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ACTIVE CONTROL OF COMPRESSOR NOISE RADIATION USING PIEZOELECTRIC ACTUATORS

by

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ABSTRACT

Active control of sound radiation from a fractional-horsepower reciprocating piston compressor is experimentally investigated. Sound radiation from the compressor is effectively reduced by controlling the shell vibration using piezoelectric actuators bonded to the surface of the compressor shell. Noise reductions of 11-25 dB are shown for individual compressor pumping harmonics. Basic design considerations are also reviewed.

INTRODUCTION

With the current wave of environmentalism and concern about the depletion of the earth's ozone layer, traditional refrigerants (R-12 and R-22) are being eliminated. The Montreal Protocol revised in June 1990 (UNEP, 1987) calls for the complete phase out of CFC's by the year 2000 and HCFC's by 2020. In addition, President Bush has recommended (Bush, 1992) that the timetable for CFC removal be accelerated up to 1996. As a result of these actions, several alternate refrigerants have been developed which offer little or no ozone depletion potential. Unfortunately, the elastomer materials commonly used to isolate the reciprocating compressor mechanism vibrations from the hermetically-sealed shell are incompatible with most of the new alternate refrigerants. Production of compressors without these isolators would likely give rise to a significant increase in the compressor noise radiation. In such a case, active control of the compressor noise provides a novel alternative to traditional noise control strategies in order to maintain or further reduce the low frequency noise radiation to acceptable levels.

Recently, Toshiba has applied active noise control to a household refrigerator to control low frequency compressor noise (Saruta *et. al.*, 1991). Toshiba's system utilizes a small control speaker to cancel the noise emitted through a ventilation opening in the otherwise sealed enclosure containing the rotary compressor. The active control system coupled with the refrigerator's sealed enclosure combine to give an average sound pressure level reduction of 7 dB between 0-16 kHz.

Sound radiation from a compressor is transmitted by the vibration of the compressor shell. Therefore, instead of controlling the radiated sound with an acoustic source, the noise can also be effectively reduced by controlling the shell vibration directly. Recently, piezoelectric actuators have attracted much attention in the active noise and vibration control field since they have several advantages over conventional point actuators including being space efficient, inexpensive, lightweight, and easily shaped and bonded to surfaces. However, most previous research investigations with piezoelectric actuators have been limited to highly idealized problems such as vibration control of cantilever beams (Baz and Poh, 1987) or sound radiation (or transmission) control of simplified plate and shell structures (Wang and Fuller, 1990; Lester and Lefebvre, 1991).

In this study, a first attempt of actively controlling compressor noise and vibration using piezoelectric actuators is experimentally investigated. Several basic design considerations are discussed including reference signal feedback problems, selection of error transducers, and safety concerns with using piezoelectrics.

EXPERIMENTAL SETUP

A 1/4 horsepower reciprocating piston compressor, typical of those found in household refrigerators, was used as the test compressor in this investigation. A load stand was designed to operate the compressor under standard operating conditions. In order to minimize the effects of ambient noise on the test measurements, the load stand was located inside an anechoic chamber. The load stand is configured for a simple refrigeration cycle (Figure 1). The compressor is suspended on springs from a metal frame in order to provide vibration isolation from the support frame.

The control source in this experiment was a piezoelectric ceramic actuator (25.4 mm x 38.1 mm x 1.0 mm thick), produced by Atomergic Inc., model 2134) bonded to the top surface of the compressor shell. Piezoelectric materials mechanically deform when an electric field is applied across their electrodes, thus providing the force necessary to control the shell vibration. Because piezo-ceramic materials are inherently brittle, the actuator could not be bent to conform to the compressor shell curvature. To alleviate this problem, the compressor shell was mechanically flattened on top prior to attaching the piezo-actuator with an epoxy compound. Another, more suitable alternative for attaching an actuator would be purchasing a piezo-ceramic with a curvature identical to the compressor shell, but the added expense for curved piezo-actuators did not merit consideration for these preliminary studies. In addition, a new flexible co-polymer piezoelectric material with enhanced actuator capabilities has been recently developed (Atochem Sensors Inc.). This material could easily be bent to conform the the shell surface, however it is not yet commercially available.

