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A ROBUST SENSOR FOR MONITORING THE OPERATIONAL STATUS OF AGRICULTURAL VENTILATION FANS

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ABSTRACT. A new vibration sensor for monitoring the operational status of exhaust fans in confined animal feeding operations (CAFOs) and other ventilated structures was developed and tested. The sensor utilizes integrated Micro Electro Mechanical Systems (iMEMS) technology to accurately and reliably detect the vibration of agricultural fans, an indicator of fan operating status. When coupled with a sensor to measure pressure drop across the fan and an appropriate fan performance curve, the vibration sensor can enable the collection of real-time building ventilation airflow data. The sensor integrated an iMEMS accelerometer along with signal conditioning components to convert the cyclic acceleration signal into a filtered TTL digital signal appropriate for a wide variety of data acquisition equipment. Sensor current draw was 0.9 mA, which allowed multiple devices to operate from a single power bus. Laboratory and field testing has shown that the sensor is 99% effective in determining the total on-time of agricultural fans when compared with existing methods. Testing has also shown that the sensor response is not affected by changes in operating environment temperature. Sensor installation takes only a few minutes and requires only a single hole placed in the existing fan mounting structure. Furthermore, by encapsulating the sensor in a potting compound, all critical electronic components can be sealed from the corrosive effects of moisture and gases common to CAFOs and other ventilated structures.

Keywords. Air quality, iMEMS, Ventilation, Vibration sensor.

Building ventilation is a fundamental means to control indoor thermal environments and air quality. Sufficient ventilation control of animal buildings is especially important to animal comfort, health and productivity, and energy consumption within concentrated animal feeding operations (CAFOs). Concerns regarding air emissions from CAFOs have grown in recent years. Widespread work by researchers across the continental U.S. continues to focus on methods to accurately determine pollutant emission baseline measurements as well as mitigation techniques. One component of this research is the estimation of pollutant emission rates from CAFOs. Emission rates are calculated as the product of the pollutant concentration and the building ventilation rate. Both air pollutant concentration and building ventilation rate are equally important in determining baseline air emission rates for CAFOs and must be

measured with high accuracy. However, accurately determining real-time animal building ventilation rates has traditionally been difficult because of the large number of exhaust fans and the wide range of installation practices seen in many CAFOs, as well as a lack of appropriate monitoring devices.

Building ventilation rate is the sum of airflow rates of each individual building fan operating at any time. Accurately determining the total ventilation rate of a building requires measurement of flow rates of each individual fan. A standardized protocol for determining ventilation rate of an agricultural fan is described by ASABE Standard S565 (ASABE Standards, 2005) and ANSI/ASHRAE Standard 51-1999 (ANSI/ASHRAE, 1999). The BESS Laboratory at the University of Illinois conducts fan tests according to ASABE S565 and ANSI/ASHRAE 51-1999 to provide unbiased ventilation fan performance data for most commercial agricultural fans. Fan performance data, including airflow rates at differing static pressures, fan speed, and fan efficiency, are published regularly. Therefore, airflow rates under various static pressure conditions are easily obtained. Research has shown that fans installed at CAFOs are susceptible to dust buildup and loose drive belts. Field-installed fans that have been poorly maintained can have airflow rate reductions of as much as 67% of original capacity (Janni et al., 2005). Janni et al. (2005) also found that the *in situ* performance of well maintained fans ranged from 20% to 40% lower than in Bess laboratory tests. It was concluded that variations in fan performance were unpredictable and caused by many issues, including fan operation and maintenance, shutters design and condition, and precision of installation. Accurate knowledge of fan performance is only possible through field calibration of each fan system.

