Quality Research, Development, and Consulting Inc.

SMART SCREENING SYSTEM (S3)

IN TACONITE PROCESSING

SEMI ANNUAL REPORT

Department Of Energy (DOE)
Report Start Date: Mar. 9, 2005
Report End Date: Sept. 8, 2005
Principle Investigator: Dr. Daryoush Allaei
Report Issued Date: September 9, 2005
DOE Award # DE-FC26-02NT41470

Q.R.D.C., Inc.
PO Box 562, Excelsior, MN 55331

Smart Screening System (S3) In Taconite Processing

Semi Annual Report

This report is prepared for

Department Of Energy (DOE) & Partners
(Partners include: Albany Research Center, ISPAT Inland Mining,
U.S. Steel-Minntac, and S3i)

DOE Award # DE-FC26-02NT41470
Report Issued Date: September 2005

Report Author
Dr. Daryoush Allaei, P.E.
Mr. Angus Morison

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

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

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the Unites States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendations, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ACKNOWLEDGMENT

This Semi-Annual report titled "Smart Screening System (S3) In Taconite Processing" was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-02NT41470. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.

ABSTRACT

The conventional screening 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 almost every processing plant. Most of the current material separation technology uses heavy and inefficient electric motors with an unbalanced 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 development program is on schedule.

The last semi-annual report described the process of FE model validation and correlation with experimental data in terms of dynamic performance and predicted stresses. It also detailed efforts into making the supporting structure less important to system performance. Finally, an introduction into the dry application concept was presented.

Since then, the design refinement phase was completed. This has resulted in a Smart Screen design that meets performance targets both in the dry condition and with taconite slurry flow using PZT motors. Furthermore, this system was successfully demonstrated for the DOE and partner companies at the Coleraine Mineral Research Laboratory in Coleraine, Minnesota.

TABLE OF CONTENTS

LIST OF FIGURES

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 for 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 [2-6].

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 is the combination of smart materials and these vibration energy managing methods that make this approach unique and innovative.

In the second reporting period [7], 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.

The fourth semi-annual report [9] included detailed results of SmartScreens™ system test with modified supporting structure under dry and wet conditions. The lab test results of full system and vibration reduction on supporting structure was very encouraging. It also details the computer based analysis to further improve system performance in field installation and to reduce the stringent installation requirement. The report also included the results of a successful longevity test of smart motor using a quarter system while operating round the clock for over a year.

The fifth semi-annual report [10] documents significant work was done through experimentation and through computer simulations to minimize installation sensitivity and further improve system performance. Various suspensions were designed and tested both in lab and field. The lab and field test results showed significant performance improvement and less sensitivity to the installation. However system performance suffered during wet tests due to the effects of added damping. The motors did not have enough power to compensate for the losses and forced QRDC team to go back to the drawing table. There were two options, either to operate the system at a different mode which is less sensitive to external damping or to further improve system performance (overpower system) to compensate for the losses. Considering time constraints, it was decided to improve system performance. Through innovative isolation design and few other minor changes the system performance was almost doubled under lab conditions. The fifth semi-annual report also details the work done at Albany Research Center lab for strain measurement on the S3i-101 unit and the feasibility of using SmartScreens™ technology for dry application.

During this reporting period, a comprehensive design refinement was completed that resulted in a Smart Screen design that fully meets project requirements. This design was tested in the lab and at CMRL. Furthermore, a demonstration of this design was also given for the DOE and partner companies, again at CMRL. Additional effort has been placed into leveraging the PZT drive system to provide functionality simply not available on the market today. This report documents work done with alternative input functions to create screen motion profiles different that the traditional sinusoids. It is theorized that these motion profiles can have a significant impact on screen blinding and therefore add further performance and efficiencies to an already successful design. Finally, this report documents the continuing work on a dry application for SmartScreens™ .

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 of the screening process helps to remove particles of the correct size and thus increase the throughput, reduce material re-circulation, and significantly reduce in power consumption.

During last two quarters, QRDC has focused on developing a successful PZT driven screening machine. This goal was accomplished and a demonstration of this design was presented to the DOE and other project partners. Further work into creating more added value through Smart Screens was investigated in the form of alternative input functions. Also, development of a dry application for Smart Screens was advanced.

This report summarizes the work since the last semi-annual report (Quarter 4-2004 & Quarter 1-2005) and has three main chapters. Chapter 1 is directed toward the refinement and validation of an improved PZT Smart Screen. Chapter 2 summarizes the investigation into alternative input functions. Chapter 3 gives details of a feasibility study of using SmartScreens™ technology for a dry application. A summary of findings, results, and recommendations are found in Chapter 4.

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 of 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™ have the capability to control the flow of energy and confine this energy to the screen itself rather than shaking the entire machine and the surrounding structure, which comprises conventional vibratory screening machines. Better control of 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 the 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 such as bearings and bulky unbalanced 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 an 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 requirements 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 SmartScreen™.

During the past 2 quarters, QRDC tested the optimized system in terms of performance and isolation in field under dry and wet conditions. The performance recorded so far is the highest ever recorded, exceeding twice the target performance. This system was successfully demonstrated for the DOE and partner companies at the Coleraine Mineral Research Lab in Coleraine, Minnesota. Furthermore, design of the dry screening application has progressed significantly.

In the next reporting phase, QRDC intends to finish fabrication and evaluation of a screening machine for the seed separating industry. This prototype will demonstrate ability of Smart Screens' core technology to extend across industries and will serve as a springboard for commercial applications of Smart Screens outside of the mining industry.

The SmartScreens™ 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 – DEVELOPMENT OF FINALIZED PZT SYSTEM

1.1 Refinement of PZT-based Taconite Screening System

Testing at ISPAT Inland Mining Company[10] revealed that the strap suspended, PZT powered system did not create enough stroke to meet the design requirements under flow conditions. In response to this, an action plan was implemented to investigate three possible corrective actions:

1. Increase actuator size to apply more energy to the system
2. Redesign resonators to yield greater performance
3. Modify overall system to yield greater performance

Of these three possibilities, modifying the overall system proved to be the best solution. Initial work in [10] showed that coil springs held promise. Subsequent investigation showed that a substantial increase in displacement of the live deck was observed by reverting to a solid leg machine frame, but coupled this time with a coil spring suspension. This design concept is referred to as the Suspended Solid Leg PZT system, or SSL-PZT, and can be viewed in Figure 1.1.1. Two other resonator designs were also fabricated and tested, but neither of these designs provided a performance advantage over the existing resonator design. Finally, investigation was done into the performance limits and cost structures of commercially available PZT actuators. Extensions of the work done in [10] with regard to PZT stack performance modeling allow QRDC to estimate how various PZT stacks will perform in the QRDC Smart Screen design. While more powerful actuators are certainly available, they are viewed as a last resort by the QRDC team due to their prohibitive cost and electrical power requirements.

1.2 Evaluation of Final Design

Testing at CMRL provided multiple chances to measure the prototype's performance in simulated plant conditions. A comparison of data recorded at two visits to CMRL as well as data collected in the QRDC lab at Chaska show that the SSL-PZT system exceeds the design objectives for panel motion and performs consistently from time to time and place to place. Table 1.2.1 summarizes recent dry test results recorded on the live deck. Very little change can be observed, even when moving from a concrete floor (QRDC) to a steel superstructure (CMRL). Tables 1.2.2 and 1.2.3 compare slurry test results of the SSL-PZT system to the previous prototype design on an absolute and percentage basis. Figure 1.2.1 is a simplified diagram relating the point IDs listed in Tables 1.2.1 through 1.2.3 to their physical locations on the machine live deck. It is immediately clear that the solid leg frame prototype delivers far superior results as compared to the previous prototype. Moreover, the measured levels of stroke meet or exceed those typically used with the magnet powered system under similar slurry conditions. Finally, noise levels of machine operation in the no slurry condition at CMRL are generally about 65 dBA. Noise measurements of the screening system are not possible during slurry testing at CMRL due to the extreme noise levels created by the pilot plant's pumping equipment. More simply put, the noise generated by the Smart Screen is lost to plant background noise. This design meets the project requirements.

Table 1.2.1 Recent Dry Screen Test Results

		QRDC: 3-16-2005		**CMRL: 4-11-2005**		**CMRL: 6-26-2005**	
		Frequency 39.7 Hz	Voltage 90 V pk-pk	Frequency 40.4 Hz	Voltage 90 V pk-pk	Frequency 40.5 Hz	Voltage 90 V pk-pk
		Solid Leg PZT System		**Solid Leg PZT System**		**Solid Leg PZT System**	
Point ID		Flow Dir. (mil pk-pk)	Normal Dir. (mil pk-pk)	Flow Dir. (mil pk-pk)	Normal Dir. (mil pk-pk)	Flow Dir. (mil pk-pk)	Normal Dir. (mil pk-pk)
Live Deck	1	32	42	25	41	25	30
	2	33	44	36	45	33	35
	3	27	37	28	38	27	37
	4	31	63	25	64	25	53
	5	32	65	33	63	26	61
	6	25	58	26	54	30	59

Table 1.2.2 Comparison of Slurry Tests

		Ispat Inland: 1-19-2005		**CMRL: 4-11-2005**	
		Frequency 38.8 Hz	Voltage 193 V pk-pk	Frequency 40.4 Hz	Voltage 193 V pk-pk
		Strap Suspended PZT System		**Solid Leg PZT System**	
Point ID		Flow Dir. (mil pk-pk)	Normal Dir. (mil pk-pk)	Flow Dir. (mil pk-pk)	Normal Dir. (mil pk-pk)
Live Deck	1	10	9	28	36
	2	13	10	32	40
	3	10	9	26	35
	4	9	16	28	58
	5	12	18	34	59
	6	9	17	28	48

Table 1.2.3 Percentage Comparison of Slurry Test Data
(Absolute values can be found in Table 1.2.2)

Point ID		Flow Direction	Normal Direction
Live Deck	1	178%	303%
	2	149%	302%
	3	157%	293%
	4	210%	264%
	5	186%	230%
	6	206%	181%
Average Improvement		**181%**	**262%**

1.3 Moving Forward

The SSL-PZT system was tested successfully at CMRL and meets the project performance goals in terms of vibration and metallurgical results. The system, however, needs few refinements before production of this innovative system can be realized. What follows in this report is a brief description of areas of improvement and possible solutions.

