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Smart Screening System (S3)

In Taconite Processing

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Report Author
Dr. Daryoush Allaei, P.E.
Mr. Asim Syed Mohammed

Report Editors
Dr. Daryoush Allaei, P.E.
Mr. David Tarnowski
Mr. Asim Syed Mohammed

Any questions or comments regarding this report
should be directed to the principle investigator

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ABSTRACT

The conventional vibrating machines used in processing plants have had undesirable high noise and vibration levels. They also have had unsatisfactorily low screening efficiency, high energy consumption, high maintenance cost, low productivity, and poor worker safety. These conventional vibrating machines have been used in most every processing plant. Most of the current material separation technology uses heavy and inefficient electric motors with an unbalance rotating mass to generate the shaking. In addition to being excessively noisy, inefficient, and high-maintenance, these vibrating machines are often the bottleneck in the entire process. Furthermore, these motors, along with the vibrating machines and supporting structure, shake other machines and structures in the vicinity. The latter increases maintenance costs while reducing worker health and safety.

The conventional vibrating fine screens at taconite processing plants have had the same problems as those listed above. This has resulted in lower screening efficiency, higher energy and maintenance cost, and lower productivity and workers safety concerns. The focus of this work is on the design of a high performance screening machine suitable for taconite processing plants.

SmartScreens™ technology uses miniaturized motors, based on smart materials, to generate the shaking. The underlying technologies are Energy Flow Control™ and Vibration Control by Confinement™. These concepts are used to direct energy flow and confine energy efficiently and effectively to the screen function. The SmartScreens™ technology addresses problems related to noise and vibration, screening efficiency, productivity, and maintenance cost and worker safety. Successful development of SmartScreens™ technology will bring drastic changes to the screening and physical separation industry.

The final designs for key components of the SmartScreens™ have been developed. The key components include smart motor and associated electronics, resonators, and supporting structural elements. It is shown that the smart motors have an acceptable life and performance. Resonator (or motion amplifier) designs are selected based on the final system requirement and vibration characteristics. All the components for a fully functional prototype are fabricated. The system is assembled and tested under laboratory and field conditions. The lab results are promising and the field test resulted in system performance drop due to plant structure not able to provide the required stiffness. The PZT-based Smart Motors performed better than expected. None of the Smart Motors failed during testing and the results were very encouraging. The development program is on schedule.

Supporting structure was modified to improve system rigidity and integrity to help improve overall system performance. The improved supporting structure was fabricated and tested in the lab and in field. Results showed a significant improvement in reducing undesirable supporting structure vibration, better system performance and ease of installation.

We plan to work on system installation sensitivity to relax plant structure foundation requirement. This would be necessary for the PZT-based system to perform better and not loose energy into the plant structure.

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INTRODUCTION

Current screening machines have one thing in common: they operate using an electrical motor with a rotating unbalanced mass to generate shaking. Based on the information from Minntac Grant Application [1], Minntac has struggled with finding engineering solutions to noise and vibration problems caused by conventional screening machines. Evaluations of isolation curtains/walls, different screening machine brands, and lower speeds have resulted in minimal improvements in noise levels and have significantly compromised production. Blinding of screens is another major cause for loss in production. Minntac has estimated that approximately 2494 megawatt hours per year alone are lost due to poor screening recovery and wasted energy.

The ultimate goal of this project is to develop SmartScreens™ that will replace the inefficient massive electric motors. SmartScreens™ will have miniaturized smart motors (ceramic- or electromagnet-based). SmartScreens™ will incorporate an energy management technique to control energy flow and will confine injected shaking energy to the screen panels. In 2002, the QRDC team proposed to combine state-of-the-art smart materials, the concept of single or multi-stage resonators, and the patented energy management technique. This innovative technology has won several Research and Development awards from the U.S. Army, Navy, and Air Force and commercial organizations [2-5].

In the previous reporting periods, it was shown through computer simulations and laboratory prototypes that smart motors, accompanied by specially designed resonators, meet current screening vibration levels while simultaneously significantly reducing power consumption and energy loss. The ceramic materials and electromagnetic drives used in these motors are well suited for applying large dynamic forces and the required shaking functions to resonators. The smart motors consume 50% to 96% less energy than the bulky electrical motors, and are capable of operating over a wide range of frequencies. They are almost maintenance free, as they do not have any moving components and do not need lubrication. Additionally, smart materials (such as PZT) can function as both collocated sensors and actuators for active control of the shaking action and process automation.

In the first semi-annual report [7], it was shown that cantilever resonators of appropriate shape and size could be used to amplify the displacements and accelerations of the miniaturized ceramic motors so that the screening function was optimized. Finally, it was shown through simulations that the system can be optimized and completed by incorporating the energy management techniques that have been developed by QRDC. Energy management is composed of energy diversion, confinement, dissipation, conversion, and cancellation. It was the combination of smart materials and these vibration energy managing methods that made this approach unique and innovative.

In the second reporting period [8], QRDC was able to design, fabricate, and evaluate the key components of the SmartScreen™. The benefits of these prototypes were shown to be close to the predicted performance. They included: broader *and* finer control of the screening frequency, extremely low power consumption, tremendous reduction in operating noise level, and remarkable reduction in transmitted vibration from the screen to the supporting structure. The increased control over the motor frequency allowed QRDC's SmartScreens™ to be tuned for optimum operation and to be regularly changed to potentially avoid blockage or blinding of screens. Power consumption reduction allows for savings as well as increased potential number of screens to be in operation at one time. Noise and floor

vibration level reductions improve worker safety as well as productivity. Additionally, reductions in vibration transmittance to the supporting structure potentially reduce floor vibrations, which may prevent interference in one screen's operation from another.

The third semi-annual report [8] shows the finalization process of the key components that includes smart motor, resonator and supporting structure. It also details the assembly and evaluation of full SmartScreens™ system under laboratory conditions. This report also covers the details of Oscillating Mass (OM) driver to power full SmartScreens™ system and the lab test results.

