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Smart Screening System (S3)

In Taconite Processing

Semi Annual Report

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Semi Annual Report

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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. The electronics required for the smart motors are presented in this report. 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 conditions. The results are promising. The development program is on schedule.

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.

We plan to modify the supporting structure to improve system rigidity and integrity that should help improving the overall system performance. The improved supporting structure will be fabricated in the next period.

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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 SmartScreensTM that will replace the inefficient massive electric motors. SmartScreensTM will have miniaturized smart motors (ceramic- or electromagnet-based). SmartScreensTM 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 [2-4].

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 [6], 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 [7], QRDC was able to design, fabricate, and evaluate the key components of the SmartScreenTM. 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 SmartScreensTM 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.

In this reporting period, the design and fabrication of the key components are finalized. A full SmartScreens™ system was assembled and evaluated under laboratory conditions. Details of the system and the test results are presented in this report.

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 finalizing the design, fabrication, testing, and evaluation of the key components of the proposed smart screen systems. These key components were fabricated and assembled. The full system was evaluated under dry and wet conditions.

This report summarizes the work since the last semi-annual report (Quarter 4-2003 & Quarter 1-2004) and has two main chapters. Chapter 1 is directed towards the final design and evaluation of the key components, and details on the test results and evaluation of the full system. A summary of findings, results, and recommendations are found in Chapter 2.

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.

We plan to modify the supporting structure to improve system rigidity and integrity that should help improving the overall system performance. The improved supporting structure will be fabricated 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 – RESULTS AND DISCUSSION

A few of the remaining key components of the SmartScreen™ system were designed and analyzed during this reporting period. These components are presented in this section. To fully understand the content of this section, the reader is advised to review the previous reports [6-7].

1.1 Retrofitting Mounting Block

As shown in Figure A.1.1, the supporting block was designed to mount the resonator and the PZT-based Smart Motor (SM) assembly on the current magnetic-based system that has been in production since mid 2003. The block was designed to fit in the same footprint of production unit mounting blocks. This design uses only four bolts to mount the block on the static plate. The PZT-based SM was made as an integral part of the block to minimize bolts and fabrication time. The blocks are scheduled to be used on both suspended unit and fixed legs system as described in the next chapter.

1.2 Resonators

Split curved resonators were used as the final design for two reasons. First, the current magnetic-based system 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.

Analysis was conducted on the performance of the resonators with excitation forces applied near the fixed end of the resonators. The existing model of the production unit with split resonators was analyzed. To compare the performance of the system with single-leaf and double-leaf resonator, the same computer model was used with one exception; the split (or double-leaf) resonators were replaced with single-leaf resonators. The single-leaf resonator system was tuned to match the target mode frequency of the split resonator system.

Analysis comparing the split and single resonator system was conducted. The same amount of force was applied at the root for all four resonators. For the split resonator system, force analysis results showed a 3% drop in peak performance of the system in the vertical direction. No loss of performance was found in the flow direction when compared with the single resonator system. Figures 1.2.1 through 1.2.4 shows analysis results that include mode shapes and forced response of the system. The modal responses (see Figures 1.2.1 and 1.2.3) of both systems were similar. The forced responses of the systems are shown in Figures 1.2.2 and 1.2.4.

Fatigue life calculation: The life of the resonators was predicted using the S-N method under various design parameters. Though it was challenging to accurately estimate the fatigue life due to uncertainty in the design and fabrication parameters, the best attempt was made by considering several key parameters. Fatigue life depends on surface finish, ultimate tensile strength, stress levels, endurance limit, loading and operating conditions, and beam size/shape. It was determined that “Surface factor (C_{surf})” is a very critical parameter in determining fatigue life that depends on surface roughness and tensile strength. Little information was available on C_{surf} for various materials and material processes. As an example, the estimation of the service-free life of 5160 steel is shown in Table 1.2.1.

The following terms are used in Table 1.2.1. Stress under load is the resonator bending stress as calculated by FEM simulation model. S_{ut} is the ultimate tensile stress of the material. C_{surf} is the surface factor that depends on how the material is heat treated, processed, machined, and formed. Frequency is the operating speed expressed in cycle per second. NofY, NofD, NofHr are the calculated life in years, days, and hours, respectively. It should be noted that C_{surf} is available only for machined or grounded surfaces. For other treatments or processes, C_{surf} is estimated.

Table 1.2.1 Calculated fatigue life for resonators made of steel 5160

Conditioning the Resonators	Stress under load [psi]	S_{ut} [psi]	C_{surf}	Freq [Hz]	NofY	NofD	NofHr
Raw Material	22,000	140,000	0.72	60	0	28	672
Only Shot Peened	22,000	144,000	0.95	60	26	9,401	225,624
Only Heat Treated	22,000	239,000	0.28	60	0	0.3	7
Heat Treated & Shot Peened	22,000	225,000	0.8	60	3	1,112	26,688

Figure 1.2.5 shows the stress distribution on the split resonator design with a maximum peak to peak displacement (or stroke) of 80 mils measured at the top end. The highest stress was measured at the top of the inner beam. However, under certain loading conditions, the stress concentration area shifted to the bottom end. In this figure, only the resonator is viewed rather than the full system.