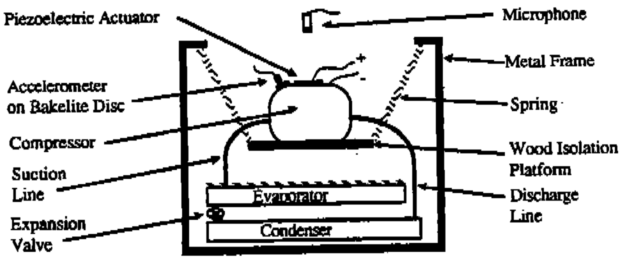

Figure 1. Compressor Load Stand.

In order to develop sufficient control force from the piezo-actuators at low frequencies (300-500 Hz), it was sometimes necessary to apply a relatively high voltage (200 V) across the actuator. This presented a safety concern since one of the terminals suppling voltage to the actuator was soldered directly to the compressor shell. This condition could be easily avoided by using a piezo-element with an insulating coating applied to its bottom surface. To minimize any safety hazard, the compressor shell was electrically isolated from the test stand. Similarly, the accelerometer error sensor was isolated using Bakelite disks that were epoxied to various locations on the compressor shell.

The harmonic nature of compressor noise is well-established and is indicated by the presence of many evenly-spaced peaks in the frequency spectrum. The harmonics occur at multiples of the motor frequency (58 Hz) which differs slightly from the line frequency (60 Hz) because of slippage. The objective of this study was to achieve control of select compressor harmonics in order to demonstrate the feasibility of using piezo-actuators to control compressor noise radiation.

A harmonic controller was used to reduce select compressor harmonics. Figure 2 shows the controller configuration. The controller uses the Filtered-X LMS algorithm (Widrow and Stearns, 1985) to minimize one of two different error signals: one from an accelerometer attached to the shell and a second from a microphone located 0.6 meters directly above the compressor. The microphone directly detects the local reduction in the sound field, whereas the accelerometer detects the local reduction in the compressor shell vibration. An input to the controller is provided by a harmonic signal generator adjusted to the frequency of the compressor harmonic for which control is desired. In order to control the system, the controller must estimate the error path between the controller output to the actuator and the returning signal from the error sensor. The error path was modelled by sending a known sinusoidal signal to the actuator and then receiving the signal from the microphone or accelerometer (error transducer). Using an iterative process, the controller creates a digital filter model of the error path transfer function. Once the error path is modelled, the compressor is allowed to reach a steady state condition. The controller is then activated and the harmonic begins to be controlled. The LMS algorithm is adaptive, so the controller can maintain control under slowly varying operating conditions.

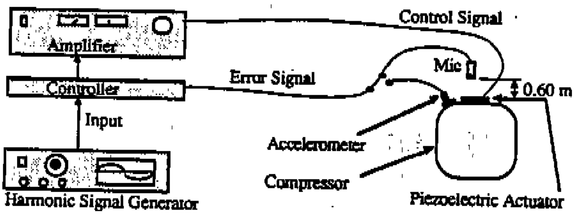

Figure 2. Controller Configuration.

As mentioned above, to successfully implement the Filtered-X LMS algorithm, an accurate model of the error path transfer function between the control actuator and the error transducer must be identified. Since the properties of the piezo-actuators are temperature dependent (Jaffe, 1971), the effect of temperature on the performance of the actuator bonded to the compressor was studied. A 200 Volt, 412 Hz sinusoidal excitation was applied to the actuator, and the resulting sound pressure level was measured for temperatures between 37 °C and 73 °C. Figure 3 shows that the sound radiated by the actuator-driven compressor shell decreases with increasing temperature with a reduction in the total radiated sound level of almost 5 dB over the temperature range studied. In practical operation, this temperature dependency along with other system variations must be understood and modelled in order to maintain control throughout the temperature range of normal operation. Thus, in practice, a control system with an "on-line" system identification would be required. However, for this study, the control was conducted only at steady-state operating conditions (approx. 73 °C). Thus, the system identification process was performed "off-line" (i.e., with the compressor off) but under "hot" conditions (73 °C).