Simmons et al. (1998) and Gates et al. (2004) demonstrated a field fan testing system, Fan Assessment Numera-

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tion System (FANS), for *in situ* evaluation of exhaust fan performance for individual fans at animal production facilities. The FANS unit uses a traveling linear array of five anemometers to measure airflow speed at the cross-section of a fan for a precise calculation of the fan airflow rate under a range of typical building static differential pressure conditions. The FANS system provided researchers a tool to evaluate fan performance individually in the field and account for variations between fans. However, due to its cost and complexity, it is not feasible to use a FANS-type system to continuously monitor the real-time ventilation rate of multiple agricultural ventilation fans simultaneously.

A general research approach to evaluate ventilation from a production facility is to calibrate each fan's ventilation rate by conducting multiple FANS fan performance evaluations. The revised fan performance data for each individual fan can then be used to determine the airflow rate of the entire building when coupled with information on the fan operating status and static differential pressure (Wheeler et al., 2002; Darr, 2006). While measurement of static pressure is fairly standardized among various research groups through the application of electronic differential pressure transducers, measurement of individual fan status has been more challenging. Hoff et al. (2004) concluded that it is still a formidable task to accurately determine real-time ventilation rate of an animal housing facility. Therefore, monitoring fan operational status is crucial to determine accurate building ventilation rates.

Various methods have been attempted to continuously monitor fan activity (Hoff et al., 2004). These methods aim to measure the cause or derivative activity of a fan's operation status, such as electric current into the fan motor, fan control relay status, airflow, fan motor rotation, shutter position, and fan vibration. Current transducers and switches have been used to monitor current flow into the fan motor. If current flow is present, it is assumed that the motor is operating (Gay et al., 2006). Split-core current monitors are simple and cost-effective to install when the motor wiring is exposed. If the motor wiring is encased in conduit, modifications to the facility must be made to allow for current sensing (Xin et al., 2003). Similarly, monitoring of the fan control relay contacts that drive the ventilation fans has also been used to determine the real-time fan activity level (Ni et al., 2005b). During this study, an open-contact relay was supplied with a 5 V signal, and the opposite contact terminal was monitored by a data acquisition system. This method proved to be simple to install, but it was dependent on the availability of an additional set of contact relays for each fan stage within the production facility. It also had no means to determine if individual fans within a single stage had failed.

A propeller anemometer can be installed in front of an agricultural ventilation fan to determine the magnitude of exhaust (Hoff et al., 2004). These devices are also subject to mechanical failure caused by dust buildup on the sensor rotational element. Rotational speed sensors attempt to record the ventilation rate by measuring the rotational speed of the electric motor that drives the propeller blade (Janni et al., 2005). Typically, speed is measured on the electric motor shaft, rather than the propeller shaft. This methodology has the added benefit of being able to determine fan speed, and thus can more accurately calculate the exhaust rate of variable-speed fans. Drawbacks to rotational speed monitoring are difficulty in installation and in data acquisition. Many

commercial Hall-effect rotational speed sensors require that the sensor be mounted within 12 mm of the metallic element being measured, and deviations from this distance can diminish sensing quality. Furthermore, rotational speed sensors output a pulse train signal, which has a frequency corresponding to the rotational speed of the measurement device. Few commercial data acquisition systems allow for multiple simultaneous measurement of the frequency content.

Sail switches have been used as a low-cost and simple method to indicate fan operational status (Hoff et al. 2004). A sail switch operates as a normally open momentary switch with a large sail wing attached to the switch element. When an airflow condition occurs, the switch is closed and the output signal can be recorded by the data acquisition equipment. Likewise, mechanical shutter switches work in a similar method and change state when a shutter is displaced from its normal zero ventilation position. Using resistive networks, multiple switches can be analyzed by a single analog input channel to reduce data acquisition requirements. However, sail switches are susceptible to mechanical failure and are sensitive to dust build-up, which could result in non-reliable monitoring.