In this reporting period, a full SmartScreens™ system was successfully tested under dry and wet conditions. The lab test results of full system and vibration reduction on supporting structure were better than expected. Longevity test of smart motor using a quarter system achieved more than a year of operating time while operating round the clock. Full SmartScreens™ system with PZT-based smart motors was successfully tested in field for one week and none of the smart motor showed any signs of failure. During this period a detail computer based analysis was also done to further improve system performance and to reduce stringent installation requirement.

The ultimate goal of this project is to develop SmartScreens™ that will replace the inefficient massive electric motors. SmartScreens™ will have miniaturized, ceramic-based smart motors. SmartScreens™ will incorporate an energy management technique to control energy flow and will confine injected shaking energy to the screen panels. As part of the development efforts of SmartScreens™, a Steering Committee for Smart Screen Systems (SC-S3) was formed. Members of SC-S3 are QRDC (leading role), ARC (Albany Research Center, provide solutions that makes National's energy systems safe, efficient, and secure), U.S. Steel-MINNTAC (Minnesota ore operations), Ispat Inland Mining, S3i (Smart Screen System Inc.), and a representative of DOE-NETL. The QRDC team proposed to combine state-of-the-art smart materials, the concept of single or multi-stage resonators, and QRDC's recently patented energy management technique. This innovative technology has won several Research and Development awards from the U.S. Army, Navy, and Air Force and commercial organizations [2-4].

A miniaturized motor consumes 96% less energy than the bulky electrical motors and is capable of operating over a wide range of frequencies. These motors are almost maintenance free as they do not have any moving components and do not need lubrication. Piezoelectric ceramic material (Such as PMN= Lead Magnesium Niobate, and PZT=Lead Zirconate Titanate) can be miniaturized. Ceramic materials are well suited for applying large dynamic forces and the required shaking functions to resonators. In addition, ceramic materials will function as collocated sensors and actuators for active control of the shaking action and process automation. Cantilever resonators of appropriate shape and size will be used as resonators to amplify the displacements and accelerations so that the screening function is optimized. The combination of resonators and smart materials will offer full control and precision of the shaking function. Finally, the system will be optimized and completed by incorporating the energy management techniques that have been developed by QRDC. It is the combination of smart materials and the vibration energy managing method that makes the approach unique and innovative. Energy management is composed of energy diversion, confinement, dissipation, conversion, and cancellation.

The proposed technology offers significantly better energy management by controlling the flow of energy and confining it to screen panels rather than shaking the

supporting frame, motor and surrounding structure. SmartScreens™ offers better control over the speed of operation, and type and magnitude of motion. These abilities help to quickly clean the screens and avoid blockage or blinding of screens. Use of miniaturized motors and by focused energy, SmartScreens™ eliminates and/or downsizes many of the structural components typically associated with industrial screens. As a result, the surface area of the screen increases for a given space envelope. This increase in usable screening surface area extends the life of the screens and reduces required maintenance. Energy management and better control on the screening process helps to remove particles of the correct size and thus increases the throughput, reduces material re-circulation and significant reduction in power consumption.

During last two quarters, we have focused on testing, evaluation and refinement of the key components of the proposed smart screen systems. These key components were fabricated, assembled & tested in lab and in field. The full system was evaluated under dry and wet conditions. Through computer based analysis, an attempt was made to minimize installation requirement and improve system performance.

This report summarizes the work since the last semi-annual report (Quarter 2-2004 & Quarter 3-2004) and has three main chapters. Chapter 1 is directed towards the lab and field testing of the full system. Chapter 2 gives details on computer based analysis to improve system performance, reducing sensitivity to installation and improve fatigue life of resonators. A summary of findings, results, and recommendations are found in Chapter 3. Appendix A contains proprietary information and is referenced in the main body of the report.

EXECUTIVE SUMMARY

Two undesired components of the material processing industry are excessive consumption of energy and extreme noise and vibration. Current screening machines use an electrical motor with a rotating unbalanced mass to generate shaking. These motors not only generate motion in the screen panels but also shake the supporting structures and other machines and structure in a plant. During initial field investigation on existing screening machines, it was found that the existing vibrating screens are inefficient, noisy and waste significant amounts of energy. Many areas were identified that need either improvement or complete changeover. These areas include, material handling, screening process, screen blinding, moving mass, motion, energy consumption, noise levels and vibration transmission, and workers safely.

To address the above-mentioned issues, QRDC proposed an innovative concept, SmartScreens[™] technology, based on smart materials (miniaturized motors), and Energy Confinement and Flow Control. This project is jointly funded by the DOE and industry partners that include representatives of the mining industry ISPAT INLAND MINING, U.S. Steel-MINNTAC (Minnesota ore operations), QRDC (a technology company with an extensive relevant track record), S3i (screen manufacturing company transferring the prototypes to full marketable and producible products), and the Albany Research Center (provide solutions that makes national energy systems safe, efficient, and secure). The key objective of this project is to demonstrate the feasibility of energy management-based SmartScreens[™] that can efficiently handle and process material separation. SmartScreens[™] has the capabilities to control the flow of energy and confine this energy to the screen itself rather than shaking the entire machine and the surrounding structure that comprise the conventional vibratory screening machine. Better control on energy flow results in better screen recovery and reduced re-circulating load of the slurry. Single or multi-stage resonators with an advanced sensory system will be used to continuously monitor screening processes to improve productivity. Smart material-based miniaturized motors offer better control over speed of operation, and type/magnitude of motion. These abilities help to effectively clean the screens and avoid blockage or blinding of the screens. Miniaturized motors eliminate any moving components like bearings and bulky unbalance rotating mass. This in turn virtually eliminates noise. With the proposed SmartScreens[™] technology, the weight of the moving mass can be reduced by as much as 80% and thus, results in significant reduction in energy usage.