To improve the fatigue life and reduce the cost of processing and fabrication, stainless steel 17-4 or 17-7 may be used in the future work. These steels do not require any treatment such as heat treatment and corrosion resistive coating. In addition, they eliminate defects due to heat treatment, corrosion, protective coatings, and shot peening.

Another option is to use 5160 steel without heat treatment. This may eliminate cracks and possible defects. In general, steels with an ultimate strength over 200 ksi form carbide inclusions during the tempering of martensite. These nonmetallic inclusions serve as crack initiation points. Furthermore, eliminating heat treatment may improve fatigue life by making metal more ductile and avoiding possible defects that could result from improper heat treatment. Finally, fatigue life theory can more accurately estimate the service-free life without heat treatment.

A third option is to use 5160 steel without heat treatment and buff the surface after shot peening. Removing excess materials after shot peening could double the fatigue life. Improving surface roughness could also improve fatigue life.

1.3 Oscillating Mass

This section details the final stage of the work on the development of Smart Screen System powered with an Oscillating Mass (OM) driver. In this case, the OM is the source of input force that shakes the live deck. Depending on the type of motion and the required stroke, one or more Oscillating Masses may be attached to a live deck.

The oscillating mass concept was experimentally evaluated. The key objective was to minimize operating sensitivity of the system to boundary conditions and supporting structures in a plant. To explore the potential of the OM concept based on the results generated by our computer model and previous tests [7], oscillating mass assemblies were fabricated and tested. Design details for the OM are discussed in Appendix A, section A.2 and shown in Figure A.2.1.

Modal Results: Figures 1.3.2-1.3.7 show the frequency response results for each of the impact tests performed on the system under three different conditions. In the first case, the system was rested on a relatively rigid structure referred to as the fixed leg systems. The measured response are shown in Figures 1.3.2 and 1.3.3 and agreed with prediction. Based on the results of the impact test performed on the live deck, we were able to predict a system resonance at or near 23 Hz (see Figure 1.3.4). In the second case, the system was rested on a relatively soft supporting structure. The resonance of the OM almost remained unchanged (see Figures 1.3.5 and 1.3.6) due to boundary conditions, but the system resonant frequency dropped near 20 Hz (see Figure 1.3.7). In the third case, sand bags were placed on the supporting structure. Impact tests were not performed once the sand bags were added to the system. To determine the resonance in the latter case, the system was excited with a harmonic input whose frequency was changed manually until the highest motion was detected by an accelerometer attached to the live deck. The results are described below.

Response Due to Single Harmonic Input: Figures 1.3.8 and 1.3.9 show the locations of the sensors (i.e. accelerometers) on the live deck and supporting structure. Measurements were made on the live deck, supporting structure, and resonators. The results are shown in Tables 1.3.1 through 1.3.4. All the tests were repeated with sandbags resting on the supporting structure.

Table 1.3.1 shows the measured results for the first case, the system with fixed legs. In this case the system was excited at the first live deck resonance. Each set of measurements is shown for two conditions, with and without sand bags. In this table, the displacements of the OMs are not shown. However, they were measured. The mass of the first OM was moving 20 mils vertically and 17 mils horizontally, while the mass of the second OM was moving 23 mils vertically and 19 mils horizontally. The OMs were moving in-phase vertically and horizontally with respect to each other. Different points on the live deck measured were shown to be in-phase vertically and horizontally.

Table 1.3.2 shows the results for the system with fixed legs excited at the first OM resonance. For this case, the OMs were deflecting 92 mils vertically and 40 mils horizontally for the first mass, and 67 mils vertically and 27 mils horizontally for the second mass. There was a slight phase difference (about 10°) between the two masses in both vertically and horizontally direction. For this mode the live deck was again measured to be in-phase in both the vertical and horizontal directions.

Table 1.3.3 depicts the results for the second case, when the system is rested on soft supports, with excitation at the first live deck resonance. For this case, the OMs were found

to be in-phase. The live deck was in-phase horizontally and 60° out-of-phase vertically with the OM. For the last case, the system was rested in the soft-support and excited at the first OM resonance. In Table 1.3.4, “yes” and “no” in the third column indicate the cases with and without the sandbags, respectively. In this case, the first OM had 15 mils and 40 mils in the horizontal and vertical directions, respectively. The second OM was able to have a stroke of 13.8 mils and 40 mils in the horizontal and vertical directions, respectively. The live deck was in-phase in the front-to-back direction as well as normal to the screen panel, and the OM was in-phase.