A vibration sensor method was developed to provide auxiliary fan operational status to the relay contact sensing method and prevent false positive and false negative susceptibility (Ni et al., 2005a, 2005b). This system utilized a vibration sensor (Catalog No. 49-521A, RadioShack, Fort Worth, Texas) to detect fan activity. Typical agricultural fans produce a mechanical vibration when running, which is transmitted through the fan frame and into the hood that surrounds the fan periphery. Ni et al. (2005a, 2005b) demonstrated the use of a low-cost mechanical sensor to detect this vibration signal and thus monitor the status of the fan operation. The advantages of detecting hood vibration rather than fan motor vibration include verification that the motor is attached to the fan blade drive shaft and improved safety and ease in installation. This technique also avoided false signals in the case of a broken fan belt, when the motor was still turning but the fan blade was not. However, it was reported that the sensor was not reliable during long-term measurement in the harsh environment of animal buildings, and a more reliable vibration sensor is needed for fan monitoring at CAFOs (Ni et al., 2005a, 2005b). Commercial vibration sensors are available from several manufacturers, and many are designed to provide an alarm signal when a certain vibration is reached for use in industrial maintenance diagnostics. Several reasons exist why these industrial sensors are not suited for application in agricultural ventilation monitoring, including absence of continuous monitoring capabilities, non-adjustable sensitivity, lack of a digital output signal, or lack of a proper housing for installation in harsh animal environments.

Furthermore, other non-mechanical sensing techniques are available for ventilation monitoring within CAFOs. Carbon dioxide (CO₂) is a metabolic product of animals and can be used to estimate ventilation. By monitoring indoor and outdoor concentrations and estimating the animal production rate, model-aided CO₂ balance is another method to calculate ventilation rate in livestock buildings. This method could be applied to both natural and tunnel ventilation buildings. Pedersen et al. (1998) compared the ventilation rates in poultry and livestock buildings with different ventilation systems estimated by using the mass balance method based on animal CO₂, heat, and moisture production. Although good agree-

ments were found between the three methods, only the CO₂ method was recommended for both insulated and non-insulated facilities because of its insensitivity to heat transmission loss (Pedersen et al., 1998). Zhang et al. (2005) used this method in estimating gas emission rates from nine naturally ventilated dairy buildings in Denmark, and van't Klooster and Heitlager (1994) determined the minimum ventilation rate in a swine facility with nature ventilation system using the CO₂ mass balance method. The existing research results show that the CO₂ balance method is reliable in calculating ventilation rate from animal feeding operations. However, this method is dependent on the accuracy of the model that predicts the CO₂ production rate of the animals, and it can only be applied to those buildings in which the only CO₂ source is the animals (Zhang et al., 2005).

Upon full investigation of previous work in monitoring fan activity for use in determining agricultural fan ventilation rates, it was determined that no sensor adequately meets all requirements of determining the on/off status of fans.

OBJECTIVES

The objective of this work was to develop a new sensing device to accurately determine the operational status of an agricultural ventilation fan. The sensor must reliably detect fan activity under all environmental conditions including high dust and extreme temperatures, provide a range of sensitivities and be field adjustable for various sizes and speeds of fans, be easily installed and not interfere with the surrounding facilities, and provide an industry-standard digital output signal that will easily interface with commercial data acquisition devices.

MATERIALS AND METHODS

The sensing methodology used for this project was an indirect sensing of fan operational status based on detecting the vibration of fan hoods during motor operation. An embeddable accelerometer was used to detect the presence of vibration, and a signal conditioning circuit was used to convert the vibration signal into a purely digital signal. The digital output was compatible with TTL signal levels.

ACCELEROMETER SELECTION

An accelerometer was used to measure the magnitude of vibration present on the fan hood (ADXL320, Analog Devices, Norwood, Mass.). The accelerometer utilizes iMEMS (integrated Micro Electro Mechanical Systems) technology to provide a ± 5 g, 2-axis accelerometer along with signal amplification into a 4 mm wide $\times$ 4 mm long $\times$ 1.4 mm tall package. This integrated sensor and signal amplifier provided a sensitivity of 312 mV g⁻¹ when powered by a 5 V power supply. An external 0.01 μ F capacitor was installed to limit the sensor bandwidth to 500 Hz. The maximum expected vibration frequency was calculated based on a 3600 rpm fan with a 6-blade propeller, which would produce a vibration frequency of 360 Hz.