1.3.1 PZT/Smart-motor Design and Packaging

QRDC does not currently have a robust, reliable, production ready smart motor. Even though the longevity test of smart motor using quarter system in lab condition is very successful, motor failures were encountered during field testing. Currently, the system operates at its maximum capacity. More powerful motors are needed to provide overhead capacity in instances where plant conditions require more power.

Furthermore, Smart-motors need to be packaged to survive in harsh environments. In the current design, a seal is in place but is not robust enough to avoid moisture buildup inside the packaging during prolonged exposure.

1.3.2. Electronic Equipment

Equipments (amplifier, function generator etc) used so far are laboratory grade and most of them are not suitable for industrial use. Sources for production grade instruments need to be identified and business relationships developed.

1.3.3. Production Ready Control Scheme

QRDC does not have packaged control hardware to continuously monitor SSL-PZT performance and tune automatically subject to change in operating conditions. As with the other electronics, suppliers will be identified and the hardware sourced.

1.3.4. Structural Refinement

Frame redesign is necessary to better incorporate coil spring suspension for performance as well as structural stability. The frame should be redesigned so that the springs are recessed into the machine legs. In the current configuration, the springs may slowly become packed with taconite, making them less effective over time. Also, installation of feed box and undersize hopper should be reviewed to account for changes in frame height created by the coil springs.

CHAPTER 2 – MULTIPLE FREQUENCY INPUTS

Development of a PZT powered screening machine has thus far focused on meeting current fine screen performance levels while significantly reducing energy usage, and cost. PZT motors can, however, provide performance capabilities not possible with conventional fine screens. One of these capabilities is multiple frequency excitation. This has the potential to create a major improvement in screen deblinding, by making a deblinding capability automatic and integral to the screen actuation methodology.

Currently, single frequency sinusoids are the only type of input function used to drive Smart Screen Systems' taconite screeners. Consequently, only one mode, the primary resonator bending mode of the screening system, can be targeted by the input function. While this is effective at creating overall screen motion, it ignores the positive contributions to the screening process that could be made by exciting other modes. Of particular interest are panel modes of the screen itself, because it is hypothesized that exciting these modes may promote screen deblinding, and therefore improve screening efficiency. Two systems have been investigated. First, a quarter system was used to provide QRDC engineers with a wide knowledge base of information. These results were used to formulate a more focused evaluation plan for a more complex assembly made of four resonators and a screen panel.

2.1 Quarter System Experimentation

A simplified quarter system consisting of a single resonator with an attached steel mass was used for this study. Figure 2.1.1 shows a picture of the quarter system set-up. A single accelerometer mounted on the steel mass, measuring in the vertical direction, was used to characterize the system's response.

2.1.1 Summation of Sinusoids

The first type of multiple frequency input evaluated was the summation of two sinusoids. The primary sinusoid was set to the frequency of the first resonator bending mode, 26 Hz. The frequency of the second sinusoid was varied so that the effects of exciting a second resonance frequency as well as a non-resonance frequency could be investigated. Figure 2.1.1.1 shows the input voltage signal and accelerometer response to a summed sinusoid of 26 and 108 Hz (the first two modes of the system). Clearly, both components are visible in the response. When the secondary sinusoid is changed to 150 Hz, the response looks much different. Figure 2.1.1.2 shows that only the primary signal is visible in the response. These results show that secondary resonance frequencies can be effectively targeted with the multi-sinusoid approach. It is possible that this approach could be extended to multiple secondary resonances by summation of three or more sinusoids. It is important to note that in all cases throughout Section 2.1 of this report, the accelerometer response is not calibrated to units of acceleration. The traces are valuable for comparison between cases and observation of signal characteristics, but not absolute acceleration level.

2.1.2 Square Wave

A square wave input is another possible method of promoting screen deblinding while still maintaining gross screen motion. It is well suited to this purpose from both a time domain and frequency domain perspective. From a time domain perspective, the square wave applies a sudden, jarring, load to the screen, which should knock trapped particles loose. From a frequency domain perspective, the square wave contains energy at a theoretically infinite number of discrete frequencies over an identically infinite bandwidth. In practice, however, the number of terms and bandwidth are dependant on the limitations of the instrument used to generate the signal. By setting the primary frequency of the square wave to excite the main system resonance, overall screen motion should be created. The rest of the frequency content should excite higher frequency modes, including screen panel modes. A benefit of this is that many panel modes can be excited at once, as compared to the first approach, where only a single secondary mode is excited. A drawback is that the energy is distributed over a broad frequency range, and as such none of the panel modes may be sufficiently excited to promote screen deblinding. Investigation with the laboratory system was primarily targeted at observing the transient behavior due to the step changes in the applied force. Figure 2.1.2.1 shows the response to a square wave with a primary frequency equal to the main system resonance. The response shows two characteristics: a quasi-sinusoidal response at the main system resonance frequency and impulse responses corresponding to the step changes. In this respect, the results show great promise. A major limitation, however, was discovered in the available voltage amplitude.

The maximum voltage that could be supplied to the PZT actuator before reaching the current draw limit of the amplifier was dramatically lower than the actuator's true voltage limit. This threshold will be subsequently referred to as the over-current voltage limit. It is suspected that voltage step changes cause extremely high transient currents within the output circuitry of the amplifier, since from a time domain perspective, current draw through a capacitor is proportional to the derivative of voltage over the capacitor (see Equation 2.1.2.1). This explanation can also be viewed from a frequency domain perspective. Step changes in voltage contain components at very high frequencies. Current draw by the capacitor is defined in the frequency domain with Equation 2.1.2.2, showing that an increase in frequency causes an increase in current draw. Even though the voltage level of the components of the square wave becomes quite low as the frequency becomes higher, the frequency term of the equation itself is enough to compensate for this and make the current requirement noticeable and problematic. Two possible solutions to this problem were investigated. First, PZT actuators are seen by the amplifier as a capacitive/resistive load, meaning that they have very little inductance, and therefore very little ability to resist extreme rates of current change. By adding an inductor in series with the actuators, it was hoped that the ability of the amplifier to respond to these high transient currents would be diminished. Inductors supplied by AE Techron for use with their amplifiers (a different amplifier than was used in this experiment) were added to the experimental set-up. The inductors did not prove useful in raising the over-current voltage limit. The reasons for this are unclear, but the most likely reason is that the inductance of these coils was simply not high enough. According to AE Techron, these inductive coils were built for impedance matching of their amplifier to a specific PZT actuator, not to limit transient current.

$$i = C \cdot {dv}/{dt} \tag{2.1.2.1}$$

$$I = j\omega C \cdot V \tag{2.1.2.2}$$

Before significant effort was invested into sizing a more useful inductor, another method was investigated. Limiting the input signal's bandwidth with a low pass filter was shown to be successful in raising the over-current voltage limit, at the expense of the impulse response characteristics of the output signal. Filtering was accomplished with a negative feedback operational amplifier by including a capacitor in the feedback loop. Equation 2.1.2.3 is the frequency response function of the filter. The values of R_1 and R_2 were held constant and equal to keep the DC gain of the filter at unity while the capacitance value was varied to control the cut-off frequency. This filter is a very basic one, with a shallow roll-off rate. The listed cut-off frequencies, therefore, should be viewed as rough estimates only. Figures 2.1.2.2 and 2.1.2.3 show the square wave input and response with various levels of filtering applied. By inspection of all the square wave input and response plots, it is clear that lowering the cut-off frequency of the filter increases the achievable voltage (Figures 2.1.2.1 though 2.1.2.3 all show the system responding very near to each case's over-current voltage limit) but makes the impulse response portion of the response signal less apparent. Experimentation on a full scale system (screening system, amplifier, and PZT actuators) is necessary to find the best compromise of voltage limit and frequency content. The amplifier directly controls the current limit, the ceramic actuators dictate the capacitance of the system, and the screen unit itself dictates the necessary frequency range, all of which together control the achievable voltage, and therefore the amount of motion achieved by the screening system.

$$G = \frac{-R_2/R_1}{1 + j\omega R_2 C} \tag{2.1.2.3}$$

2.1.3 Saw tooth

The saw tooth function has many of the same strengths and weaknesses as the square wave. However, both the strengths and weaknesses are moderated. The voltage changes are not as severe, making the impulse response characteristics not as good, but allowing for a greater over-current voltage limit. Figure 2.1.3.1 shows a saw tooth input and the system response. Since the same arguments and theories that hold true for a square wave hold true here, little investigation of quarter system performance with saw tooth inputs was necessary to understand the phenomenon. Since it is essentially a less extreme version of square wave excitation, it may prove to be very important in full system implementation.

2.1.4 Impact on Sine

Another way of combining a consistent response at the system's primary resonance while imparting a momentary load to the system is by combining a sine wave with an impulse. Two types of impulse are available from the AFG 320 function generator used in these experiments. The duty cycle of the square wave can be set so that it resembles a pulse train. Alternatively, the generator will produce a sin(x)/x signal which also resembles a pulse train. Comparisons of the two input signals and responses are given in Figures 2.1.4.1 and 2.1.4.2. The differences in system response are predictable. The pulse train generated from the square wave creates better impulse response features in the output, but the maximum achieved voltage is diminished.

2.1.5 Random-on-Sine

A final method of targeting multiple modes is by combining a sine wave with a random signal. As with previous methods, the sine wave excites the primary system resonance, ensuring adequate gross screen motion. The random component excites all modes within its bandwidth, so that it can be tailored to target only certain number of panel modes, rather than spreading the energy over near infinite number of modes, panel and otherwise. The function generator used during this investigation does not have a bandwidth limitation for the random signal, so this aspect was not investigated. Figures 2.1.5.1 and 2.1.5.2 show the response of a sine wave alone and the same sine wave with an added random component. It is important to note that in these figures, there is some noise on the output measurements due to the measurement system alone. An added random component, due to the added random input, can clearly be seen in the output of Figure 2.1.5.2, showing that the energy of the random signal can be transferred through the resonator. It seems likely that screen panel modes can be excited in this manner.