The main focus of this series of tests was to determine whether the OM concept would be applicable to Smart Screen Systems. It is for this reason that we focused on the results that show the influence of boundary conditions on the system performance. It was demonstrated that when we added the sandbags to the supporting structure and the system was excited at the resonant frequency of the live deck, the performance decreased significantly. However, when the system was excited at the resonant frequency of the OM, the sandbags had insignificant effect on the system performance. For given boundary conditions, however, the system displayed a higher performance when it was excited at the live deck resonance.

When the elastic pads (soft support) were added to the system, the overall system performance dropped when operating at the resonance of the live deck. However the system performance at the resonance of the OM was much less affected. It was also demonstrated that the addition of the sandbags had no significant effect on the stroke of the live deck. The floor vibrations also decreased significantly from that of the fixed leg system.

Based on these results, it is concluded that the tuning of the OM and system natural frequencies must be carefully designed. We were not able to achieve the required stroke on the live deck because the OM was not driven at the desired stroke. Our 8-DOF model was used to predict an oscillating mass-to-live deck displacement ratio for various mass ratios. Displacement ratios of 6:1 and 5:1 were predicted. This proved to be an accurate representation of the system performance in the case of the fixed leg system. For this case, approximately 70 mils stroke was realized on the oscillating mass and 12 mils stroke on the live deck; a stroke ratio of 5.8:1 (6:1 predicted). If we desired to achieve a higher stroke on the live deck, a higher stroke on the OM was required. The OM concept needs to be further investigated. Additional details on the OM test results are discussed in Appendix A, section A.2.

In summary, the system is not sensitive to boundary condition while operating at the OM resonance. When operating at OM resonance, added weight and damping (i.e. sandbags) had insignificant effect on the overall system performance. The overall vibration of the live deck was classified as very strong. Adding operator’s body weight on the live deck had no significant influence on the system performance. One drawback is that we require higher motion on the OM if we aspire to achieve the level of stroke necessary in taconite screening application. We need to determine a more powerful means or a different approach of driving the OM.

Table 1.3.1 Stroke results for system resting on fixed legs and excited at the first LD resonance

Location	Position	Sand Bag	Frequency [Hz]	Vertical Stroke [mils]	Horizontal Stroke [mils]
Live deck	1	No	24.3	17.10	17.07
Live deck	2	No	24.3	19.59	18.89
Live deck	3	No	24.3	20.19	19.02
Live deck	4	No	24.3	18.96	16.29
Live deck	5	No	24.3	19.74	18.42
Live deck	6	No	24.3	20.07	18.95
Live deck	1	Yes	19.8	1.74	1.49
Live deck	2	Yes	19.8	1.74	1.49
Live deck	3	Yes	19.8	1.70	1.53
Live deck	4	Yes	19.8	1.68	1.44
Live deck	5	Yes	19.8	1.89	1.61
Live deck	6	Yes	19.8	1.74	1.54
Supporting Structure	1	No	24	0.17	0.93
Supporting Structure	2	No	24	0.13	0.79
Supporting Structure	3	No	24	0.15	0.65
Supporting Structure	4	No	24	0.30	1.00
Supporting Structure	5	No	24	0.62	0.84
Supporting Structure	6	No	24	0.42	0.63
Supporting Structure	7	No	24	0.55	1.01
Supporting Structure	8	No	24	0.47	1.07
Supporting Structure	9	No	24	0.33	1.10
Supporting Structure	10	No	24	0.24	0.60
Supporting Structure	11	No	24	0.26	0.60
Supporting Structure	12	No	24	0.20	0.62
Supporting Structure	1	Yes	19.9	0.04	0.18
Supporting Structure	2	Yes	19.9	0.05	0.08
Supporting Structure	3	Yes	19.9	0.02	0.08
Supporting Structure	4	Yes	19.9	0.10	0.12
Supporting Structure	5	Yes	19.9	0.10	0.09
Supporting Structure	6	Yes	19.9	0.06	0.09
Supporting Structure	7	Yes	19.9	0.10	0.12
Supporting Structure	8	Yes	19.9	0.10	0.15
Supporting Structure	9	Yes	19.9	0.05	0.09
Supporting Structure	10	Yes	19.9	0.03	0.08
Supporting Structure	11	Yes	19.9	0.05	0.06
Supporting Structure	12	Yes	19.9	0.08	0.16
Supporting Resonators	Front L	No	24	16.18	3.98
Supporting Resonators	Front R	No	24	15.12	4.48
Supporting Resonators	Rear L	No	24	17.56	3.54
Supporting Resonators	Rear R	No	24	17.55	4.45
Supporting Resonators	Front L	Yes	19.9	2.19	0.41
Supporting Resonators	Front R	Yes	19.9	1.97	0.60
Supporting Resonators	Rear L	Yes	19.9	2.26	0.43
Supporting Resonators	Rear R	Yes	19.9	2.03	0.55