In the development efforts of SmartScreens[™], baseline data was obtained and initial field investigation was completed to identify problem areas in the current fine screens. Based on this information, a plan was developed that identified the basic design requirement to improve and efficiently handle the screening process. Various conceptual designs were identified for the key components of the system. These key component designs (i.e., smart motor and motion amplifiers or resonators) were modeled in CAD programs and analyzed through computer simulation and experimental tests. Some of the key component designs were selected and a full system was modeled that included the screen panel, four resonators, miniaturized smart motors, and the supporting structure for resonators and screen panel. The performance of these key components and systems was analyzed under various loading conditions through finite element analysis and experimental tests. Based on these results,

three systems were selected. After a detailed review, one or two of these key components and systems were fabricated as a prototype for the SmartScreenTM.

The PZT-based system and current production units performed better than expected. The results of the suspended unit were very encouraging. None of the Smart Motors failed during testing. The tests were successful. The modified supporting structure not only improved system performance but also reduced undesired supporting structure vibrations. The longevity test of smart motor surpassed one year operating time without any signs of performance loss or failure.

We plan to investigate and modify system installation design to make system operation independent of installation. A system which is less sensitive to boundary condition (installation) should help improve overall system performance. Besides experimentation, finite element analysis of few designs to isolate system from plant structure, improve resonator fatigue life and improve overall system performance was carried out during this period. Further analysis and fabrication will be carried out in the next period.

The SmartScreensTM technology with its capabilities to reduce current energy requirement, maintenance cost in screening operations, improve throughput, and reduce noise and vibrations levels can impact the global process industries. The widespread application of the proposed technology could change the way material separation is handled in general processing industries. Candidate industries are oil and gas, mineral processing, food processing, and pharmaceutical applications.

CHAPTER 1 – EXPERIMENTAL

The full SmartScreen™ system and key components were evaluated under dry and wet conditions during this reporting period. The details of each test that includes supporting structure evaluation, full system performance in lab and field, dynamic force measurement of smart motor and longevity test of smart motor are presented in this section. To fully understand the content of this section, the reader is advised to review the previous reports [7-8-8].

1.1 Supporting Structure Evaluation

As shown in Figure 1.1.1, the supporting structure on which the resonator and smart motor were mounted was redesign to improve overall system performance. The key objective of this effort was to reduce structure vibration, retrofit magnetic/smart motor and eliminate soft structures (static plate & legs, refer Figure 1.1.2). Some of the improvements expected out of this new supporting structure design were:

- Single member design that eliminates need of static plate, most of the attachment, nuts and bolts and various fabrication processes.
- Improve system performance by reducing losses between various interfaces and structure deformation, Figure 1.1.3 shows FEM results on structure.
- Improve overall rigidity of the system and provides better coupling between each resonator.
- Improve fatigue life of resonators by minimizing resonator rotation due to undesired supporting structure deformation.
- Requires less time for assembly and minimizes maintenance cost.

As shown in Figure 1.1.1, the supporting structure was designed to directly mount the resonator and the PZT-based Smart Motor (SM) assembly on the structure without any additional interface. The resonator and PZT-based SM mounting block which is integral part of the supporting structure was designed to fit both magnetic motors and PZT-based SM. This design allows to independently install smart motor and resonator and uses only two bolts to mount the smart motor. It requires less than 5 minutes for changing the smart motor by one person. This modified structure was much stiffer than the old supporting structure and the natural frequency of first mode was above 200 Hz (refer Figure 1.1.4). Figure 1.1.5 show a final production unit with modified structure and conduit wiring. As expected the modified structure improved system performance and significantly reduce undesired vibration on the supporting structure. Lab and field results of full system with this modified supporting structure are described in detail in the following section.

1.2 Full System Evaluation

Full system that includes all critical parts that influence system performance were assembled and evaluated at the QRDC laboratory, S3i laboratory, CMRL (Coleraine Mineral Research Laboratory) and in field at Ispat Inland Mining. Critical part includes panel, livedeck, split curved resonator, PZT-based smart motor and supporting structure. Other parts

used that do not influence system performance were feed box, under-size hopper and over-size bin. Split curved resonators were used as the final design for two reasons. First, the current magnetic-based production unit uses the same resonators. This makes the retrofitting much simpler. Second, the split resonator was shown to have lower stress levels and therefore, an improved fatigue life.

To optimize system performance, consistent procedure was adopted every time system is moved and assembled on different structure. Calibrations were performed to optimize each smart motor performance for given preloads. For this purpose one motor at a time was turned on and the performance was optimized by adjusting the preload and adding shims between push rod and resonator as necessary. In the final product these adjustment won't be necessary and PZT-based SM can be used as plug & play device. The below Figure 1.2.1 shows the displacement measurement location on livedeck for all the tests conducted in lab and in field. All data was collected in mils peak-to-peak.

Figure 1.2.1 Measurement location on panel

Test Results: Although the redesign supporting structure minimized interface losses and undesired structure vibration, the system was still sensitive to boundary conditions (foundation). Due to this sensitivity the vibration data collected at different labs and in the field test does not match. To optimize system performance, the same procedure was adopted at all three labs and in the field test.

Vibration measurement under dry and wet condition: Under dry condition system performance was measured at six locations along the panel. Under wet condition system performance was measured on panel at 3 locations on the rear end (feed end).

QRDC Lab: System was tested under both dry and wet condition. For wet condition a garden hose pipe with finite number of holes was used to uniformly distribute water on the screen. Table 1.2.1 shows system performance with one smart motor on and other three off. Due to resonator orientation, system angle and center of mass, system is not symmetric between front and rear end. This results in different system performance and operating frequency with rear and front end motors. Optimum performance of the system with rear motor active was found at 43Hz and at 41.8Hz with the front motor active.