2.1.6 Conclusions from the Quarter System

This investigation yielded many positive results. Secondary resonances of the quarter system can be excited and both stationary as well as transient type signals can be transmitted through the resonator and are visible in the response. Several key areas to address in subsequent testing were also identified:

1. **The ratio of energy directed to the primary resonance as compared to secondary modes:** As more energy is pulled away from the primary system resonance, overall gross motion of the screen is likely to drop. An acceptable tradeoff will need to be found. It is also possible that larger actuators may be necessary so that the same amount of energy may be directed to the primary resonance with the added capacity being used to excited secondary resonances.
2. **High frequency energy limits the achievable drive voltage:** This is a concern for all of the input types which have a theoretically infinite number of terms in their Fourier series (square, saw tooth, impulse). Including frequency content higher than necessary to target panel modes will use a disproportionate amount of the amperage available from the amplifier, which may result in lower achievable voltage to drive the actuators, and therefore less deflection on the screen.
3. **PZT actuator cracking:** Two primary failure modes have been observed with the ceramic actuators so far. Electrical short circuits to the smart motor housing have been controlled to a great extent with careful application of liquid and standard electrical tape, in fact failures of this sort have been nearly eliminated. Failures due to crack propagation through the ceramic layers continue to be a problem. The causes for these cracks are unclear, but they seem to be related to non-uniform stress distribution across the actuator face (either by non uniform loading or stress risers internal to the ceramic material). It seems likely that moving from purely sinusoidal forces to more transient loading patterns will exacerbate this problem.
4. **Increased SPL:** It is unmistakably apparent to the ear when high frequency content is added to the input signals. It seems likely that exciting panel modes will increase the overall SPL of the screening machine in operation. In the case of square waves or impulse functions, the added sound energy will be spread across a large frequency range, including octave bands which are important to speech intelligibility as well as

annoyance rating. Random-on-sine or sine-on-sine type inputs can be controlled to target specific modes or frequency bands, hopefully avoiding some of these critical frequency ranges.

2.2 Simplified Screen Testing

Multiple frequency input testing was extended from the quarter system to a simplified screen system, seen in Figure 2.2.1. The system is constructed of four flat beam resonators attached to a screen panel at one end and fixed to ground at the other. Two classes of multi-frequency inputs were used to drive the machine and a response was measured at the center of the screen panel. The primary resonance frequency of the system is at 72 Hz. Secondary modes exist at many other frequencies, including 130 Hz and 184 Hz. Figure 2.2.2 (72 Hz and 184 Hz) shows that secondary responses are visible in both the flow and normal to the screen directions, since the 184 Hz mode participates in both of these directions. Conversely, Figure 2.2.3 (72 Hz and 130 Hz) shows secondary mode participation in only the normal direction because the 130 Hz mode does not have much motion of its own in the flow direction. This demonstrates that many different motion profiles can be achieved by targeting different secondary modes. Figure 2.2.4 (72 Hz and 150 Hz) presents a case where the 150 Hz input does not excite any secondary mode, and is therefore not very visible in either response signal. An impulse contains a broad bandwidth of frequency information, so that many secondary modes can be excited at once. Figure 2.2.5 shows the added effect of a pulse train to this system. The effects of the pulse train are clearly visible in the response in both directions, but the effect is much more apparent in the normal direction, probably because most of the panel modes participate in the normal direction while substantially less participate in the flow direction. Figure 2.2.6 provides a baseline for comparison to the other cases.

These results show that the opportunities for panel excitation through secondary frequency inputs are nearly boundless. Careful combination of modes can create infinite motion profiles on the screen deck, and can even create different motion profiles on different areas of a single screen. A large scale testing program should be considered to fully investigate how to harness these important new capabilities.

CHAPTER 3 - DRY APPLICATION PROTOTYPE DEVELOPMENT

In the previous reporting period, a commercially available seed cleaning machine was evaluated in terms of dynamic performance and overall design features. This allowed QRDC to develop a set of design opportunities for the application of Smart Technologies in a grain screening prototype [10]. With this information, QRDC devised a design and evaluation plan for a grain screening prototype.

3.1 Dry Application Development Plan

Two actuation problems are presented by the grain screening prototype. First, overall shoe actuation and second, actuation of the screen itself. In order to most completely investigate both of these factors in a time effective manner, a seed screening prototype as well as an experimental mock-up will be developed. The experimental mock up will allow for fast evaluation of potential screen actuation methodologies without the expense and lead time associated with modifying a large prototype. The large prototype will give understanding into overall shoe actuation techniques. As the Dry Application phase of the project draws to a close, a single modification can be made to incorporate the most successful screen deblinding methodology into the large prototype. The following are as general guidelines developed by QRDC for the dry application prototypes:

<u>Seed Separation Prototype</u>

- Incorporate a “smart” drive mechanism for overall shoe motion
- Maintain as much commonality of design with a Cimbria 101 unit as possible

The overall prototype is not expected to be fully functional during this project phase. During this phase, the seed separator prototype

Must:

- Create overall gross motion necessary for seed separation
- Have the necessary features to direct grain through the system
- Be constructed so that it could be brought up to full functionality in a subsequent phase

Will not require:

- A feed system capable of delivering accurate flow control
- A deblinding method of any type
- An air handling system to remove light and fine particles

<u>Single Screen Pre-prototype (experimental mock-up)</u>

- Show capability in screen deblinding

The single screen mock-up is envisioned to be a developmental tool that will allow QRDC to experimentally verify deblinding methods. It should be approached more as a research tool rather than a prototype design. During this phase, the pre-prototype

Must:

- Allow seeds to flow over the screen
- Show blinding when QRDC deblinding technology is not applied
- Maintain non-blinded condition when QRDC deblinding technology is applied

Will not require:

- A feed system capable of delivering accurate flow control
- Overall gross motion of the screen surface

3.2 Design Concepts

Several initial concepts were formulated focusing on overall machine layout and function. Subsequently, a design review was held where each configuration was graded on its merits. The most favorable concept from this exercise is currently undergoing an in-depth design and analysis process. Figures 3.2.1 through 3.2.3 show the three possible screen configurations evaluated in the design review. Figure 3.2.1 represents the most basic concept. This concept retains a nearly identical shoe and simply tries to replace the existing drive mechanisms with Smart Technology. The linear motor and mechanical linkage concept (Fig. 3.2.2) retains a nearly identical shoe but provides motion though a linear motor and mechanical linkage. The primary improvement here would be in removing the traditional motor and eccentric masses, but would retain a relatively complex linkage mechanism. Multiple independent screens (as demonstrated in Fig. 3.2.3) will require independent control and actuation mechanisms, adding greatly to cost and complexity. It is realized, however, that large scale prototypes may benefit greatly from dividing the moving mass, and that this may justify a multiple shoe concept in larger machines. In fact, current large-scale industry machines use a two shoe concept with the shoes moving out of phase to help cancel out horizontal dynamic forces.

The most promising overall concept proved to be a single shoe design powered by either electromagnets or PZT motors. This design was deemed most viable because of its simplicity and because of the attractiveness of design to potential commercial partners, who expressed interest in removing the motor and linkage while retaining some commonality of design with existing machines. Figure 3.2.4 shows a cut-away view of the current shoe concept. The prototype shoe will be built from wood and the actual screen surfaces are being sourced through an industry partner. The top screening surface is designed to remove oversized material while the middle deck is designed for removal of undersized material. The bottom screen can be used for either purpose. The overall look and feel of the shoe itself is quite similar to designs common to the industry. Rather than starting from scratch, QRDC is focusing on improving existing designs from the standpoint of energy usage and maintenance cost by introduction of a “smart” actuation system.

3.3 Analysis and Modeling

Besides developing a design concept, it was also necessary to set quantitative goals by which to measure performance. Since QRDC is focusing on improving an existing design, the performance goals for the QRDC prototype are pulled directly from the measured performance of a commercially available Cimbra 101 unit inspected at QRDC's Chaska Laboratory. Table 3.3.1 contains these numeric performance targets.

Table 3.3.1

Performance Metric	Target
Operating Frequency	4.75 Hz
Horizontal Gross Motion	1.15 in
Vertical Gross Motion	0.090 in

The high ratio of horizontal to vertical motion suggests that the resonators for this design must be quite long. While the existing machine does not use a tuned resonator, it does suspend the shoe with long steel straps, approximately 25 inches long, 2 inches wide, and one eighth inch thick. The length and width dimensions are essentially held constant to protect the horizontal to vertical motion ratio while the thickness can be tuned to achieve the correct resonance frequency. Figure 3.3.1 shows the free vibration response of the current shoe concept with tuned resonators. By holding the thickness of the resonators to a commercially available value of 0.1875 inches and making only slight changes to resonator length and width dimensions, a natural frequency of 4.8 Hz is achieved.

Currently, efforts are underway to finalize the design by incorporating a steel structure to support the shoe and assess the most advantageous force application location, as well as the amount of force necessary to create the desired stroke levels.

CHAPTER 4 – CONCLUSION

In this report, our progress since the last semi-annual report was detailed. A successful PZT based Smart Screen System was developed and demonstrated for the DOE and partner companies. This system, created by combining a solid leg frame with a coil spring suspension, meets or exceeds screen motion performance goals in both the dry and slurry conditions. This represents a major step in fulfilling the primary objectives of this project. Furthermore, the noise levels created by this prototype were undetectable when compared to the background noise of the CMRL pilot plant.

The longevity test of the PZT based quarter system with smart motor (started in Q3, 2003) continued to run with no sign of performance loss or failure. That system has now accumulated over 750 million cycles and continues to be successful.

Extending the performance of a PZT based system from simply matching screen dynamics of existing machines to adding built-in deblinding capabilities was investigated. Tests on a quarter system and simple screen set-up both show significant promise in this area. This is the first of a new horizon of possibilities created by leveraging smart materials.

Also, significant progress was made on developing a prototype for a dry screening application. Basic design and analysis was completed for a Smart Technology based seed cleaning machine. In-depth evaluation is currently underway and will continue in the next reporting period, culminating in a viable dry screening prototype.

In summary, this project is progressing at a healthy rate and is continuing to meet goals and expectations.