Table 1.3.2 Stroke results for system resting on fixed legs and excited at the first OM resonance

Location	Position	Sand Bag	Frequency [Hz]	Vertical Stroke [mil]	Horizontal Stroke [mils]
Live deck	1	No	47	4.70	9.49
Live deck	2	No	47	6.40	6.88
Live deck	3	No	47	4.13	5.16
Live deck	4	No	47	9.73	7.98
Live deck	5	No	47	9.14	8.44
Live deck	6	No	47	5.20	5.10
Live deck	1	Yes	46.4	5.55	9.96
Live deck	2	Yes	46.4	6.84	8.25
Live deck	3	Yes	46.4	5.15	6.29
Live deck	4	Yes	46.4	8.42	10.48
Live deck	5	Yes	46.4	9.39	9.18
Live deck	6	Yes	46.4	6.78	6.63
Supporting Structure	1	No	46.6	2.96	2.82
Supporting Structure	2	No	46.6	3.34	2.10
Supporting Structure	3	No	46.6	2.74	1.44
Supporting Structure	4	No	46.6	0.49	2.63
Supporting Structure	5	No	46.6	0.34	2.11
Supporting Structure	6	No	46.6	0.23	1.37
Supporting Structure	7	No	46.6	0.69	2.64
Supporting Structure	8	No	46.6	1.56	2.78
Supporting Structure	9	No	46.6	2.45	3.00
Supporting Structure	10	No	46.6	0.28	1.23
Supporting Structure	11	No	46.6	1.37	1.28
Supporting Structure	12	No	46.6	2.30	1.31
Supporting Structure	1	Yes	46.4	2.32	2.33
Supporting Structure	2	Yes	46.4	2.55	1.66
Supporting Structure	3	Yes	46.4	1.06	1.22
Supporting Structure	4	Yes	46.4	0.40	2.05
Supporting Structure	5	Yes	46.4	0.29	1.60
Supporting Structure	6	Yes	46.4	0.20	1.07
Supporting Structure	7	Yes	46.4	0.57	2.03
Supporting Structure	8	Yes	46.4	1.21	2.14
Supporting Structure	9	Yes	46.4	1.88	2.29
Supporting Structure	10	Yes	46.4	0.23	0.98
Supporting Structure	11	Yes	46.4	0.99	0.98
Supporting Structure	12	Yes	46.4	1.71	1.09
Supporting Resonators	Front L	No	46.6	6.47	5.47
Supporting Resonators	Front R	No	46.6	4.12	4.14
Supporting Resonators	Rear L	No	46.6	7.86	3.16
Supporting Resonators	Rear R	No	46.6	5.84	1.83
Supporting Resonators	Front L	Yes	46.4	5.12	4.18
Supporting Resonators	Front R	Yes	46.4	3.30	3.10
Supporting Resonators	Rear L	Yes	46.4	6.04	2.42
Supporting Resonators	Rear R	Yes	46.4	4.67	1.49

Table 1.3.3 Stroke results for system resting on soft support and excited at the first LD resonance

Location	Position	Sand Bag	Frequency [Hz]	Vertical stroke [mils]	Horizontal Stroke [mils]
Live deck	1	No	25.9	4.08	1.94
Live deck	2	No	25.9	4.61	2.25
Live deck	3	No	25.9	4.89	2.26
Live deck	4	No	25.9	5.1	1.95
Live deck	5	No	25.9	5.45	2.27
Live deck	6	No	25.9	5.26	2.31
Live deck	1	Yes	26.2	3	1.66
Live deck	2	Yes	26.2	3.34	1.66
Live deck	3	Yes	26.2	3.55	1.72
Live deck	4	Yes	26.2	3.62	1.74
Live deck	5	Yes	26.2	3.66	1.74
Live deck	6	Yes	26.2	3.79	1.79
Supporting Structure	1	No	25.9	0.5	1.61
Supporting Structure	2	No	25.9	0.55	1.75
Supporting Structure	3	No	25.9	0.57	1.81
Supporting Structure	4	No	25.9	1.08	1.69
Supporting Structure	5	No	25.9	0.95	1.83
Supporting Structure	6	No	25.9	0.82	1.87
Supporting Structure	7	No	25.9	1	1.66
Supporting Structure	8	No	25.9	0.77	1.66
Supporting Structure	9	No	25.9	0.57	1.67
Supporting Structure	10	No	25.9	0.75	1.95
Supporting Structure	11	No	25.9	0.66	1.76
Supporting Structure	12	No	25.9	0.52	1.93
Supporting Structure	1	Yes	26.2	0.4	1.38
Supporting Structure	2	Yes	26.2	0.46	1.48
Supporting Structure	3	Yes	26.2	0.54	1.58
Supporting Structure	4	Yes	26.2	0.76	1.44
Supporting Structure	5	Yes	26.2	0.75	1.52
Supporting Structure	6	Yes	26.2	0.66	1.66
Supporting Structure	7	Yes	26.2	0.77	1.42
Supporting Structure	8	Yes	26.2	0.66	1.44
Supporting Structure	9	Yes	26.2	0.48	1.42
Supporting Structure	10	Yes	26.2	0.71	1.61
Supporting Structure	11	Yes	26.2	0.64	1.66
Supporting Structure	12	Yes	26.2	0.62	1.57
Supporting Resonators	Front L	No	25.9	2.25	1
Supporting Resonators	Front R	No	25.9	1.93	1.37
Supporting Resonators	Rear L	No	25.9	2.63	1.17
Supporting Resonators	Rear R	No	25.9	2.54	1.05
Supporting Resonators	Front L	Yes	26.2	1.78	0.85
Supporting Resonators	Front R	Yes	26.2	1.95	1.12
Supporting Resonators	Rear L	Yes	26.2	2.21	1.01
Supporting Resonators	Rear R	Yes	26.2	2.31	0.97