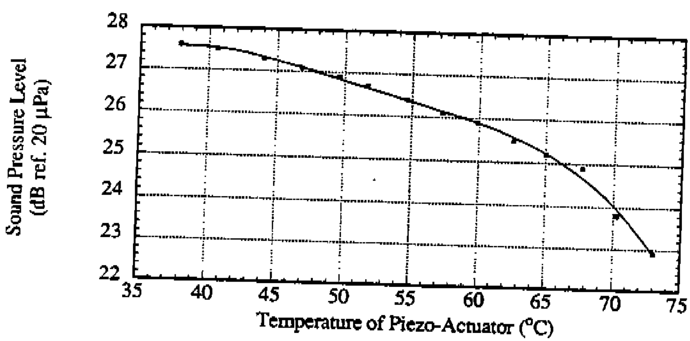

Figure 3. Effect of Temperature on the Performance of Piezo-Actuator.

Two major difficulties were encountered from an experimental standpoint. First, obtaining a clean reference signal as an input to the controller proved to be a difficult problem. Initially, an attempt was made to use an accelerometer signal from the compressor as the reference input signal. However, because of the highly harmonic nature of the signal, single peaks were not easily isolated using the simple analog filters available during testing. A more sophisticated notch filter may be able to provide a cleaner signal to the controller. For this reason, a signal generator was used to provide the reference signal at the desired frequencies. A second difficulty was the inability of the amplifier used to generate a clean signal. Unfortunately, the high-voltage amplifier available for testing produced considerable distortion at higher harmonics of the control frequency. Thus, the performance of the controller was adversely affected to some degree at higher compressor harmonics. However, for future investigations this problem can be easily rectified by using a higher quality amplifier.

RESULTS AND DISCUSSION

To demonstrate the feasibility of actively controlling compressor noise radiation using piezoelectric actuators, a single pumping harmonic at 412 Hz was selected for study. This frequency was chosen because it coincides closely to one of the acoustic cavity resonances of the compressor. Cavity resonances tend to amplify the pumping harmonics thus aggravating the noise problem. This is an especially important concern considering the current trend toward variable speed compressors which eliminates the ability to design around resonant frequencies.

Figures 4a and 4b show the uncontrolled and controlled acceleration and noise spectra using the accelerometer error sensor. A net reduction at the error accelerometer of 18 dB (re 0.707g) was achieved at 412 Hz. However, the sound radiation from the compressor actually increased by 13.3 dB (re 20 μPa) at the microphone. Local control of the acceleration results in a modal restructuring of the shell vibration in which the structural modes combine to cancel at the error accelerometer (Clark and Fuller, 1991). However, apparently in this process some vibrational energy was "spilled" into structural modes which have higher acoustic radiation efficiencies, thus amplifying the noise problem. This result emphasizes the importance of using an error sensor which accurately represents the control objective. The acoustic performance may possibly be improved by locating the error accelerometer closer to the middle of the top surface of the shell. A second alternative would be to cover the top shell surface (except for the actuator patch) with a piezo-polymer film sensor. This sensor provides a spatial integration effect which would naturally bias the sensor to emphasize lower order structural modes of higher acoustic radiation efficiencies. However, these alternatives are beyond the scope of the present investigation.

Figures 5a and 5b show the uncontrolled and controlled acceleration and noise spectra using the microphone error sensor. A net reduction at the error microphone of 13.5 dB was achieved at 412 Hz. However, the shell vibration at the accelerometer decreased only by 4.5 dB. In this case, the microphone error sensor directs the controller to reduce the modes of high radiation efficiency at the expense of other higher-order uncontrolled modes. Thus, only a slight decrease in the shell vibration level at the accelerometer position is not surprising.

In addition to the error transducer results of Figures 5a and 5b, a second performance microphone was traversed around the compressor to qualitatively evaluate the global nature of the control at 412 Hz. Results indicate that the sound radiation above the shell was effectively controlled, but noise reduction diminished as the performance microphone was traversed towards the sides of the compressor. In fact, at some locations, slight increases in the radiated sound field were measured. This result is not surprising since only a single actuator and error microphone were used. Nevertheless, the qualitative results suggest that global reduction of the compressor noise radiation may be best achieved using three piezo-actuators: one on top and one on each of the large flat sides of the compressor shell. In general, the small sides and bottom of the compressor are inefficient radiators of sound because of their higher stiffness.

