining their independence, the Measurex Corporation was bought by Honeywell. Both J&L and Beloit are in the business of selling metal. They do not have the experience to also market electronic technology. In order to regain the advantage of having an experienced electronics vendor in our commercialization planning, discussions were opened between DynaMetrix and the Honeywell-Measurex Corporation. These talks continue with interest expressed by Honeywell-Measurex in participating, also pending the successful demonstration of the Willamette field trials.

DynaMetrix has undergone extensive planning for the manufacturing process to produce the measurement system for the paper industry. We are lined up to procure, assemble and test the systems prior to moving them into the marketing/sales channels of our commercial partners. The details and logistics are evolving with the expectation that a rapid ramping up of capability will be necessary shortly after the field system becomes operational.

Comprehensive description of results

While these plates were used, they still had over half of their useful life remaining. The level of the signal from the sensor was good. When we examined the data, we were surprised to see additional structure in the signal. These used plates were not processed to remove the residual magnetism, and the effect of this property became evident in the signal we recorded. Figure 7 shows this signal. It is evident that the target pulses are present, along with signals from something else. Upon analysis of the data, the positions of the additional "noise" corresponded to the location around the circular path of the rotating disk where the interface between the individual plate segments were positioned. This was the segment to segment differential residual magnetism interfering with the normal measurement process. The level of these spikes were such that the algorithm to detect the peak was finding additional "targets" that were not useful.

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We set a threshold level that would allow us to find the correct targets, but this process would not work over time and at gap settings that were not consistent. The mechanical runout was evident

Figure 7. Graph of mill data with residual magnetic interference from non-degaussed plates.

as well from the shift in the baseline over the disk revolution. We were able to understand what the machine operators were doing as they first started up the process. This provided additional evidence to us that the economics of the return calculations had a verifiable element. This is associated with the ability to recover after an upset on the machine. When the operators restart the entire paper machine, they lightly load the refiners while the other aspects of the operation are lined out. This can take 15 to 45 minutes. They then slowly load the refiner to the level needed for optimal quality of the sheet. This loading can take an additional 10 minutes as they inch the refining up. Having a direct measure of the gap will allow the operators to quickly ramp the refining level to the correct amount and get to producing grade-A paper 9 to 10 minutes earlier. This quickened response has significant value to the operation of the paper machine.

The mill was to have a shutdown approximately once a month. J & L committed to redo the plate order correctly so that the new plates could be mounted. Figure 8 shows data from this next trial.

Figure 8. Graph of mill data with new "degaussed" plates.

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The extraneous spikes were diminished compared to the data in figure 7, but are still of such a nature that they will not allow the peak detection algorithm to operate in a robust manner. We did confirm that all of the components in the system were functioning correctly. We confirmed that the length of the run from the field panel to the main enclosure could be longer than we specified without degradation of the signal. We recorded the data at both ends of the long run and saw the same exact signal. This is good information because the potential users of this technology usually have several refiners dispersed around the paper machine complex and the single main system will be able to monitor and manage most of the refiners at any one location.

The software was functioning as we expected, notwithstanding the difficulty with the extraneous magnetic spikes in the signal. We created an additional program that can run in a PC that is remote from the actual measurement system. This can either be via modem or via the network link. The user of this program can see an image that duplicates what the operator sees at the field panel display. This was tested at the corporate Southern Region Headquarters in Fort Mill, South Carolina. We demonstrated this for Jim Myers, the Vice President of the fine paper operation. Our executive level support within the Willamette Industry organization remains strong.

Departures from planned content

Second-generation sensor design/fabrication

We returned to the mill the following month to test the new plates from J & L. These plates had been processed for the residual magnetism removal, although they could only claim that the level remaining would be less than one Gauss. We had no means of determining if that was clean enough and were very interested in viewing these in the actual refiner system. When we had the refiner operating, we could see that the amplitude of the magnetic spikes was diminished, but they still existed. Figure 8 shows this data. It is evident that the spikes are smaller, but they are still there and are conflicting with the peak detection algorithm. We discussed the findings with the mill and informed them that we needed to adjust the front-end component of the system that did the sensing inside the refiner. The rest of the system would remain the same. The system was left in an operating condition with the displays indicating that the DOE trial was undergoing calibration trials. We described that the use of ultrasonics offered us a means of making the distance measurements without any interference difficulty with the magnetic properties of the disks. They agreed to hold off with the trial while we prepared the new second-generation sensors for the system.