Table 1.3.4 Stroke results for system resting on soft support and excited at the first OM resonance

Location	Position	Sand Bag	Frequency [Hz]	Vertical stroke [mils]	Horizontal Stroke [mils]
Live deck	1	No	46.6	4.5	1.81
Live deck	2	No	46.6	5.59	1.82
Live deck	3	No	46.6	5.59	1.83
Live deck	4	No	46.6	6.7	1.99
Live deck	5	No	46.6	8.33	2.94
Live deck	6	No	46.6	7.09	2.63
Live deck	1	Yes	47.3	4.42	1.79
Live deck	2	Yes	47.3	4.9	2.1
Live deck	3	Yes	47.3	4.46	2.29
Live deck	4	Yes	47.3	6.78	1.81
Live deck	5	Yes	47.3	7.89	2.49
Live deck	6	Yes	47.3	6.85	2.42
Supporting Structure	1	No	46.6	2.31	2.43
Supporting Structure	2	No	46.6	3.38	2.7
Supporting Structure	3	No	46.6	4.23	2.84
Supporting Structure	4	No	46.6	2.44	2.71
Supporting Structure	5	No	46.6	2.08	2.98
Supporting Structure	6	No	46.6	1.73	3.22
Supporting Structure	7	No	46.6	2.35	2.56
Supporting Structure	8	No	46.6	1.65	2.46
Supporting Structure	9	No	46.6	1.82	2.32
Supporting Structure	10	No	46.6	1.23	3.22
Supporting Structure	11	No	46.6	2.07	3.21
Supporting Structure	12	No	46.6	3.94	2.96
Supporting Structure	1	Yes	47.3	1.94	2.4
Supporting Structure	2	Yes	47.3	2.84	2.53
Supporting Structure	3	Yes	47.3	3.47	2.72
Supporting Structure	4	Yes	47.3	2.07	2.67
Supporting Structure	5	Yes	47.3	1.74	2.87
Supporting Structure	6	Yes	47.3	1.74	3.07
Supporting Structure	7	Yes	47.3	1.977	2.54
Supporting Structure	8	Yes	47.3	1.66	2.42
Supporting Structure	9	Yes	47.3	1.56	2.41
Supporting Structure	10	Yes	47.3	1.74	2.95
Supporting Structure	11	Yes	47.3	1.62	2.97
Supporting Structure	12	Yes	47.3	1.65	2.96
Supporting Resonators	Front L	No	46.6	2.8	1.55
Supporting Resonators	Front R	No	46.6	2.92	2.35
Supporting Resonators	Rear L	No	46.6	3.5	2.77
Supporting Resonators	Rear R	No	46.6	2.9	2.44
Supporting Resonators	Front L	Yes	47.3	2.44	1.38
Supporting Resonators	Front R	Yes	47.3	2.5	1.93
Supporting Resonators	Rear L	Yes	47.3	3.17	2.55
Supporting Resonators	Rear R	Yes	47.3	2.78	2.36

1.4 Evaluation of the Full System and Supporting Structure

The key objective of this part of the work was to evaluate the full system under laboratory dry and wet conditions. The fully assembled system was evaluated at the QRDC laboratory, S3i (Smart Screen Systems, Inc.) laboratory, and CMRL (Coleraine Minerals Research Laboratory).

Four actuator assemblies were fabricated according to engineering designs developed by the QRDC team. Each assembly contained one 38-mm stack PZT (piezo ceramic). The assemblies were mounted to three different configurations of SmartScreen™ systems. As expected, these PZT-based motors easily replaced the magnet-based motors. The resulting PZT-based system is displayed in Figure 1.4.1.