FIGURES

Figure 1.1.1 PZT based system mounted on coil springs at QRDC lab

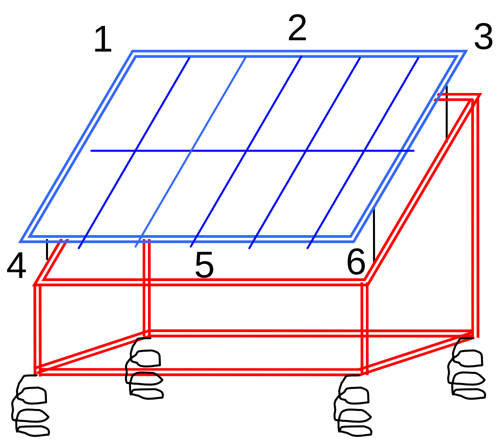

Figure 1.2.1 Simplified Diagram Showing Point IDs for PZT Performance Comparison

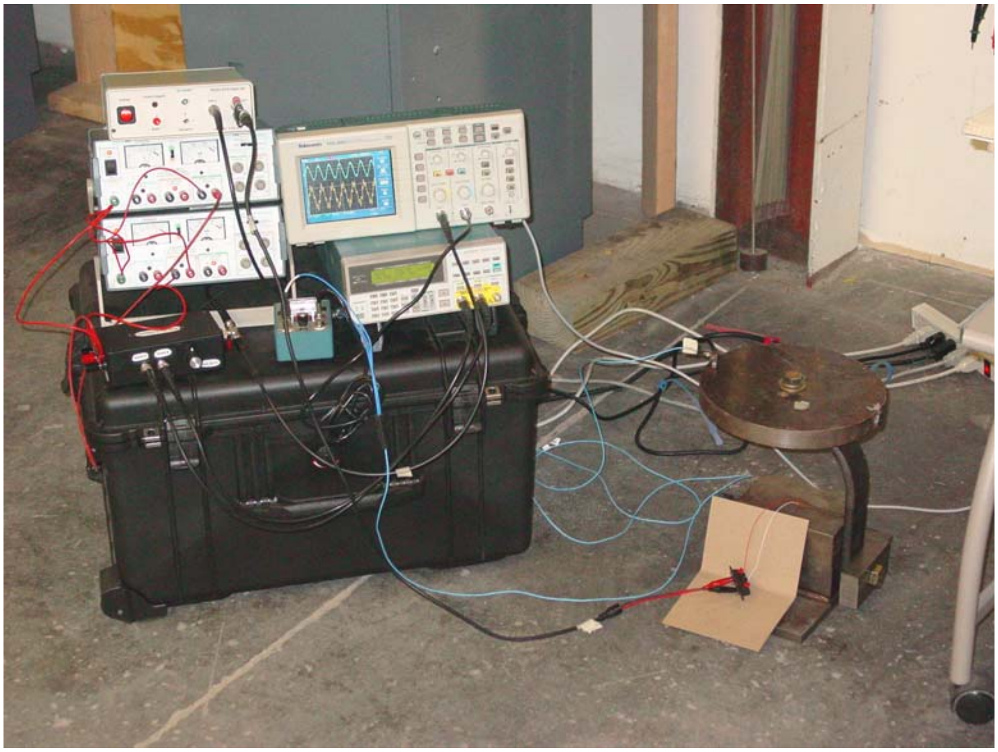

Figure 2.1.1 Single Resonator System for Study of Alternative Inputs

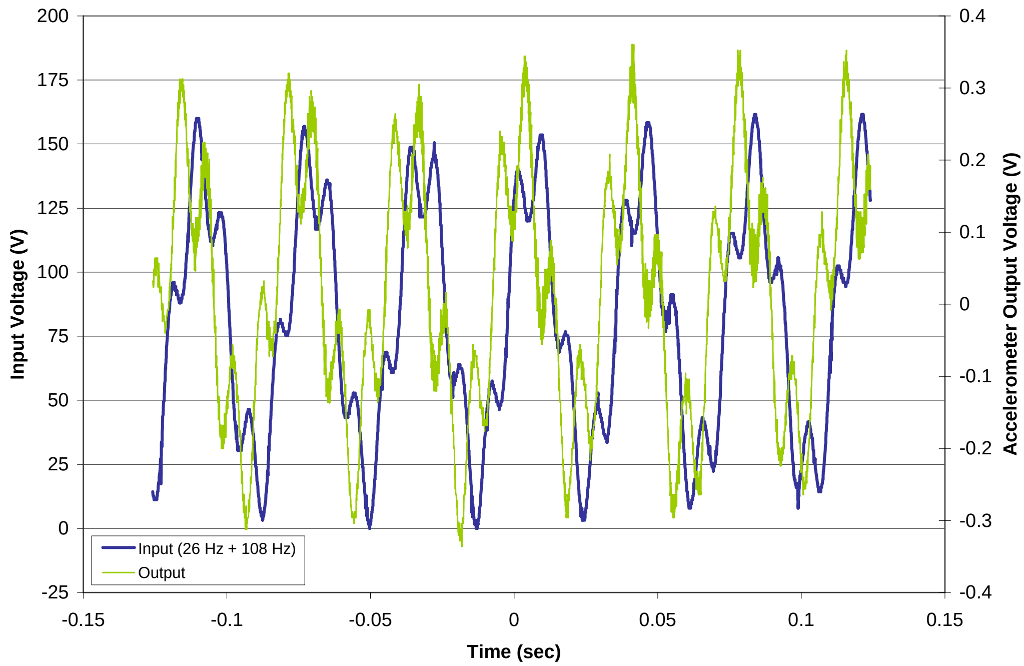

Figure 2.1.1.1 Multiple Sinusoid Input – 26 and 108 Hz

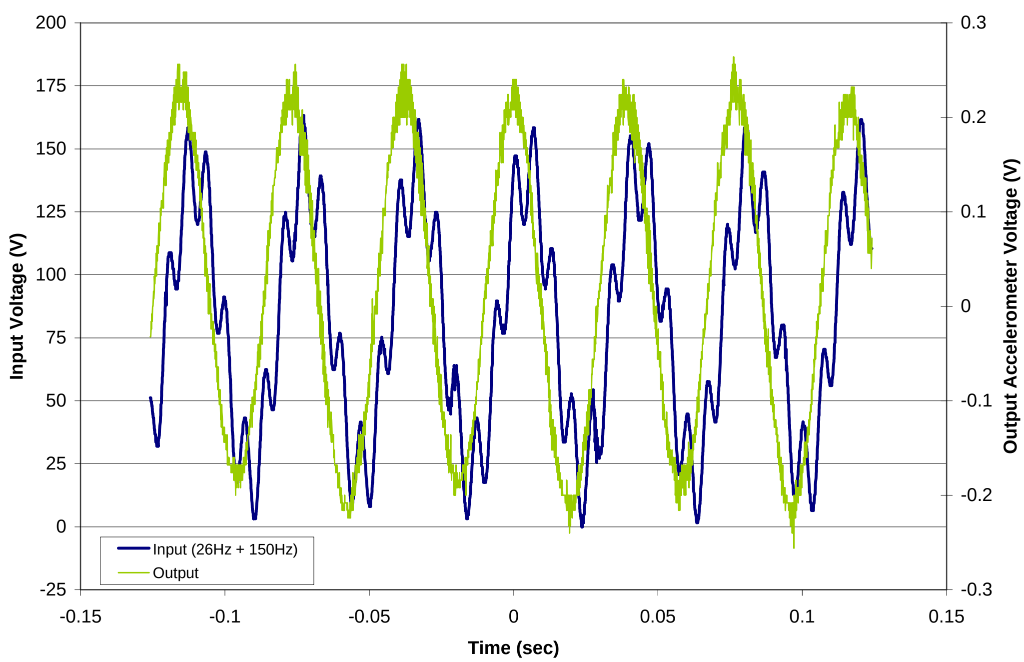

Figure 2.1.1.2 Multiple Sinusoid Input – 26 and 150 Hz

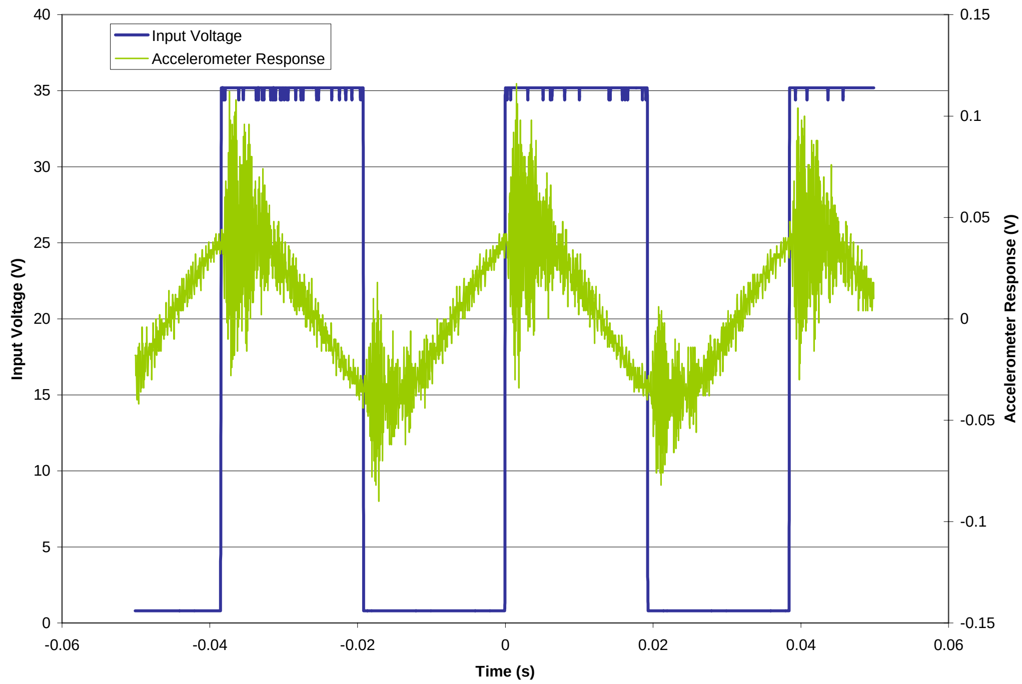

Figure 2.1.2.1 Square Wave Input and Response, No Filtering

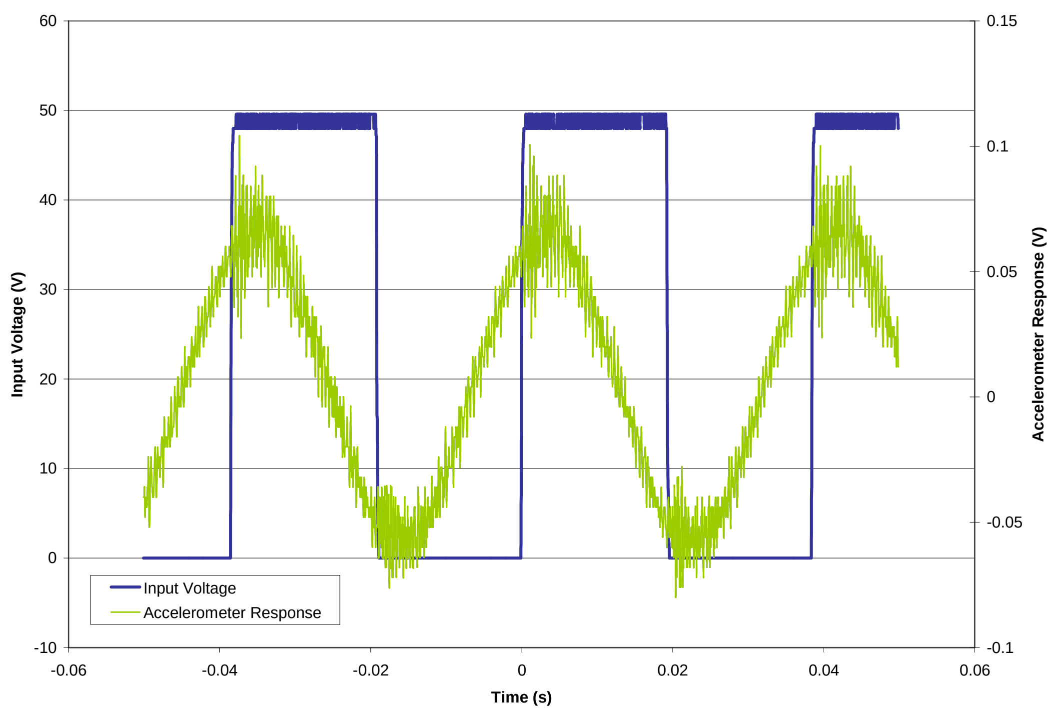

Figure 2.1.2.2 Filtered Square Wave Input and Response, f_c=1775 Hz

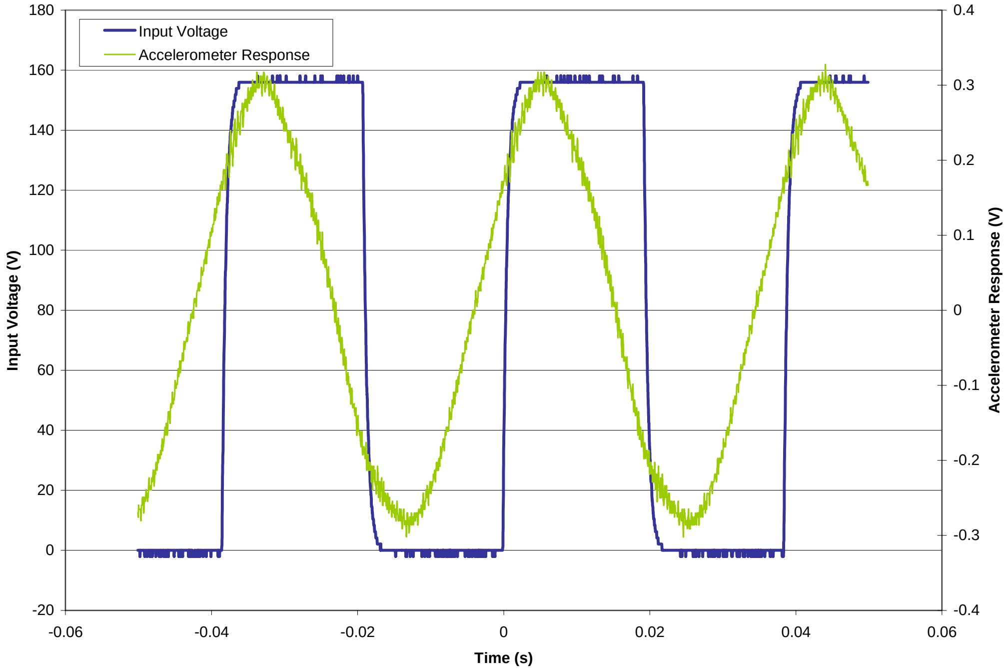

Figure 2.1.2.3 Filtered Square Wave Input and Response, f_c=285 Hz