Table 1.2.2 depicts system performance with both front smart motor active and rear motors off and vise-versa. Once again the performance of the system is better with both front motors active that agrees with the results in Table 1.2.1.

Table 1.2.3 shows the results of full system with all four PZT-based smart motors active under dry and wet condition. In this case system performance is consistent in the flow direction however in the vertical direction rear end has more stroke than the front end. The

difference in vertical motion is because of the resonator orientation, which can be reversed by reversing the resonator. However it is desirable to have more motion at the feed end to effectively process the material.

Table 1.2.1 System performance with one PZT motor ON & other three OFF

Meas. Location	D R Y T E S T							
	loc.1 motor active		loc.3 motor active		loc.4 motor active		loc.6 motor active	
	Flow	Vertical	Flow	Vertical	Flow	Vertical	Flow	Vertical
1	5.35	5.66	5.38	5.55	8.73	9.62	9.22	10.18
3	5.46	6	5.22	5.84	9.91	10.28	8.77	9.02
4	5.22	2.39	5.34	2.14	8.86	4.15	8.51	3.17
6	5.45	2.46	5.4	3.07	8.61	3.44	9.06	3.77
Note: Freq with motor 1 & 3 active: 43Hz and with 4 & 6 active: 41.8Hz; Units: mils p-p								

Table 1.2.2 Vibration measurement on livedeck with two smart motors active at a time

Measurement Location	D R Y T E S T			
	Front – On & Rear – Off		Front – Off & Rear – On	
	Flow	Vertical	Flow	Vertical
1	17.6	19.62	11.43	12.57
2	20.18	21.06	13.5	13.87
3	18.03	17.49	12.1	12.4
4	18.14	8.82	11.62	5.61
5	18.55	8.07	12.5	6.19
6	17.15	6.54	12.11	4.91

Table 1.2.3 Vibration measurements on live deck with all PZT motors active

Meas. Location	D R Y T E S T			W E T T E S T		
	Flow	Vertical	Resultant	Flow	Vertical	Resultant
1	24.51	25.82	35.6	20.39	21.15	29.37
2	28.76	29.74	41.37	24.11	25.82	35.32
3	24.37	27.55	36.78	22.28	24.69	33.25
4	24.71	9.81	26.58	-	-	-
5	26.22	11.67	28.69	-	-	-
6	25.26	11.25	27.65	-	-	-

Observations:

- 1) Damping due to added water was very minimal and system maintained its performance over the period of time.
- 2) Motion was very strong on the livedeck however there was some vibration transmission to the floor.

S3i Lab: Similar test as explained above was conducted at S3i lab in Chisholm. System was tested only under dry condition as the lab was not quipped to run wet test. Both production unit (suspended magnetic system) and PZT-based full system were mounted on common structure. The results of these tests are shown in Tables 1.2.4 through 1.2.6. Results clearly show the system performance improved from QRDC lab test. The reason for the performance improvement was rigid foundation that provided optimum boundary condition to the system.

Table 1.2.4 System performance with one PZT motor ON & other three OFF

Meas. Location	D R Y T E S T							
	loc.1 motor active		loc.3 motor active		loc.4 motor active		loc.6 motor active	
	Flow	Vertical	Flow	Vertical	Flow	Vertical	Flow	Vertical
1	15.61	18.3	15.4	17.8	14.39	16.91	17.79	20.71
3	15.88	19.1	15.75	15.5	15.01	17.55	17.55	22.16
4	15.25	10.28	14.18	10.15	13.54	9.32	17.54	11.85
6	15.67	10.33	15.7	10.3	13.34	8.11	17.41	11.61
Note: operating frequency with all motors was 46.8 Hz; displacement units: mils p-p								

Table 1.2.5 Vibration measurement on livedeck with two PZT motors active at a time

Measurement Location	D R Y T E S T			
	Front – On & Rear – Off		Front – Off & Rear – On	
	Flow	Vertical	Flow	Vertical
1	25.8	30.3	23.5	27.75
2	30.1	34.5	28.1	32.4
3	28.1	34.0	23.2	30
4	25.3	17.4	23.3	15.5
5	28.0	19.6	25.3	17.6
6	27.3	17.7	24.5	15.7

Table 1.2.6 Vibration measurements on livedeck with all PZT-based smart motors active

Meas. Location	Dry Test			Wet Test		
	Flow	Vertical	Resultant	Flow	Vertical	Resultant
1	48.4	57.3	75	-	-	-
2	57.3	67.9	89	-	-	-
3	50.4	62.6	80	-	-	-
4	47.6	32.0	57	-	-	-
5	52.3	36.0	63	-	-	-
6	50.2	33.3	60	-	-	-

Observation:

There was no cross talk between suspended magnetic system and PZT system. Running both units at the same time did not influence PZT system performance.

CMRL Lab: System was tested under both dry and wet condition. PZT system was mounted on an elevated lab structure supported on I-beams. Both production unit with magnetic motors and PZT-based system were mounted on common structure. Dynamics of the system was significantly influenced by CMRL structure resulting in significant PZT system performance drop. A quick impact test on livedeck resulted in many system natural frequencies (41, 45, 48, 51, 54, 60) closely spaced near target mode. Figure 1.2.2 shows the result of impact test on live deck in vertical & flow direction and Figure 1.2.3 shows impact test result on CMRL structure. On further analysis, it was found that the supporting columns of the structure were just resting on the floor without any rigid connection with the floor. This caused the PZT-based smart motors to leak energy to the lab superstructure and vibrations were observed all over the structure. Table 1.2.7 shows measurement on panel at single location with one motor on at a time. Due to small stroke, measurements were not recorded at other points.