We conducted laboratory tests under two types of excitations and then the system was subjected to normal operating conditions. An impact test was performed to determine the resonance of the system. Next, the system was excited over a range of frequencies to determine the resonances at which the system demonstrated the highest response. The system was then driven at the target mode and its performance was measured in terms of acceleration levels and stroke. It was shown that when rubber pads were inserted beneath the supporting structure, the system responded with small strokes. The suspended system performed well when compared to the magnetic system, and showed great promise in its ability to be retrofitted by the PZT-based drivers. The system had the best overall performance when the supporting structure was bolted down (fixed) to concrete floor. In the latter case, the live deck stroke was as great as that of the magnetic system.

Impact Tests: After assembling each of the systems, an impact test was performed to better understand the frequency response characteristics of the system. A single tri-axial accelerometer was placed on the center of the live deck, and the system was excited with an impact hammer. An SA390 analyzer was used to measure system response. The transfer functions were recorded and saved for the transverse direction (side-to-side), the flow direction (the direction in which slurry flows), and normal to the screen (perpendicular to the screen plane).

Frequency Sweeps: After analyzing the transfer functions obtained by the impact tests, the response of the system was measured over a 10-100 Hz range. The goal was to determine the resonant frequencies of the system and to identify the target mode of the system. To achieve this, the PZT actuation systems were turned on and the frequency was shifted up from 10-100Hz by increments of 0.1 Hz. An accelerometer attached to the center of the front beam of the live deck was used to measure the response, and an SA390 analyzer was used to view those measurements. The response was recorded and saved.

System Response Measurement: Once the correct driving frequency was determined, the PZT actuators were driven at that frequency and stroke was measured at each of six locations on the screen, live deck, and supporting structure. Figure 1.4.2 exhibits the numbering scheme for measurement reference.

The stroke was measured through the use of a tri-axial accelerometer and an SA390 analyzer. Measurements were recorded only in the directions parallel and normal to the flow. No transverse motion was measured because the initial tests showed that it was negligible. In addition to stroke measurements, phase was measured between the four corners on each system to ensure the PZT actuators were synchronized. Two accelerometers were used and the transfer function and phase were measured for the corresponding axes of the accelerometers. That measurement was analyzed dynamically through the use of the SA390

analyzer, and the phase was recorded at the operational frequency both in directions parallel and normal to the flow.

Modal Extraction of the Suspended System: Performance of the suspended system was difficult to predict due to its nonlinear dynamics. To realize this, a modal extraction was performed such that the mode shapes could be studied in Star Modal. The impact test data was recorded on a floppy disk and loaded in Star Modal System (SMS) format. Measurements were taken at each of the six points on the live deck and supporting structure.

ODS of the Suspended System: To gain a better understanding of the performance and dynamics of the suspended system, Operational Deflection Shapes (ODS) were measured and analyzed. Referring to Figure 1.4.2, a reference accelerometer was placed at location 3 on the live deck, and its axis normal to the surface of the screen was monitored. Another tri-axial accelerometer was used to measure the auto power spectrum (APS), cross power spectrum (CPS), and frequency response function (FRF) of each of the 12 points corresponding to that figure on the live deck and supporting structure. The data was measured with the SA390 unit and was exported to Star Modal.

Summary of Results

Impact Test Results: Figures 1.4.3 and 1.4.4 are the results of the impact tests performed on the system supported by rubber pads. The resonances were identified at 2, 25, 36, 52, 86, 92, and 99 Hz. Figures 1.4.5 and 1.4.6 show the results of the impact test performed on the system with the frame bolted to the floor. The resonant peaks are much wider in this configuration when compared with the previous case. The latter may be due to higher damping than rubber. The source of the additional damping might be the dry friction that comes from bolting the system to the floor, or due to the presence of closely-spaced resonances. Those wide response bands occurred near 17-25 Hz, 30-50 Hz, 50-60 Hz, and 70 Hz. Based on these results, we assumed that the system will demonstrate the highest response at nearly 40 Hz. Depicted in Figures 1.4.7 and 1.4.8 are the results of the impact test performed on the suspended system. In this graph, it is shown the highest response parallel to flow occurs at 50 Hz while the highest response normal to the panel occurs near 90 Hz. Additional resonances were observed at 20 and 30 Hz.