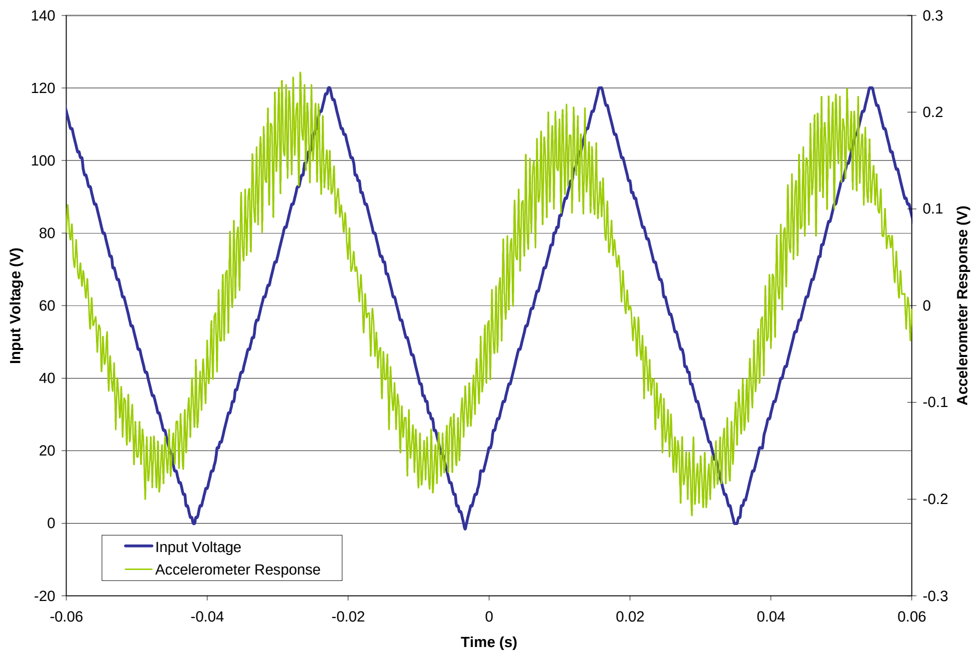

Figure 2.1.3.1 Saw Tooth Input and Response

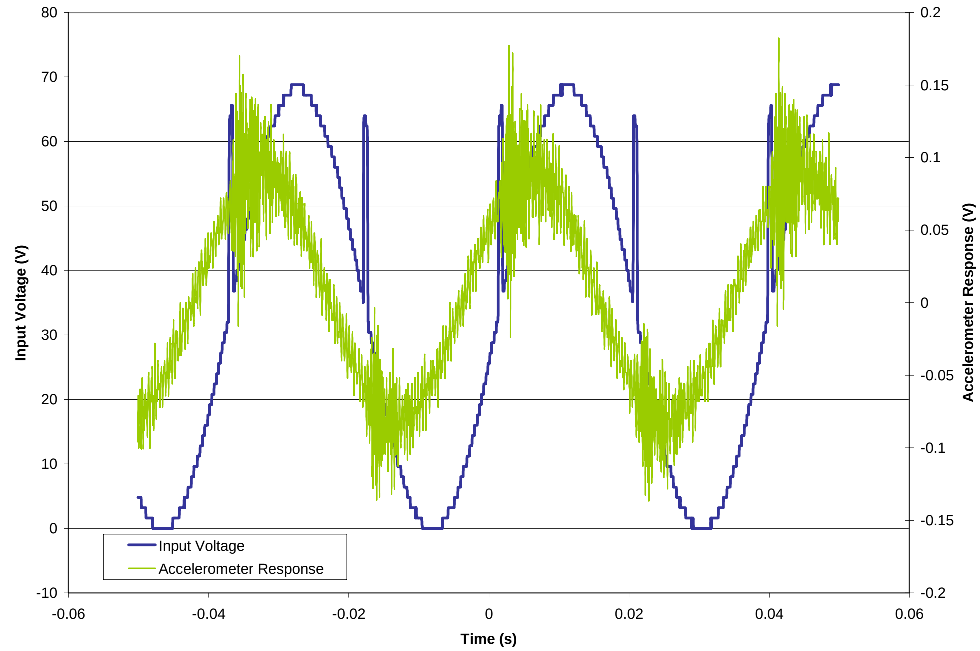

Figure 2.1.4.1 Impulse on Sine – Square Wave Method

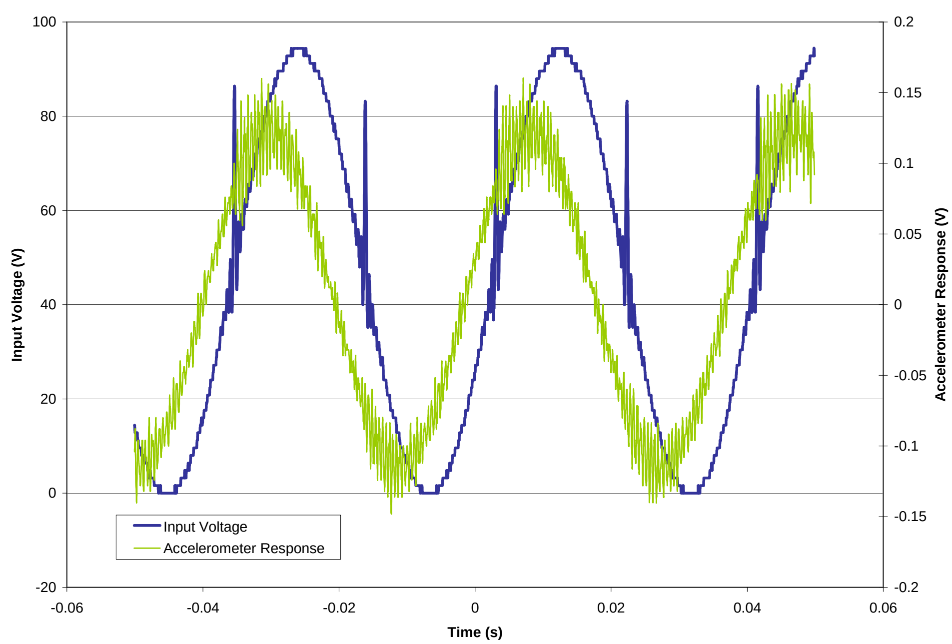

Figure 2.1.4.2 Impulse on Sine – Sin(x)/x Method

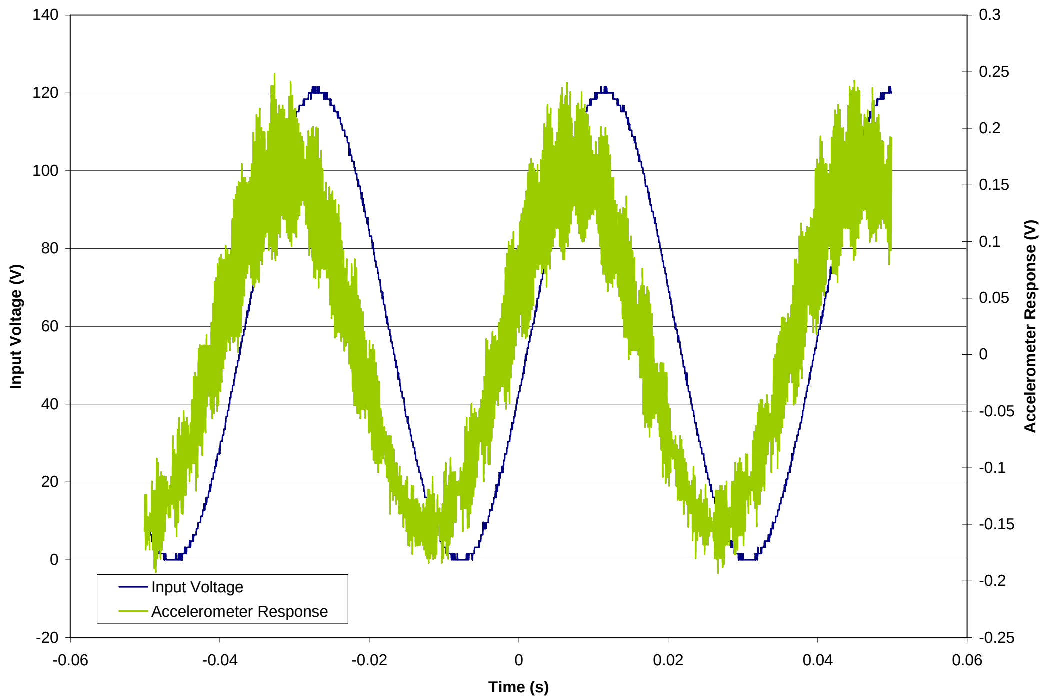

Figure 2.1.5.1 Sine Wave Only Input and Response

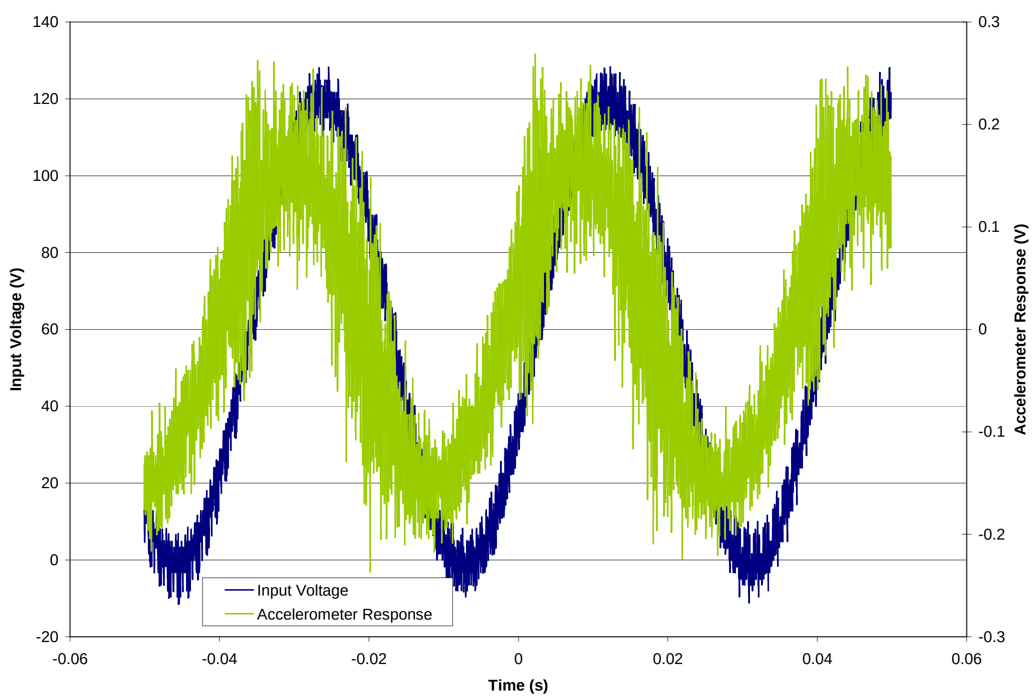

Figure 2.1.5.2 Random on Sine Input and Response

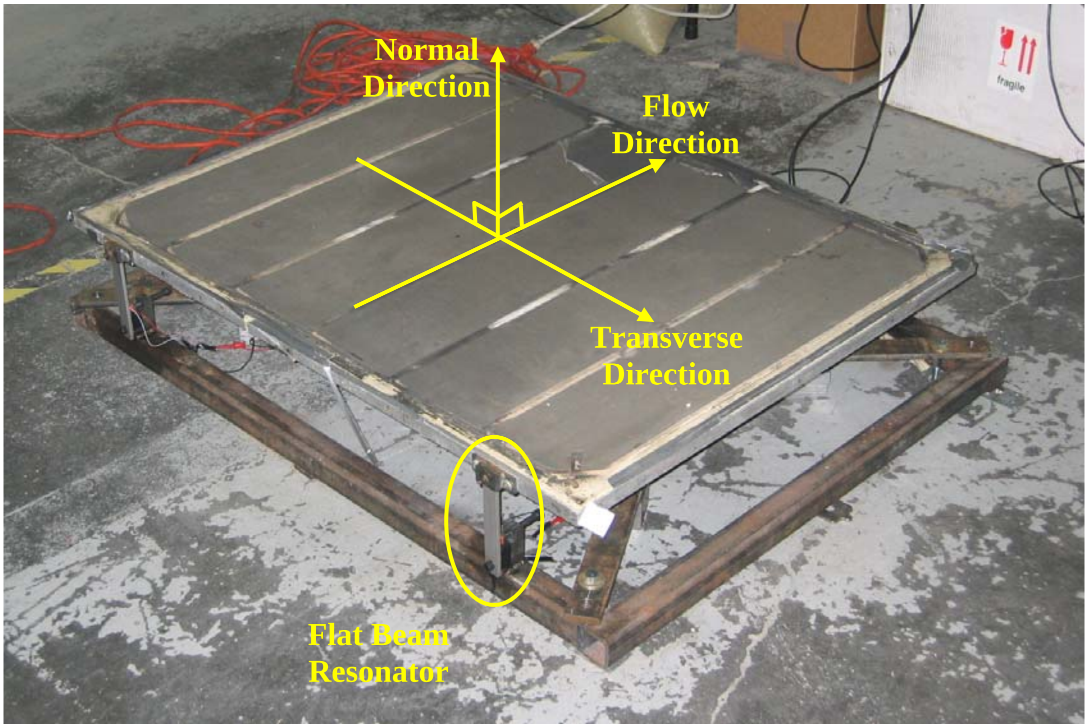

Figure 2.2.1 Simplified Screen System

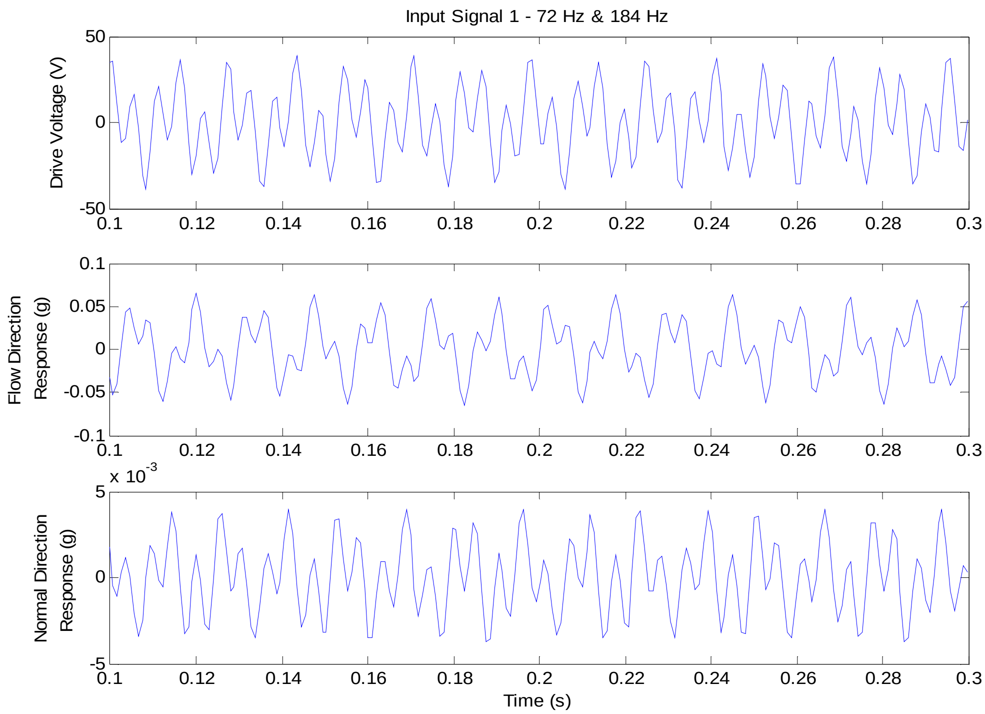

Figure 2.2.2 Multiple On-Resonance Sinusoids, 2 Direction Response

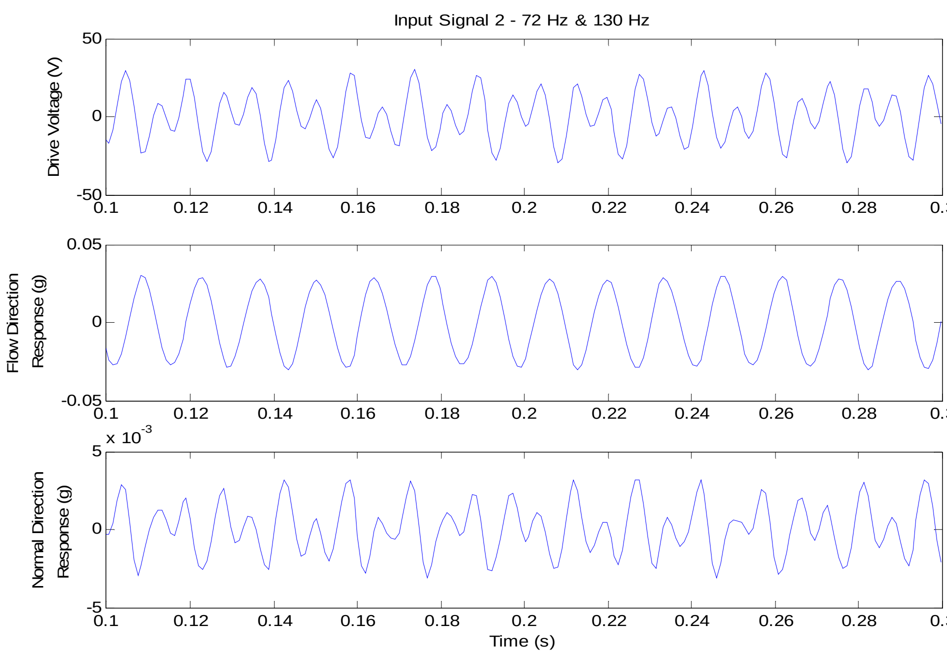

Figure 2.2.3 Multiple On-Resonance Sinusoids, 1 Direction Response

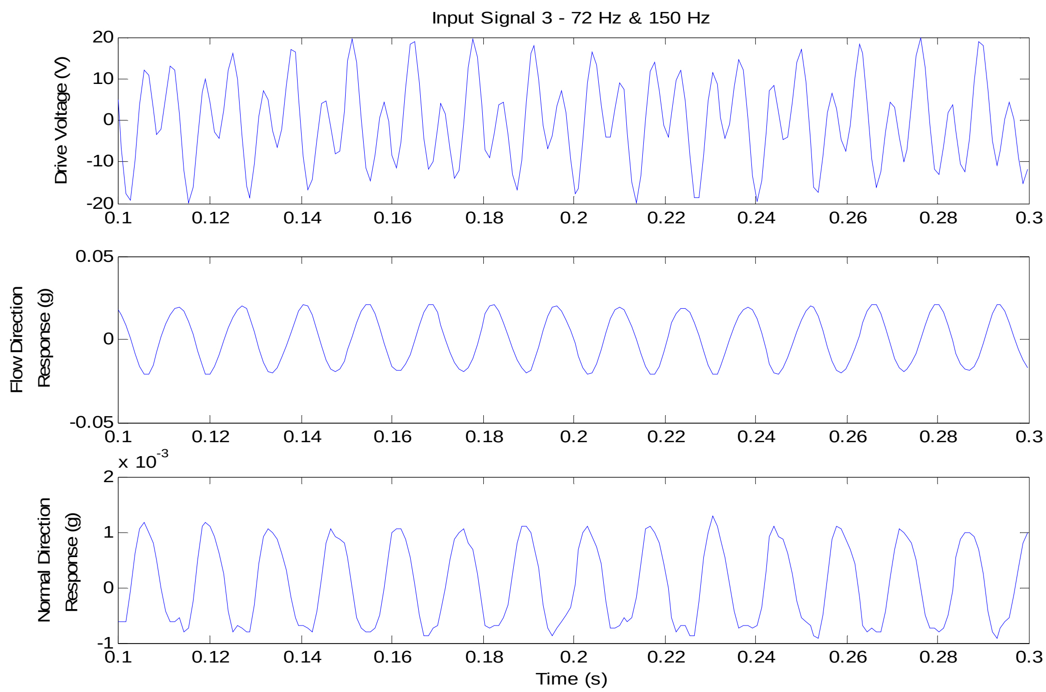