Table 1.2.8 illustrates system performance at two different frequencies to which the system responded well. Operating deflection shape (ODS) data collected on the PZT system resulted in unexpected deformation shape. Data at 41Hz showed significant out-of-phase motion between livedeck and supporting structure and data at 51Hz resulted in rotational mode, refer Figure 1.2.4 for ODS plots.

During wet test system lost some performance while operating at 41Hz and the second best performance was recorded at 46.8Hz. Table 1.2.9 shows wet test results. To evaluate the influence of magnetic unit on PZT system performance, one unit was made active at a time and the performance was recorded on both systems. From Table 1.2.10 it is clear that there was hardly any noticeable influence of one unit on another.

Table 1.2.7 System performance with one PZT motor ON & other three OFF

Meas. Loc.	D R Y T E S T							
	PZT at loc.1 ON		PZT at loc.3 ON		PZT at loc.4 ON		PZT at loc.6 ON	
	Flow	Vertical	Flow	Vertical	Flow	Vertical	Flow	Vertical
2	3.6	5.1	3.5	4.7	6.3	8.8	5.2	7.2
Note: data was recorded while the system was tune to 41.2Hz.								

Table 1.2.8 Vibration measurements on live deck at two different frequencies

Location	D R Y T E S T					
	Freq: 41.2			Freq: 50.5		
	Flow	Vertical	Resultant	Flow	Vertical	Resultant
1	9.8	8.8	13	13.5	10.2	17
2	10.57	10.28	15	17	12	21
3	10.8	8.6	14	15.8	12.3	20
4	8.6	4.1	9	12.7	4	13
5	8.9	4.9	10	16	4.8	17
6	9.2	5.2	11	16	3.8	16

Table 1.2.9 Vibration measurements on live deck with slurry – all PZT motors active

Location	W E T T E S T					
	Freq: 41.2			Freq: 46.8		
	Flow	Vertical	Resultant	Flow	Vertical	Resultant
1	5.7	4.5	7	9.1	11.4	15
2	6.5	5.1	8	10 - 11	13 – 16	16-19
3	6.3	6.2	9	9.3	11.8	15

Table 1.2.10 Influence of suspended system on PZT system & vice versa

Meas. Loc.	Magnet: ON; PZT: OFF		Magnet: OFF; PZT: ON		Both ON	
	Flow	Vertical	Flow	Vertical	Flow	Vertical
Measurement on production unit (Suspended magnetic unit); Freq: 51.88						
1	61	71	2.2	2.2	66	77
2	76	78	2.3	2.2	83	85
3	54	59	2	1.7	53	58
Measurement on PZT-based system; Freq: 51.19						
1	2.2	2.2	11	10.1	11	9.4
2	2.2	2.2	14.5	11.8	13	11
3	2.1	2.1	14	11.6	12.8	10.9

Observation:

- 1) Performance of the PZT system under dry condition dropped by more than 75% compared to S3i lab results.
- 2) Number of persons standing on the structure and their location influenced system performance either by dropping or improving the performance.
- 3) A displacement of up to 3.3 mils p-p was recorded on CMRL structure columns.

Ispat Inland Mining (IIM) Plant: Similar problems as faced during test at CMRL were experienced with IIM structure. Two similar units one with PZT-based motors and other with magnetic motors (without suspension) were installed on common structure. Performance of both units dropped significantly, which means isolation between plant structure and SmartScreens™ system is required irrespective of motor type i.e. magnetic motor or PZT-based SM. Beside target mode frequency, smart motors were tuned to wide range of frequencies to find other system resonance.

Table 1.2.11 show all the measured data collected at the center of rear end (location 2) in both vertical and horizontal direction. It is clear from the data that both system cross-talk and no matter which unit is active both systems vibrate. Phase measurements were taken on Magnetic system on the side of panel near feed end and the bottom of supporting structure.

Table 1.2.11 Vibration measurement on PZT and magnetic unit at Ispat Inland Mining test

Active System	Measured System	Freq [Hz]	Test Condition	Disp. [milsp-p]		Comments
				Flow	Vertical	
PZT	PZT	48.9	Dry	11	15	Target mode
PZT	PZT	111.3	Dry	5	17	Panel mode
PZT	PZT	48.9	Wet	7	10	Loss 35%
PZT	PZT	48.2	Wet	8	11	Re-tuned
PZT	Magnetic	48.9	Dry	4.5	6.4	
PZT	Magnetic	48.9	Wet	3.4	5	
Magnetic	Magnetic	48.9	Dry	17	26	Max. power
Magnetic	Magnetic	48.9	Wet	13	18	
Magnetic	Magnetic	49.4	Wet	13	19	Auto tune
Magnetic	Magnetic	41.4	Wet	14	25	Manual search
Magnetic	PZT	48.9	Dry	20.4	24.6	
Magnetic	PZT	48.9	Wet	12	13	
Both	PZT	48.9	Dry	17-22	20-28	
Both	Magnetic	48.9	Dry	15-24	22-29	

1.3 Smart Motor Force Evaluation

This section details the final stage of work on the development of PZT-based smart motors. The purpose of this test was to determine experimentally the output force capacity of the PZT-based smart motors. To accomplish this, back portion of the smart motor assembly was modified and a PCB Piezotronics force transducer was installed inline with ceramic (PZT motor). Since only one smart motor assembly was made capable of recording dynamic force using a force transducer, in two separate test the motor was installed at two locations one in front and another in the rear. Dynamic force generated under operation was measured with one motor active at a time and finally with all four motors active. Figure 1.3.1 & Figure 1.3.2 shows the final assembly of this test. Appendix A, section A.1 gives details of the PZT-based smart motor and Figure A.1.1 & Figure A.1.2 the final assembly.