SIGNAL CONDITIONING DESIGN

The objective of the analog circuit design was to convert the oscillatory vibration signal into a clean digital signal that could be easily recognized with standard digital-input data acquisition equipment. Testing of the ADXL320 accelerom-

eter showed that when powered by a 5 V supply, the output under 0 g was 2.5 V. The output voltage would stray from this level based on specified sensor sensitivity of 312 mV g⁻¹. Laboratory testing of a 61 cm agricultural fan showed maximum accelerations from 1.5 to 2 g depending on the placement of the sensor.

An analog circuit was designed that would condition the raw analog acceleration signal using the following process (fig. 1):

1. Decouple the sinusoidal acceleration signal to remove steady-state offset.
2. Rectify the signal to enhance signal strength.
3. Filter the rectified signal to create a steady DC signal.
4. Amplify the filtered DC signal.
5. Provide a means to adjust the amplification level to exceed the positive threshold for the Schmitt trigger circuit.
6. Create a digital signal with hysteresis by passing the amplified signal through a double Schmitt trigger.

The raw accelerometer signal was decoupled by passing the signal through a 1 μ F electrolytic capacitor. A diode array was used to rectify the signal, which enhanced the overall content of the signal. The rectified signal was smoothed using a simple resistor-capacitor filter to remove the signal ripples. Values of 5.6 k Ω and 0.1 μ F were used for the RC circuit ($f_c = 285$ Hz). A 560 k Ω resistor was also placed in parallel across the capacitor to help drain the signal to ground when no os-

Figure 1. Simulation of sensor signal output from initial motor activation (t_0) to full speed fan operation (t_1).

cillations were present. This helped to prevent voltage build-up within the capacitor.

After passing through the RC filter circuit, the sensor signal was a very low DC voltage. When exposed to vibration from a fan hood, the sensor would output a higher voltage signal on the magnitude of a few tenths of a volt depending on the fan size and speed. This signal was too small for standard digital input devices to recognize, so an appropriate amplification circuit was designed. An operational amplifier (MAX495, Maxim Integrated Products, Sunnyvale, Cal.) with rail-to-rail and low-voltage single power supply operation was chosen for this design. Because fans with different sizes and installation methods produce hood vibrations with different magnitudes, the gain on the operational amplifier was designed to be field adjustable. This was accomplished by using a potentiometer as the gain resistor (R_{gain}) in the non-inverting amplifier circuit. The feedback resistor (R_{fb}) was set at $10\text{ k}\Omega$, and a $10\text{ k}\Omega$ potentiometer was used for R_{gain} . By adjusting the potentiometer resistance from $10\text{ k}\Omega$ to $2\text{ }\Omega$, a circuit gain from 2 to 5000 was achieved. No conditions were identified where a gain of 2 exceeded that necessary for proper circuit operation.

Under normal operating conditions using a 61 cm agricultural fan with a 61 cm fan hood and running at 1075 rpm, the sensor gain could be tuned to provide a 0.6 V signal when the fan was not operating and a 4.8 V signal when the fan was operating. This is sufficient for the majority of TTL digital input data acquisition systems commercially available, but given the unknown environment of future installations, a Schmitt trigger circuit was added (SN74LVC2G14, Texas Instruments, Dallas, Texas). The Schmitt trigger circuit is an inverter circuit that has different voltage thresholds for positive-going and negative-going signals. A dual trigger was used to correct the inverting logic of the initial trigger so that a positive trigger output would correspond to the fan motor being turned on. This integrated circuit provided a hysteresis of 1 V between a positive-going threshold of 3 V and a negative-going threshold of 2 V.