Figure 2.2.4 Multiple Sinusoids, 1 On-Resonance and 1 Off-Resonance

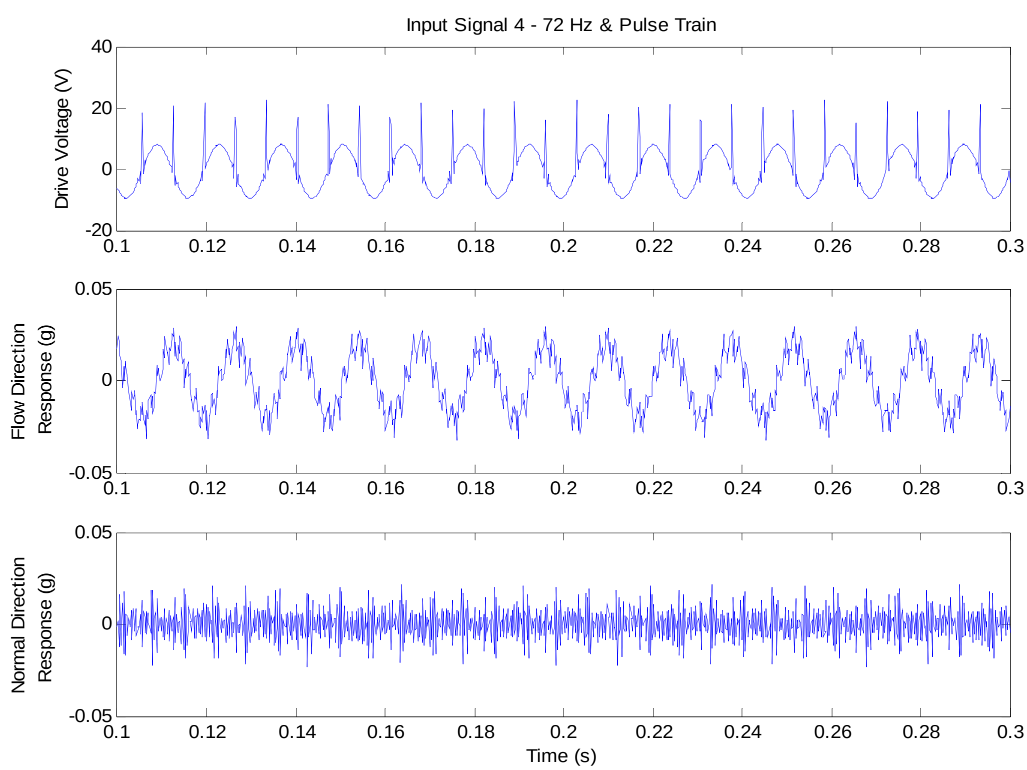

Figure 2.2.5 Impulse-on-Sine

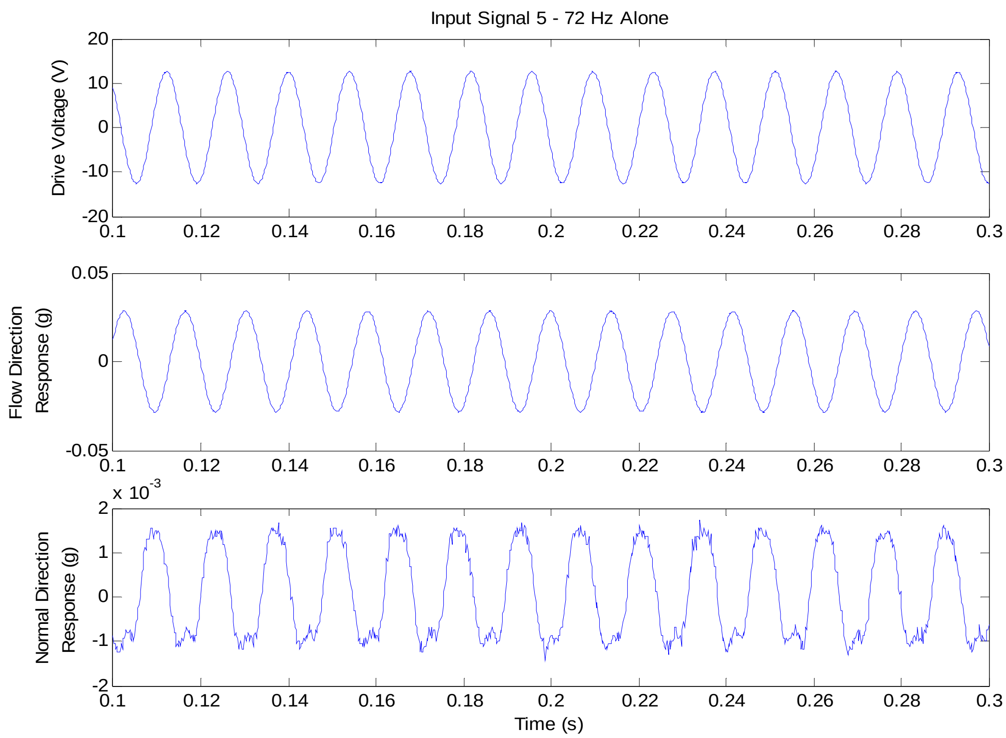

Figure 2.2.6 Single Sinusoid Reference

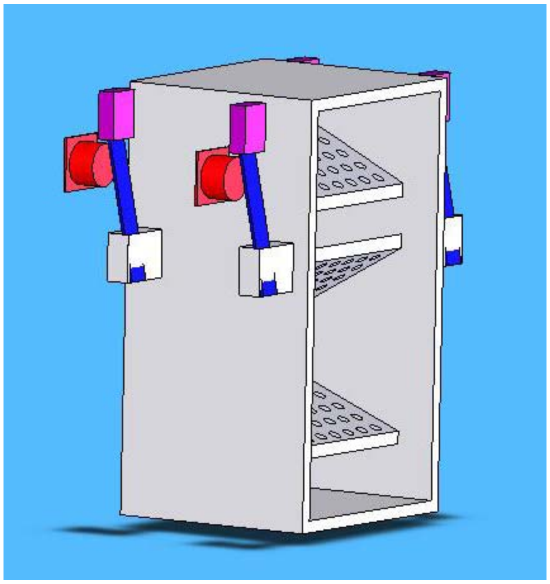

Figure 3.2.1 Single Shoe Concept Powered by Electromagnets/PZT Motors

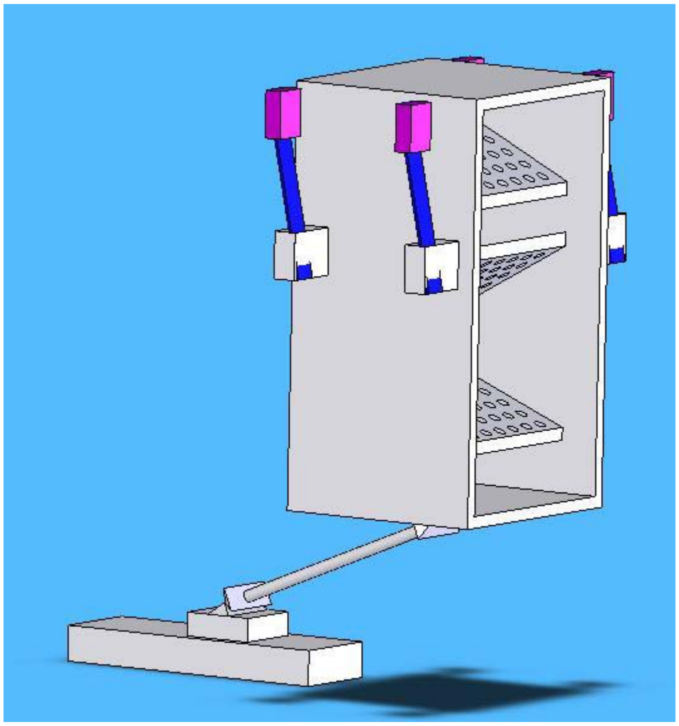

Figure 3.2.2 Single Shoe Concept Powered by a Linear Motor

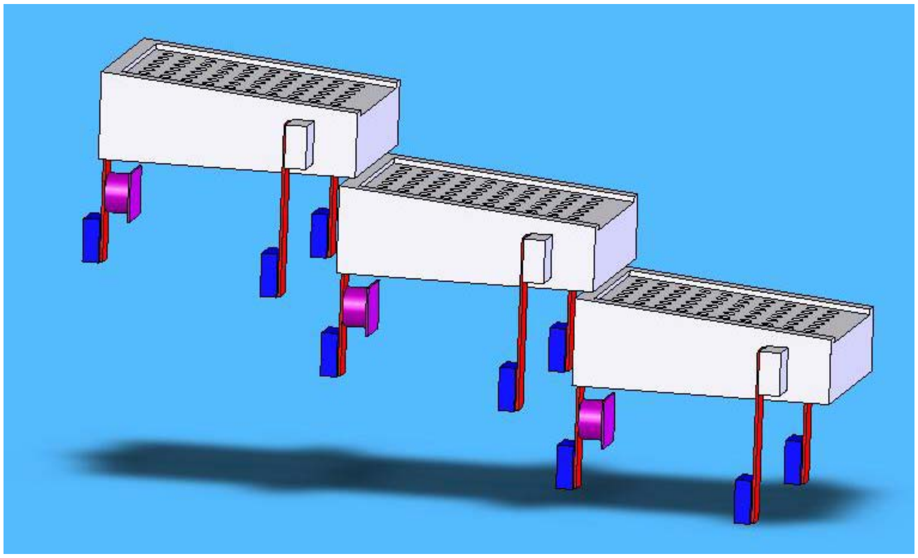

Figure 3.2.3 Multi-Shoe Concept

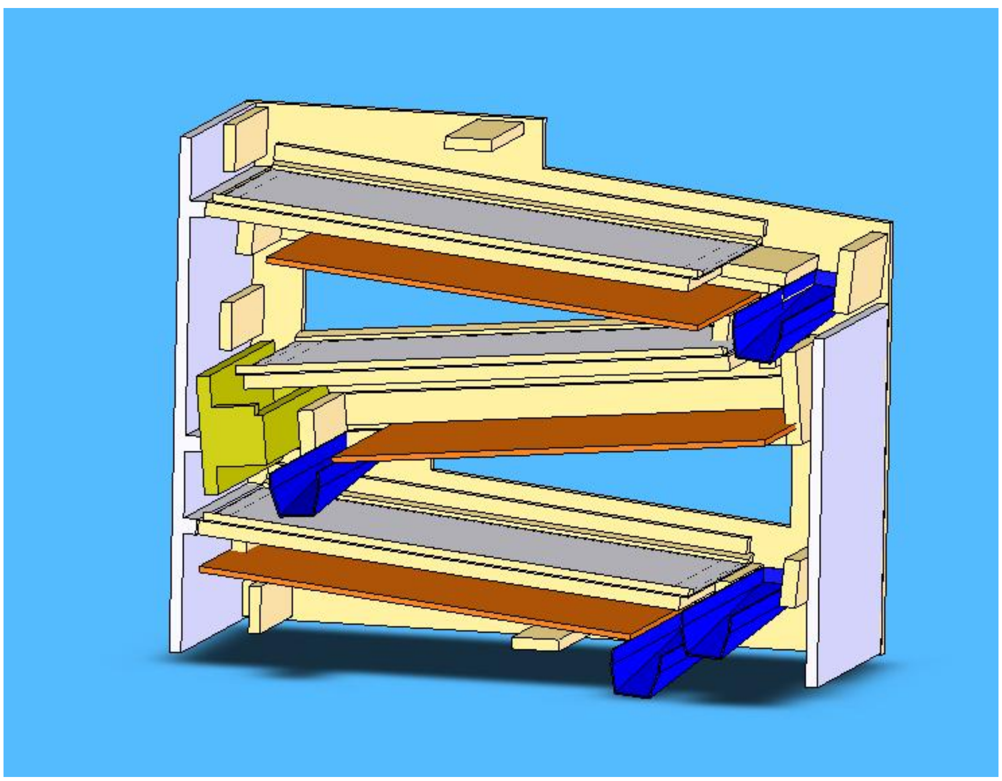

Figure 3.2.4 Current Shoe Concept

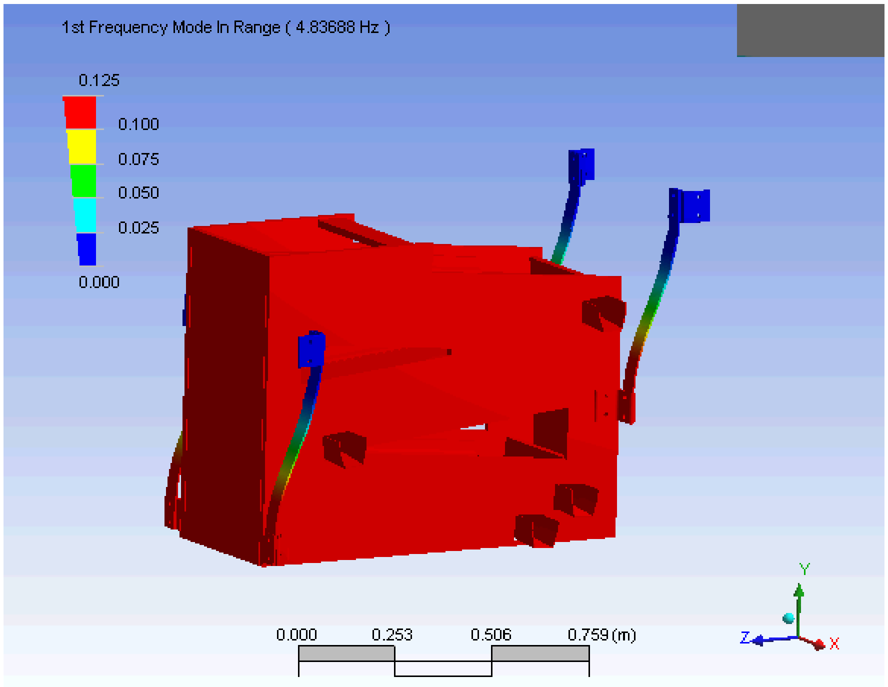

Figure 3.3.1 Free Vibration Response of Seed Cleaner

REFERENCES

1. Minntac MTI Grant, New Screen Technology Grant Application, 2001