Frequency Sweep Results: Shown in Table 1.4.1 are the results of the frequency sweep tests performed on the system supported by rubber pads. Resonances were identified near 25, 52, and 92 Hz. Also, a few resonances, that were absent in the results from the impact test, were observed. Most notably, the motion of the system was greatest about 42 Hz, which was not revealed in the impact test. Furthermore, a few of the frequencies, obtained by the impact test results, were not observed in this test. Revealed in Table 1.4.2 are the results of the frequency sweep performed on the system with the supporting frame bolted to the floor. The impact tests performed prior to this test gave us a very clear idea of where we should expect resonances. The main resonance of the system, which results in the highest motion of the Live Deck (LD), was at 39.3 Hz. Shown in Table 1.4.3 are the results of the frequency sweep performed on the suspended system. The impact tests performed were very helpful in assisting us in determining the resonances. Large motion was detected at all of the frequencies depicted in the impact test as well as at a couple additional frequencies. The main resonance of the LD was found to be at 52.9 Hz.

Motion Measurements: Table 1.4.4 shows the results of the strokes measured on the system supported by rubber pads. The strokes were 25 mils normal to the surface of the

screen and about 10 mils in the flow direction. It was noticed that the stroke dropped off significantly as we moved from the top to the bottom of the screen. To determine the reasons for such drops, the phase of each actuator relative to the actuator at point 3 was measured. The actuator at point 1 showed to be in-phase, while the actuator at point 4 was 15° out-of-phase and the actuator at point 6 was 25° out-of-phase. This could explain the drop in performance. More data is needed before any firm conclusions are reached.

Shown in Table 1.4.5 are the results of the system when bolted to the concrete floor. These results showed an acceptable performance in terms of stroke. In the direction normal to the screen, strokes as high as 60 mils were obtained. Strokes of about 40 mils were measured in the flow direction. Again it was observed that the displacement magnitudes at the bottom were smaller than those at the top of the screen. This case, however, was not as severe as in the former case. The phase between the front and back was negligible. In this trial, measurements were made on the static frame. The measurements showed that the stroke of the static frame was very closely related to the height of the supporting beam on which the entire test stand was rested. It was noted that the deflection in the flow direction decreased significantly moving down the system. This was probably due to the longer legs that were softer than shorter legs. This could likely be a reason that the Live Deck and screen had lower stroke at the bottom than at the top points. It was possible that the entire system, including legs, base plate, live deck, and screen were all moving as a single body, and the legs have a major influence on the performance.

Table 1.4.6 shows the results for the suspended system. As was expected, the system performance dropped when compared to that of the fixed system, but was better than that of the system supported by rubber pads. The system was successfully demonstrated with a stroke of about 30 mils and 20 mils in the direction normal to the screen surface and parallel to the flow direction, respectively. Phase measurements revealed that there was no rotation on the Live Deck. In addition, the base plate was out-of-phase with the Live Deck in the direction normal to the screen while it was in-phase with the Live Deck in the flow direction. This was expected because the balancing forces required to shake the Live Deck had to be absorbed by the supporting structure. Interestingly enough, this system demonstrated nearly uniform motion from front to back. This reinforced the idea that the system moved as a rigid body. When the short legs were not rigidly attached to a frame, they had a noticeable deflection. This was why the systems with fixed legs had such a decrease in motion in the front end of the system.

In summary, the PZT-based system and current production units performed better than expected. The results of the suspended unit were also very encouraging. None of the Smart Motors failed during testing. The tests were successful.

Based on these findings, we plan to modify the supporting structure to improve system rigidity and integrity that should help improving the overall system performance. The improved supporting structure will be fabricated in the next period.

Table 1.4.1 Results for frequency sweep for the system on rubber pads

Mode	Frequency [Hz]
1	20.9
2	24.1
3	27.9
4	41.6
5	53.7
6	61
7	72
8	94

Table 1.4.2 Results for frequency sweep for the fixed system

Mode	Frequency [Hz]
1	20.2
2	33 to 40 Hz
3	66.8

Table 1.4.3 Results for frequency sweep for the suspended system

Mode	Frequency [Hz]
1	18.1
2	30.9
3	52.9
4	77.1
5	88.6
6	92.7
7	95.8

Table 1.4.4 Stroke of the system with rubber pads

Part	Location	F [Hz]	Volts [V]	Normal Stroke [mils]	Flow Stroke [mils]
Live Deck	1	41.69	180	22.26	4.42
Live Deck	2	41.69	180	25.82	6.65
Live Deck	3	41.69	180	18.45	5.4
Live Deck	4	41.69	180	2.29	9.89
Live Deck	5	41.69	180	5.21	12.71
Live Deck	6	41.69	180	2.1	9.27
Screen	1	41.69	180	15.28	7.98
Screen	2	41.69	180	16.11	8.74
Screen	3	41.69	180	14.55	7.93
Screen	4	41.69	180	5.16	12.52
Screen	5	41.69	180	1.58	10.61
Screen	6	41.69	180	1.66	8.05