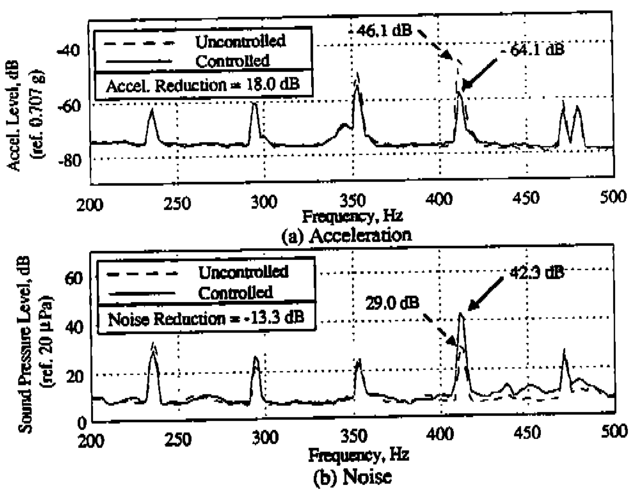

Figure 4. Uncontrolled and Controlled Acceleration and Noise Spectra Using Accelerometer Error Sensor at 412 Hz.

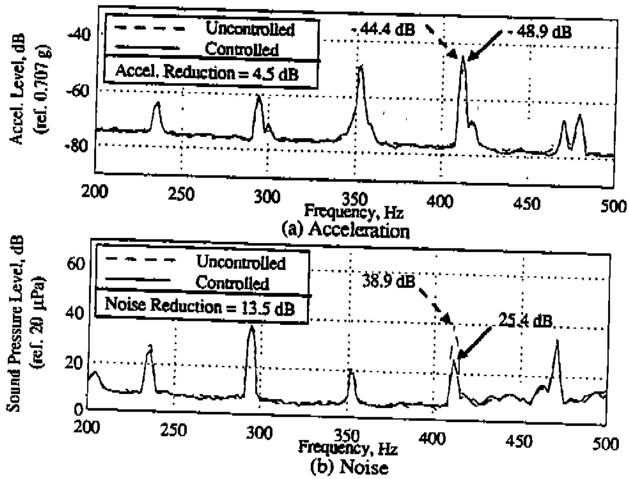

Figure 5. Uncontrolled and Controlled Acceleration and Noise Spectra Using Microphone Error Sensor at 412 Hz.

Additional studies using the microphone error sensor were also conducted to demonstrate control of the 354 Hz and 472 Hz harmonics (not pictured). At 354 Hz, the local sound pressure level was reduced by 11 dB, and at 472 Hz, the sound pressure level was lowered by 25 dB. These results clearly demonstrate the ability of piezo-actuators to control other compressor pumping harmonics. Simultaneous control of multiple harmonics could similarly be demonstrated using the harmonic controller with an input signal consisting of a sum of sine waves of the same frequencies as the harmonics to be controlled. Future investigations are planned to demonstrate the ability to control a family of harmonics

One of the difficulties in achieving control of each harmonic was the tendency of the resonant frequency to drift slowly over time. Since the input to the controller was provided by a constant frequency signal generator, the control effectiveness decreased as the harmonic shifted away from the signal generator frequency. This problem could easily be alleviated either by designing a tachometer which measures the rpm of compressor motor or by using an accelerometer as an input sensor, provided an adequate filter could be designed. Also, it is important to note that since the motor experiences slippage, the line frequency would not be suitable as an input signal.

CONCLUSIONS

In this investigation, the feasibility of active control of compressor noise radiation using piezoelectric actuators was demonstrated. It was shown that the sound pressure level of individual harmonics can be reduced by 11-25 dB at the error transducer. Furthermore, several important design considerations were identified regarding: safety considerations with piezoelectrics, potential problems with high voltage amplifiers, input signals to the controller, temperature variation of piezoelectric properties, accelerometers vs. microphones as error sensors, frequency drift of compressor harmonics, and global vs. local control. While microphones have proven valuable as error sensors for reducing the radiated compressor noise, vibration error sensors (e.g., accelerometers or piezo-polymer films) may be more desirable if such transducers can be designed to effectively represent the control objective. Finally, one of the big advantages of the active structural-acoustic approach discussed in this paper over the acoustic approach demonstrated by Toshiba, is the potential cost reduction associated with using inexpensive piezoelectric actuators and sensors instead of speakers and microphones. Also, a second benefit of the structural-acoustic approach is that the back panel of the compressor enclosure would not require substantial added mass to prevent breakout noise.

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