Baseline vibration data was collected on the full system with all four smart motors active. This data was compared with the data collected after replacing one smart motor with modified smart motor. Addition of force transducer did not have any influence on system frequency or performance. Time Trace data showed force oscillation are very smooth sinusoidal wave form, indicating there is no separation of the push pin from the PZT during operation Below are the details of experimental results:

- Force Transducer Located at Front Right (location 4)
 - Force with front right motor alone – loc. 4 motor active = 475 lbf
 - Force with front left motor alone – loc. 6 motor active = 220 lbf
 - Force with rear right motor alone – loc. 1 motor active = 125 lbf
 - Force with rear left motor alone – loc. 3 motor active = 125 lbf
 - Force with all four motor active = 775 lbf

- Force Transducer Located at Rear Left (location 3)
 - Force with front right motor alone – loc. 4 motor active = 150 lbf
 - Force with front left motor alone – loc. 6 motor active = 135 lbf
 - Force with rear right motor alone – loc. 1 motor active = 75 lbf
 - Force with rear left motor alone – loc. 3 motor active = 450 lbf
 - Force with all four motor active = 675 lbf

1.4 Smart Motor Longevity Test

PZT based smart motor assembly (refer Figure A.1.1 & Figure A.1.2) was designed with the objective to deliver stroke/force of the piezo ceramic while minimizing non-uniform reaction forces on the ceramic surface, protect the ceramic from environment and any alien objects and to maintain preload at all time. To verify the performance of this assembly over a long period of time, longevity test was started on 8th September 2003. Figure 1.4.1 show the system setup with an added mass of 45 lbs on top of the resonator. For all practical purposes this system represents a quarter system of actual full system. The operating frequency of this system was setup at 12 Hz. The test is still ongoing with more than a year of operating time and more than 378 million cycles so far. Till date there are no signs of performance loss or any damages to the ceramic or any part of the assembly.

CHAPTER 2 – FEM ANALYSIS

The key objective of this part of the work was to identify isolation requirement to make system performance installation independent and to further improve system performance and resonator fatigue life. What follows in this chapter are descriptions of what steps were taken in the design refinements, and what analysis were performed to achieve above mentioned objectives.

2.1 PZT-Based System Isolation

As mentioned in the earlier chapter, the system performance is heavily dependent on installation condition as PZT-based smart motor needs rigid structure to push against to efficiently direct the energy to moving mass, which in this case is livedeck and panel. Since the stroke generated by ceramics is very small, in the order of 2-3 mils, any movement in the structure against which the ceramics is pushing will cause a drop in overall system performance. This problem can be addressed through different ways such as, use of oscillating mass (OM) driver [6-7], different mode excitation, system isolation from foundation and feeding energy back into moving mass, displacement input instead of force input, over-powered system to compensate any losses etc. In this section, finite element analysis results of isolation mount and different mode excitation is discussed.

Analysis Details

PZT system as shown in Figure 2.1.1 was used to analyze effects of isolation mount on system performance. ANSYS 8.0 was used for this analysis and mode superposition method was used for forced analysis. Fixed system without isolation mount was analyzed and the results were used as baseline information. System was then modified and four springs were added on each corner to closely represent a coil spring surface contact. Additional boundary conditions were added to avoid rigid body modes that could not be eliminated through four springs on each corner, refer Figure 2.1.1. Various spring rates were evaluated for isolation mount along with a fixed system (baseline) and system response was analyzed under force vibration. By adding isolation mount many modes were introduced and the target in-phase mode was lost (or got complex due to contribution of other modes). However the out-of-phase mode between livedeck and supporting structure responded well to the input forces at the root of resonators. Same input force magnitude of 1000 lb was maintained in all cases and vibration data was collected at six points on panel and two points on solid frame. Following are the extreme cases that were analyzed and compared with baseline model:

Test1: same as baseline except 4 springs with spring rate of 125 lb/in each were added on all four corners between supporting structure and base supporting structure.

Test2: same as Test1 except spring rate of 12500 lb/in for each spring was used.

Based on Test1 & Test2 analysis results, a parametric study was done to minimize motion on supporting structure. It was assumed that increasing the mass of supporting structure could reduce motion on the structure and improve overall system performance. For quick analysis, the mass of the supporting structure was changed through material property

(density). Three cases were analyzed by adding 2, 4 & 6 times the current mass of supporting structure, such that the resultant mass of supporting structure was 400 lb, 800 lb, 1600 lb & 2400 lb for baseline and rest of the cases.

Using Test1 system another parametric study was done to analyze the influence of plant structure stiffness on system performance while operating in out-of-phase mode. Beam elements with I-cross section were used to quickly and efficiently model plant structure. Plant structure was tune to different frequencies (6, 11 & 15Hz) by changing overall height of the structure for parametric study.

Summary of Results

Baseline model analysis resulted in operating mode frequency of 49Hz. Based on constant input force a maximum displacement of 26 mils p-p measured at the feed end and around 10 mils p-p at discharge end in vertical direction and 65 mils p-p was measured on both ends in horizontal direction. Motion on the solid frame was very minimal (below 3 mils p-p) in both vertical and horizontal direction.

Test1 resulted in many low frequency modes and the target mode was suppressed/got complex due to contribution of other modes. However force vibration resulted in decent system performance at higher order mode i.e., out-of-phase mode between livedeck and supporting structure at around 61Hz. Motion distribution on the panel at this mode reversed compare to baseline model resulting in more motion on discharge end and less motion on feed end. The maximum displacement in vertical direction almost remained same as baseline model while the motion in horizontal direction dropped by 50%. This case also resulted in significantly large motion on the supporting structure in vertical direction that was close to 50% of the motion on panel.

Test2 results were similar to Test1 except the out-of-phase mode natural frequency changed to 65Hz and slight drop in system performance. Figure 2.1.2 and Figure 2.1.3 show the combine results of above three cases in vertical and horizontal direction respectively measured at the center of rear and front end of panel.

Figure 2.1.4 and Figure 2.1.5 show results of solid frame mass parametric study. The results clearly show increasing solid frame mass will not reduce motion on solid frame, in fact it could increase the motion and will drop system performance at livedeck level.