In addition to the Schmitt trigger output signal being transmitted to the appropriate data acquisition equipment, the signal was also used to activate a light-emitting diode (LED) located on the sensor body. This allowed for troubleshooting during sensor installation, as the installer can reference the LED to determine if additional gain adjustment is necessary.

SENSOR PACKAGING

The circuit components were installed on a printed circuit board with final overall dimensions of 4.7 cm long $\times$ 1.0 cm wide. The completed board was installed within a plastic potting box with final overall dimensions of 5.0 cm long $\times$ 1.3 cm wide (fig. 2). Five wires extended 30 cm out of the box and were mated with a three-wire and a two-wire quick-connect harness. The three-wire connector provided connection to the sensor power supply as well as the Schmitt trigger signal output. The two-wire connector was an auxiliary connection used to measure the operational amplifier output. This was used to expedite installation time by allowing the installer to set the operational amplifier output at a recommended level before performing minor gain adjustments with the fan motor running.

To prevent sensor deterioration caused by moisture and corrosion, a potting compound was used to seal the circuit board and components from the external environment. Care-

Figure 2. Sensor packaging.

ful selection of the potting compound was necessary to ensure that proper thermal and electrical properties were maintained and that the epoxy would harden rigidly. A soft silicone-type potting compound would not work because it would act as a dampener and reduce the effective vibration signal that reaches the sensor board. A hard, epoxy-based potting compound (832B, MG Chemicals, Surrey, B.C., Canada) was used for this project, and testing showed that the sensor operation was not affected by the potting material. A hole was drilled through the enclosure and potting compound after the epoxy had hardened to allow a 6-32 machine screw to pass through. This screw was used to fasten the sensor directly to the fan hood.

SENSOR INSTALLATION ON THE VIBRATION SOURCE

The sensor must be rigidly mounted directly to the fan hood or other mounting point that transfers the mechanical vibration created by the rotating fan propeller. The mechanical fastening is accomplished through the 6-32 machine screw that passes through the sensor potting compound. A single 0.35 cm diameter hole must be drilled in the fan hood to allow for the sensor mounting. The use of other soft-joint fasteners, such as self-tapping screws, is not feasible because they will loosen over extended exposure to vibration. Although the exact mounting location is not critical because of the threshold adjustment of the sensor, it is suggested that the sensor be placed at the location that exhibits the highest level of vibration.

Based on the design and configuration of the sensing element, the output signal is insensitive to the sensor orientation. Figure 3 shows an example of how the vibration sensor is typically mounted. Only the Y-axis is sensitive to vibration; thus, the X-Z plane should be mounted directly to the fan hood sur-

Figure 3. Mounting locations of vibration sensor on the fan hood.

face (fig. 3). Any vibrations along the hood would then be in the Y-axis direction and will be recognizable by the sensor.

RESULTS AND DISCUSSION

VALIDATION OF SENSOR PERFORMANCE

To test the cyclic response of the sensor over an extended time period, a simulated fan vibration system was used. A standard 227 L, 16.99 m³ h⁻¹ air compressor that vibrated at a magnitude (± 1 g) and frequency (60 Hz) similar to that of a standard agricultural fan was used as the vibration source for the test. The compressed air was exhausted at a constant rate after its pressure was reduced by a pressure regulator. A pressure transducer continuously recorded the regulator's outlet pressure, which fluctuated as a function of the pressure in the 227 L compressor cylinder. The new sensor was installed on the compressor body. The signals of the pressure transducer and the vibration sensor were sampled every second, averaged every 15 s, and recorded in a data file for comparison.

Figure 4 presents comparison of two sensor signals during compressor operation when the compressor was turned on for

Figure 4. Comparison of vibration sensor performance and the fluctuations in manifold pressure correlating to compressor activity.

Table 1. Sensor response to fans with a disengaged propeller.