Table 1.4.5 Stroke of the system bolted to the floor

Part	Location	F [Hz]	Volts [V]	Normal Stroke [mils]	Flow Stroke [mils]
Frame	1	39.3	170	13.9	10.63
Frame	2	39.3	170	14.57	11.59
Frame	3	39.3	170	14.61	14.6
Frame	4	39.3	170	14	4.05
Frame	5	39.3	170	14.16	1.02
Frame	6	39.3	170	14.52	3.95
Live Deck	1	39.3	170	57.8	32.91
Live Deck	2	39.3	170	61	40.74
Live Deck	3	39.3	170	60.17	37.57
Live Deck	4	39.3	170	44	16.61
Live Deck	5	39.3	170	42.15	15.47
Live Deck	6	39.3	170	48.76	20.05
Screen	1	39.3	170	45.31	42.31
Screen	2	39.3	170	47.98	49.59
Screen	3	39.3	170	49.21	45.75
Screen	4	39.3	170	43.46	17.86
Screen	5	39.3	170	46.54	15.72
Screen	6	39.3	170	49.83	19.27

Table 1.4.6 Stroke of the suspended system

Part	Location	F [Hz]	Volts [V]	Normal Stroke [mils]	Flow Stroke [mils]
Frame	1	52.1	170	15.91	6.84
Frame	2	52.1	170	26.2	6.92
Frame	3	52.1	170	17.82	6.31
Frame	4	52.1	170	4.47	5.59
Frame	5	52.1	170	6.6	5.81
Frame	6	52.1	170	4.69	5.82
Live Deck	1	52.1	170	32.95	21.14
Live Deck	2	52.1	170	30.56	21.78
Live Deck	3	52.1	170	20.37	16.73
Live Deck	4	52.1	170	23.82	20.64
Live Deck	5	52.1	170	30.59	19.31
Live Deck	6	52.1	170	33.63	16.41
Screen	1	52.1	170	33.53	22.55
Screen	2	52.1	170	30.12	21.5
Screen	3	52.1	170	20.54	16.7
Screen	4	52.1	170	24.2	21.46
Screen	5	52.1	170	29.57	20.48
Screen	6	52.1	170	34.18	15.18

CHAPTER 2 - CONCLUSION

In this period, we have met all the planned objectives. We improved the S3 supporting structure design to minimize interface losses and supporting structure vibration. The performance of PZT-based S3 using the concepts of SM (Smart Motor) and improve structural design was evaluated. System components were finalized. The S3 supporting structure was designed and finalized to retrofit magnetic motors with PZT-based SM or vice versa, or to use both simultaneously in one machine. One could be the primary driver and one the assist driver. The oscillating mass concept, as the source of input force attached to the live deck (moving mass), was evaluated under laboratory conditions. The fatigue life of the resonator was enhanced through fabrication and heat treating process improvement. We investigated various options and methods to drive four PZT-based SMs with single power source.

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.

We plan to modify the supporting structure to improve system rigidity and integrity that should help improving the overall system performance. The improved supporting structure will be fabricated in the next period.

FIGURES

Figure 1.2.1 First four modes of the system with split resonators, mode 1 at 52.6 Hz, mode 2 at 66.7 Hz, mode 3 at 87.5 Hz

Figure 1.2.2 Split resonator system response due to applied force at the root, (left) close up view of a resonator, (right) live deck – static plate system response at 52.6 Hz

Figure 1.2.3 First four modes of the system with single resonators, mode 1 at 54.3 Hz, mode 2 at 68.9 Hz, mode 3 at 86.1 Hz

Figure 1.2.4 Single resonator system response due to applied force at the root, (left) close up view of a resonator, (right) full system response at 54.3 Hz

Figure 1.2.5 Stress distribution along a split resonator design

Figure 1.3.2 Impact response on the first OM for the systems with fixed legs

Figure 1.3.3 Impact response on the second OM for the systems with fixed legs

Figure 1.3.4 Impact response of the live deck for the systems with fixed legs

Figure 1.3.5 Impact response of the first OM for the systems with elastic support

Figure 1.3.6 Impact response of the second OM for the systems with elastic support

Figure 1.3.7 Impact response of the live deck for the systems on elastic support

Fig 1.3.8 Measurement point on live deck

Fig 1.3.9 Measurement points on support structure

Figure 1.4.1 Stiffened supporting structure

Figure 1.4.2 Measurement points used for evaluation of the full system

Figure 1.4.3 Frequency response in the flow direction (parallel to the panel) of the system mounted on rubber pads

Figure 1.4.4 Frequency response in the vertical direction (normal to panel) of the system mounted on rubber pads

Figure 1.4.5 Frequency response in the flow direction (parallel to the panel) of the system mounted rigidly on the floor

Figure 1.4.6 Frequency response in the vertical direction (normal to panel) of the system mounted rigidly on the floor

Figure 1.4.7 Frequency response in flow direction (parallel to the panel) of the suspended system

Figure 1.4.8 Frequency response in the vertical direction (normal to panel) of the suspended 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