Addition of plant structure below the system did not affect system performance while operating at out-of-phase mode. Figure 2.1.6 show the basic model and Figure 2.1.7 & Figure 2.1.8 shows force analysis results of baseline model without plant structure and with plant structure with varying structure stiffness.

2.2 Performance Improvement

Through finite element analysis further attempts were made to improve system performance. Resonator dimensions (thickness and length) were used as the design parameters since the stroke generated by smart motor is amplified through the resonator. The key objective of this study was to improve displacement amplification through resonator design. Along with baseline case, three different cases were analyzed. For the first case, the resonator thickness was changed to extreme possible that can be easily fabricated. The length was maintained same as original resonator length. In the next two cases, the length along

straight portion was changed to bring the target mode frequency close to baseline model. Analysis results did not show any improvement and in fact showed some performance drop.

Analysis Details

The PZT system with modified supporting structure and single-leaf resonator was used to analyze the effects of resonator dimensions (thickness & length) on system performance. ANSYS 8.0 was used for this analysis and mode superposition method was used for forced response analysis. Resonators thickness was changed from 0.32" to maximum possible i.e., ¾" thick (0.75"). The following cases were analyzed with a ¾"-resonator thickness while maintaining same input force and boundary conditions.

Case 1: Original resonator length.

Case 2: Resonator length along straight sections increased by 2 in (no change along curved section).

Case 3: Resonator length increased by 3 inch along straight sections (no change along curved section).

Summary of Results

Baseline model analysis resulted in operating mode frequency of 49Hz and a maximum displacement of 27 mils p-p at feed end and around 9 mils p-p at discharge end in vertical direction and 65 mils p-p at feed end and 57 mils p-p at discharge end were measured in horizontal direction. Motion on the supporting structure was very minimal (below 3 mils p-p) in both vertical and horizontal direction.

Case 1 resulted in target mode frequency of 78 Hz and a maximum displacement of 25 mils p-p in flow direction and 10 mils p-p in vertical direction.

Case 2 resulted in higher target mode frequency (58Hz) than the baseline and system performance improved by almost 50% compare to case1.

Case 3 resulted in close target mode frequency with that of baseline model. The system performance however was lower than the baseline with a maximum displacement of 50 mils p-p in flow direction and 22 mils p-p in vertical direction.

Table1 gives a brief summary of the above discussed results. A performance factor (pf) based on the criteria below was used to compare displacement results.

- Performance factor for horizontal motion $H_{pf} = 70\% \text{ feed-end displacement} + 30\% \text{ discharge-end displacement}$
- Performance factor for vertical motion $V_{pf} = 70\% \text{ feed-end displacement} + 30\% \text{ discharge-end displacement}$.

Table 1 Brief summary of forced response analysis results for baseline and other three cases.

Case	Frequency [Hz]	Displacement Performance Factor [mils p-p]		% Change Compare to Baseline	
		H_{pf}	V_{pf}	H_{pf}	V_{pf}
Baseline	49	62.6	21.6	-	-
Case 1	78	22.9	7.2	63% drop	67% drop
Case 2	58	41.0	12.9	34% drop	40% drop
Case 3	50	46.7	15.55	25% drop	28% drop

Figures 2.2.1 and 2.2.2 compare system performance over a wide frequency range for the above cases at rear (feed) end in vertical and horizontal direction.

2.3 Resonator Fatigue Life

Since resonator is the critical part of the full system, further refinements were performed to reduce the stress levels and to better distribute stresses on the curved section of resonator. Production unit with magnetic motors was used for the analysis purpose and the performance was analyzed by varying resonator geometry. The key objective of this study was to optimize resonator shape to reduce stress levels on resonators. Two main cases were analyzed one with reduced thickness at the center of the resonator and other one with varying width of the resonator at the center away from straight section. Forced vibration analysis results showed 10% drop in resonator stress levels by reducing width at the center of the resonator while reducing thickness raised stress levels.

Analysis details

Current production unit as shown in Figure 2.3.1 and its results were used as baseline. Resonator solid models were created in SolidWorks and then transferred to Ansys. Some constraints taken into consideration during resonator optimization process were:

1. Operating mode frequency should be maintained at or above 45 Hz.
2. Overall height of resonator should remain same with a maximum tolerance of 1/8".
3. Width of the resonator should remain 3.5" on top portion and 4" on the bottom.

Following two cases were analyzed to evaluate stress levels and distribution on resonator under force vibration. Input forces and reaction forces were applied on feed end resonators and magnetic motor mounting blocks respectively to simulate magnetic motor forces input.

Case 1: varying resonator width at the center along the curved portion while maintaining same width at the top and bottom end straight section. Total six different resonator geometries were analyzed starting with 1 inch width at the resonator center and increasing width in steps of 0.5 inch. Figure 2.3.2 shows two out of six extreme cases.

Case 2: Effect of varying resonator thickness along the curved section with tapered from both straight section and going to minimum at the center as shown in Figure 2.3.3.

For all cases vibration data was collected at six points on the panel and resonator stresses were calculated only after matching average displacement (displacement average was taken by adding displacement at feed and discharge end center in both vertical and horizontal direction, i.e., a total of four points).

Assumptions:

- 1) Suspended system considered as linear system.
- 2) Static plate motion was constrained in flow and normal to flow direction to closely represent coil spring.

- 3) Boundary conditions remained same (though there might be slight change in nodes coupling due to different resonator geometry).