Second-generation sensor testing in lab

Research was done into the means that would work with ultrasonics in our application. The givens were that we needed to make about 10,000 sample readings per second in order to take sufficient measurements to capture the target holes on the fast RPM systems. We also needed to measure the range of approximately $\frac{1}{2}$ " to $\frac{3}{4}$ " from the sensor to the target. Ultrasonics is used in numerous thickness gauge systems and it has been demonstrated that the accuracy range we seek is achievable. The measurement speed did pose a problem when we did some early testing in the laboratory. We obtained some transducers that operated in the 350 kilohertz range. We used the pulse-echo technique and measured the time of flight of the pulse out to the target and back. When we sped up the measurement beyond 3,000 to 4,000 samples per second, the echo from one sample began to walk up on the tail of the previous measurement, limiting the samples per second that could be achieved. Further research into the application lead to an alternative approach that instead of transmitting short pulses, the transmit transducer would broadcast continuously. The signal would propagate into the refiner, cross the gap, reflect off of the target, and return to the sensor. A second transducer would be situated to receive the reflected signal. Additional electronics then did a comparison of the phase shift between the two signals. As the gap opened, the phase shift would increase, and visa-versa. The output of the electronics is then a pulse where the width of the pulse is proportional to the phase shift. All of the electronics fit into the sensor body. Photos 12 and 13 show this altered sensor body. The connection between the field enclosure and the main system electronics conducts this variable width pulse. A new circuit board at the main system contains an oscillator running at 100 megahertz. The transducer in the sensor is operating at 100 kilohertz, and the electronics evaluates the phase shift on every tenth

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cycle. This gives us 10,000 pulses per second from the sensor. The oscillator circuit is gated on during the pulse and a counter counts the cycles and latches the count when the pulse is completed. The main computer then uses digital input components to transfer this count into the computer memory and then resets the latch for the next pulse. This data transfer requires less internal computation compared to our previous analog approach. We should therefore be able to monitor more sensors. The testing of the new sensor has gone well in the lab. We have created a new simulator that allows to have the spinning disks immersed in water. This is needed because the water is the transmission medium for the sound waves. Our portable data acquisition system is programmed to load the latched values from the counter board and reset it for the next count. We can record enough readings to capture several revolutions of the disk.

We are ready to take this new sensor to the mill for the final functional verification. The project funding brought us to this final situation without actually performing the verification. This next testing must be coordinated with the mill system shutdowns. We are currently discussing this with the mill. When this confirmation test is completed, we will have the necessary information needed to make the decision to perform the modifications to the system to accommodate the new sensor input.

Conclusions

The project has made the majority of the milestones proposed at the beginning of the work. We did experience several unexpected technical hurdles, although the nature of research includes this eventuality as part of the definition. We have found solutions to the difficulties that confront the final success of the project. The stage we are at now is to make the final demonstration that the ultrasonic measurement technique that we have devised will in fact operate in the production refiner environment. The majority of the software written to date will continue to function with the new front-end measurement process. The mill is pleased with the work done to date, and are eager to complete the demonstration. The potential for this technology to benefit the industry continues to be demonstrated and understood. The capability of engineering in the quality parameters desired is emerging as the major potential benefit to be realized from this technology. The mill is already thinking of how to expand the ramifications of this new knowledge. They have extended the reach back into the pulp mill as an indication of changes that may likely not be noticed by other means. This alert will allow early corrections to their operation yielding a more productive overall operation of the plant.

Recommendations

DynaMetrix has submitted a proposal for a small funding extension for this work. The original project was funded at \$1.78MM, which included both the federal and non-federal elements. The federal funding limit was reduced to \$1.15MM and the non-federal contribution reached \$450K as the project ended in January, 1999. The extension requested is for \$150K in federal funding and a like amount in non-federal funding to complete the program. The estimation of six (6) months was made in order to complete the software revisions and the front-end hardware changes. This would then leave the mill with a functioning system. DynaMetrix would continue supporting the mill staff to work through the training issues and the application development under the real manufacturing conditions in the mill.

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Appendix

Photos

Photo 1. Lab simulator for gap

Photo 2. Sensor diameter test fixtures

Photo 1 shows the rotating refiner simulator with the motor speed control and the sensor holding fixture. The sensor mount is installed on the 2-axis positioning table. Photo 2 is the sensor diameter test fixtures. The diameter studied was from 1 1/8" OD to 2.0" OD in 1/8" increments. The Eddy current slots were installed to minimize the side loading of the metal body on the coils.

Photo 3. Lab simulator for wear

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This is a single-axis device consisting of ganged interleaved plate segments that are servo-controlled through the $\frac{1}{4}$ " movement range. The sensor viewed the end of the fixture to simulate refiner plates as they wear during the life of the plate. The calibration requires compensation based upon the condition of the wear.

Photo 4. Herty 16" Beloit research refiner

The sensor can be seen near the millwrights right hand. Note that the sensor is at the same radius as the mounting bolts. This posed an inconvenience to the trial, making it more tedious in extracting the trial measurement data. This plate segment is in a single cast plate.

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Photo 5. Outside view of the remote field panel mounted along side of the refiner at the mill

Photo 6. Picture of inside of the field panel during lab test

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Photo 7. Main system enclosure

These photographs show the inside of the main equipment rack. The redundant power supplies for all field devices are at upper left.

Photo 9. View of upper panel inside the main enclosure

Photo 8. Engineer testing software in field

Photo 10. View of lower panel inside main enclosure

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Photo 11. The 46" Beloit refiner at the Willamette Industries mill with the trial system installed. This particular refiner is the swing refiner that can process both long fiber and short fiber pulp streams.

Photo 12. Second-Generation sensor housing design

Photo 13. Inside view of the second-generation sensor