Sensor	Propeller Status	Number of Fan Cycles	Recorded On Events	Error (%)
1	Engaged	1459	1459	0.0
	Disengaged	1206	0	0.0
2	Engaged	1470	1470	0.0
	Disengaged	1398	0	0.0
3	Engaged	1872	1872	0.0
	Disengaged	1507	0	0.0
4	Engaged	1437	1437	0.0
	Disengaged	1448	3	0.2
5	Engaged	1339	1339	0.0
	Disengaged	1168	39	3.3

1 min and cycled every 6 min. The manifold air pressure, which was downstream from the compressor tank and pressure regulation valve, was monitored by an electronic pressure transducer. Based on the operating characteristics of the pressure regulation valve, when the compressor was turned on, the manifold pressure decreased. When the compressor was cycled off, the manifold pressure slowly increased. The results of the vibration sensor were compared to the compressor manifold pressure after a 14-day testing period. The vibration sensor output had a 100% correlation to the manifold pressure signal, indicating that each time the manifold pressure decreased, the vibration signal indicated an active state. Furthermore, during the 14-day testing period, no false positive output signals were recorded by the vibration sensor.

EFFECT OF DISENGAGED PROPELLER

Testing was conducted to evaluate the effect of a disengaged propeller on the vibration sensor performance. Disengaged propellers are a common problem when belt-driven fan systems are poorly maintained and the drive belt becomes loose or disconnected. A 61 cm diameter agricultural fan (model AT24Z, Aerotech, Mason, Mich.) was used to test the response of the vibration sensor under both engaged and disengaged propeller conditions. Five sensors were tested individually. A programmable logic controller (PLC) was used to turn the fan on for a 30 s period and then turn the fan off for a 30 s period. The status of the motor control signal and the vibration sensor output signal were recorded continuously on 0.5 s intervals. Tests were conducted individually for engaged and disengaged propeller conditions. The length of test was manually controlled; thus, the overall number of fan cycles varies among tests.

Results of the propeller tests revealed that when properly adjusted, the vibration sensor will not trigger false positive

readings when vibration is present from a motor but no propeller is present (table 1). This is due to a higher magnitude of vibration being induced by the propeller mass as opposed to the motor alone.

EFFECT OF FREEWHEELING PROPELLER

Freewheeling propellers are common on CAFO fans when an external wind source is present. When this wind blows directly into a fan, the propeller blade can begin to rotate, which causes false positive fan activity readings with rotational and anemometer-type monitors. To verify the response of the vibration sensor to freewheeling propellers, a simulated high-wind environment was created within a testing laboratory. A vibration sensor was attached to the hood of a 61 cm agricultural fan, and the sensitivity was adjusted to the normal operating conditions. An additional fan was placed directly inline and 1 m away from the test fan and was used to simulate a direct wind source. The wind simulator fan was able to produce a wind load of 16 km h^{-1} on the test fan. Again, a PLC was used to cycle the simulated wind source on and off at 30 s intervals. Three separate vibration sensors were tested continuously, each over a period of 4 h. Each sensor was subjected to 240 cycles of wind load activity. Over the duration of the test, zero false positive readings were recorded by the vibration sensors. Although the fan propeller rotated due to the wind load, the speed of rotation and thus the amount of vibration generated were not sufficient to switch the logic level of the sensor.

EFFECT OF AMBIENT CONDITIONS

Typical installation on external agricultural fans requires the sensor to withstand temperature variations from peak summer temperatures to minimum winter temperatures. It must also withstand weather events such as rain and snow. To test the design integrity against such harsh environmental conditions, five sensors were placed in a water bath at a depth of 1 m. After a 168 h period, the sensors were removed from the bath and tested again on a 61 cm agricultural fan. The response of each sensor was identical to the response prior to immersion in the water bath, indicating that the potting compound was sufficient to seal the sensor from the corrosive effect of moisture.