2. D. J. Tarnowski, D. Allaei, D. Landin, C.P. Chen, and S. Liu, “An Innovative Noise and Vibration Suppression Technique Based on the Combination of Vibration Control by Confinement and Layer Damping Approaches,” 3rd Joint Conference – Acoustical Society of America (ASA) and Acoustical Society of Japan (ASJ), Hawaii, 1996.
3. D. Allaei, “Energy-Based Hybrid Vibration Control System for Load-Bearing Skin Structures,” Phase I final briefing to Army Space & Missile Defense Command in Huntsville, AL, Paper and CD copy, 1999.
4. D. Allaei, “Energy-Based Hybrid Vibration Control System for Load-Bearing Skin Structures,” Final report as part of the MDA Phase I delivered item, 1999.
5. D. Allaei, “Smart Screening System (S3) in Taconite Processing”, DOE Project Proposal, 2001.
6. D. Allaei & A. S. Mohammed, “Smart Screening System (S3) in Taconite Processing”, semi-annual report I delivered to DOE/NETL, 2003.
7. D. Allaei & A. S. Mohammed, “Smart Screening System (S3) in Taconite Processing”, semi-annual report II delivered to DOE/NETL, 2004
8. D. Allaei & A. S. Mohammed, “Smart Screening System (S3) in Taconite Processing”, semi-annual report III delivered to DOE/NETL, 2004
9. D. Allaei & A. S. Mohammed, “Smart Screening System (S3) in Taconite Processing”, semi-annual report IV delivered to DOE/NETL, 2004
10. D. Allaei & A. S. Mohammed, “Smart Screening System (S3) in Taconite Processing”, semi-annual report V delivered to DOE/NETL, 2005

LIST OF ABBREVIATIONS

S3 – Smart Screen Systems
ARC – Albany Research Center
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
SSL-PZT – Solid Leg Frame Suspend with Coil Springs, Powered with PZT Stacks