Analysis Results

Case1: Current system with 3" wide resonator at the center was used as baseline and one of 6 cases. Analysis results showed some improvement in system performance and around 10% drop in stress levels at feed end resonator. Figure 2.3.4 & Figure 2.3.5 compares displacement on panel at front end for all six different cases with varying resonator width. It is clear from the figures that the operating mode frequency drops gradually with decreasing width however the system performance increases by 50% in vertical direction at discharge end while the performance remains almost same at feed end in both directions. To calculate stress levels force was dropped by 5% for most of the cases to match displacement with the baseline model as explained above. Figure 2.3.6 compares stress levels on right side upper and lower resonator for all cases. Figure 2.3.7 shows stress levels and distribution on resonator for extreme case and it is clear from the results that minimum width at the center of resonator will help reduce stress levels. Also stress distribution for resonator with 1in width at the center is much better and the high stress area shift from top and bottom end towards the center of the resonator.

Case2: Thickness was gradually reduced to 0.195" at the center of the resonator starting with 0.375" on both ends. Force analysis results of this configuration did not help in any improvement in terms of stress levels and system performance, instead 20% more force was required to match the average displacement with that of baseline. Figure 2.3.8 compares stress levels on the resonator for baseline model and modified case.

Three resonator system: Further refinements are on its way and one of them is three resonator system i.e. the livedeck supported by three resonator rather than four resonators. The fact that it requires three points to define a plane and thus the four resonators could be redundant. Through this investigation it is expected to drop resonator stress levels significantly and improve system performance at the same time. Figure 2.3.9 shows the basic design concept of this system.

CHAPTER 3 - CONCLUSION

In this report, our progress since the last semi-annual report was detailed. It was shown that we have met all the planned objectives and the progress has been satisfactory. We successfully tested modified S3 supporting structure, design to minimize interface losses and supporting structure vibration. Simulation and experimental results showed 80% vibration reduction on the supporting structure with the modified design. It was successfully demonstrated that the modified supporting structure eliminates need of various parts, nuts and bolts and can easily retrofit magnetic or PZT-based smart motor. Lab results of PZT based system showed better than expected results and PZT-based smart motor survived field test under harsh plant environment over one week without any signs of performance loss or any damages. Longevity test of PZT based quarter system with smart motor completed over one year of operating time. Test started on 8th September 2003 and since then driven continuously round the clock with more than 378 million cycles. Both smart motor and resonator did not show any signs of failure or performance loss and the test was very successful. Dynamic force generated by PZT-based smart motors was successfully tested at QRDC lab using a redesign smart motor assembly and force transducer.

The PZT system with isolation mounts using springs were analyzed. This study was done to minimize system sensitivity to foundation and improve overall system performance. Various other cases were analyzed to improve fatigue life of resonators and improve displacement magnification. Resonator optimization study showed some encouraging results and potential to drop stresses on resonator by at least 10%.

Further system refinements through analysis and experimentation are in progress and should be well underway by the time of next progress report. Next report will include progress on three resonator system, PZT system sensitivity to installation and lab & field test results of full PZT system and/or hybrid system with both magnetic and PZT-based smart motors.

FIGURES

Figure 1.1.1 Model of SmartScreen™ system with modified supporting structure

Figure 1.1.2 Model of SmartScreen™ system with old supporting structure

Figure 1.1.3 Modified supporting structure resulted in 80% vibration reduction on supporting structure at operating frequency

Figure 1.1.4 First mode of modified and old supporting structure

Figure 1.1.5 PZT-based production unit with conduit wiring

Figure 1.2.2 Impact test results on livedeck in vertical & flow direction

Transverse Impact Results of Three Locations

Flow Impact Results of Three Locations

Vertical Impact Results of Three Locations

Figure 1.2.3 CMRL elevated structure (Superstructure) impact test results

Figure 1.2.4 ODS of PZT-based system; Top: 40.9Hz & Bottom: 51Hz

Figure 1.3.1 Modified smart motor assembly for force measurement

Figure 1.3.2 Modified smart motor assembly installed on full system

Figure 1.4.1 Experiment setup used to evaluate PZT based phase II Smart Motor

Figure2.1.1 PZT system isolation study; Left: fixed system; Right: suspended system

Figure 2.1.2 Displacement comparison at rear & front end in vertical direction

Figure 2.1.3 Displacement comparison at rear & front end in horizontal direction

Figure 2.1.4 Panel response with varying supporting structure mass

Figure 2.1.5 Panel response with varying supporting structure mass

Figure2.1.6 I-Cross section beam structure simulating plant structure

Figure 2.1.7 System response at front end in vertical direction with varying plant structure stiffness

Figure 2.1.8 System response at front end in horizontal direction with varying plant structure stiffness

Figure 2.2.1 Vertical displacement comparison at rear (feed) end

Figure 2.2.2 Horizontal displacements comparison at rear (feed) end

Figure 2.3.1 Model of suspended production unit

Figure 2.3.2 Resonator tapered along width (2 extreme cases)

Figure 2.3.3 Resonator tapered along thickness

Figure 2.3.4 Case1 – vertical displacement comparison at front (discharge) end center

Figure 2.3.5 Case1 – horizontal displacement comparison at front (discharge) end center

Figure 2.3.6 Case1 – Stress levels comparison with varying resonator width

Figure 2.3.7 Case1 – stress levels & distribution on resonator for extreme cases

Figure 2.3.8 Case2 – stress levels & distribution on resonator; Left: baseline; Right: Case 2

Figure 2.3.9 Finite element model of three resonator system

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LIST OF ABBREVIATIONS

S3 – Smart Screen Systems
SM – Smart Motor
SC-S3 – Steering Committee for Smart Screen Systems
PZT – Lead Zirconate Titanate
PMN – Lead Magnesium Niobate
CAD – Computer Aided Design
FEM – Finite Element Analysis
OMS – Operating Mode Shapes
MSHA – Mine Safety and Health Administration's
PLC – Programmable Logic Controller
SPL – Sound Pressure Level
OM – Oscillating Mass
LD – Live Deck
OMR – Oscillating Mass Resonator
CMRL – Coleraine Mineral Research Laboratory, part of The University of Minnesota
IIM – Ispat Inland Mining