To simulate changes in the ambient temperature, three sensors were placed in a 0°C freezer for a 72 h period. The sensors were then removed from the freezer, and a test was conducted to evaluate the effect of temperature change on the sensitivity of the device. A thermocouple was embedded in the potting compound of each sensor during construction, with the leads protruding from the sensor enclosure. This allowed the internal temperature to be monitored while the sensors warmed up to room temperature. The amplitude gain of the sensor was monitored versus the core temperature of the device. Amplitude gain was calculated as the ratio of output voltage under a vibration situation to the output voltage when no vibration was present. The operational amplifier gain and the vibration magnitude were maintained constant throughout the testing period. We recorded 216 observations of temperature versus amplitude gain for all three sensors.

Figure 5 and table 2 show the results of a regression analysis concerning the influence of temperature on the amplitude gain of the sensors. While the regression line indicates that there was a slightly negative linear relationship between the temperature of the sensors and the amplitude gain of the sen-

Figure 5. Regression analysis of sensor amplitude gain versus sensor temperature ($^\circ\text{C}$).

Table 2. Regression analysis: amplitude gain versus sensor temperature ($^\circ\text{C}$).

	Predictor			
	Coeff.	SE Coeff.	T	P
Constant	54.6619	0.3269	167.23	0.000
Sensor temp.	-0.02361	0.01722	-1.37	0.172
Analysis of Variance				
	Source			
	DF	SS	MS	F
Regression	1	4.505	4.505	1.88
Residual error	215	515.373	2.397	
Total	216	519.878		

sors, further analysis showed this to be statistically insignificant based on a P-value of 0.172 for the slope of the regression line. The regression plot shows a substantial amount of variance in the amplitude gain, especially at lower temperatures where the difference between the maximum and minimum amplitude gains for a steady temperature was as high as 10%. The Schmitt trigger circuit will prevent these slight fluctuations in amplitude gain from having any negative effect on the operation of the sensor by providing a band of effective operation. When considering each sensor response individually, the influence of temperature was also statistically insignificant, with P-values of 0.179, 0.287, and 0.760, respectively.

EFFECT OF FAN SPEED

Variable-speed motors are often used to create a variable ventilation rate with agricultural fans. When the speed of a fan decreases, so does the frequency at which the hood vibrates. To test the effect of fan speed on the sensor performance, the sensor was attached to the hood of a variable-speed 61 cm agricultural fan. The fan speed was adjusted from 488 to 1075 rpm. The measured parameter was the filtered analog output signal with the amplifier gain set at 26.2. For all ventilation rates tested, the sensor provided an analog output of 5.01 V, indicating that the operational amplifier output was saturated (table 3). This condition was well above the positive-going threshold of the Schmitt trigger circuit; thus, the digital output was high, indicating that the fan was running. As a result, the sensor can accurately determine the operational status of variable-speed fans, but will not provide a varying voltage output proportional to fan speed.

Table 3. Vibration sensor output for various fan rotational speeds.

Fan Speed (rpm)	Analog Output (V)
488	5.01
641	5.01
768	5.01
895	5.01
1056	5.01
1075	5.01

FIELD EVALUATIONS OF THE SENSOR

Field testing of the vibration sensor was conducted at a poultry layer facility housing approximately 170,000 hens. Vibration sensors were connected to three fans representing stages 1, 4, and 5 of the ventilation system. Simultaneous fan stage monitoring was also recorded through direct monitoring of the fan control relays. On each of the fan control relays for stages 1, 4, and 5, a 5 V signal was applied to an extra relay contact. The feedback from this relay contact was then recorded as an indication of true fan status (Hoff et al., 2004). Continuous data were collected for 7 days and analyzed to determine the correlation between the new vibration sensor and the fan relay monitoring method. The vibration sensors were sampled and recorded six times per minute, while the fan control relay signals were sampled four times per minute. The data were classified into 1 min intervals to reduce the influence of temporal effects associated with the different sampling intervals.

Each 1 min interval was evaluated individually, with a threshold of 50% set to indicate an active fan for that particular monitoring interval. For the vibration sensors, sampled six times per minute, if at least three data points per minute reported an active fan state, then the 1 min fan data were classified as active. Likewise, for the fan relay monitor, sampled four times per minute, if at least two samples reported an active status, then the 1 min data were classified as an active fan state. The data from each sensor were then compared for each 1 min sampling interval.

Stage 1 fans remained active over the entire duration of the test and were not used for comparison purposes. For stage 4 fans, the vibration sensor method calculated a total on-time of 148.9 h, as compared to 149.15 h for the relay monitors. This resulted in a 0.17% underestimate of ventilation. For stage 5 fans, the vibration sensor method calculated a total on-time of 107.6 h, as compared to 106.75 h for the relay monitors. Again, the vibration sensors underestimated ventilation of this stage by 0.79%. This deviation can be explained by the operating principles of the two methods being compared. The vibration sensors measure fan activity only when the fan motor is running at a speed where airflow is present. The relay monitors, on the other hand, assume airflow to occur as soon as power is applied to the fan motor. This leads to an indication of fan activity before the fan reaches full speed, and thus creates longer activity times (fig. 6).

A six-month, full-scale effectiveness test was also performed at a 1000-head swine finishing facility that was outfitted with a six-stage fan control system. The test was conducted from December 2005 to May 2006. Six fans provide tunnel ventilation in this facility, and each is independently controlled by an electronic control system (AeroSpeed 2.4, Aerotech, Mason, Mich.). The vibration sensors were fixed directly to the fans via the mounting screw and were again placed very near the propeller periphery, where the largest magnitude of vibration was found. The vibration sensor data were used to calculate the ventilation rate of the building when coupled with pressure drop information for each fan (fig. 7).

The beginning of this study coincided with the placement of 1000 new animals, with an average weight of 19.2 kg per animal. In addition, during the first month of the study (December 2005), the average ambient temperature was 2.6°C, with an average maximum daily ambient temperature of 7.6°C. The combination of low animal weights and low ambient temperatures caused the ventilation system to run in minimum operation mode during the entire month of

Figure 6. Comparison of fan pressure drop to relay control and vibration sensor signal.

Figure 7. Fan activity summary from 1000-head swine finishing facility, May 2006.

December 2005. During this period, a total of 1901 minimum stage ventilation cycles were monitored by the data acquisition equipment. Also during this period, no positive readings were present from any other vibration sensors attached to adjacent fans. This was an indication that the vibration developed by a single fan will be dampened through the building to a reduced magnitude that will not trigger false readings on adjacent fans.

INFLUENCE OF SAMPLING FREQUENCY ON VENTILATION MEASUREMENT ACCURACY

Monitoring the activity status of all ventilation fans is only one factor in accurately measuring the ventilation rate from a CAFO. Significant measurement errors can be induced by neglecting to sample the fan activity monitors at a sufficient frequency. This is especially the case during minimum ventilation states, when it is common for a single fan to cycle on for as briefly as 30 s, and then cycle off for several minutes. Sampling intervals must always be less than the shortest on-time of the system to ensure that active fan events will not be missed. The single-point error associated with ventilation monitoring is also directly proportional to the width of the sampling interval, with a maximum error of one sampling interval. An illustration of this concept can be considered for a 30 s minimum stage on-time with a 30 s sampling interval. It is possible that the data acquisition system could sample the fan status at the instant that the fan started and again 30 s later on the instant before the fan stopped. The data acquisition system would then record 60 s of fan activity time and thus induce a 100% ventilation measurement error for a specific point value. As the duration of the ventilation monitoring period increases, so does the accuracy of measurement. Based on the central limit theorem, the summation of a random variable with a finite variance, such as fan activity, will be approximately normally distributed. As the number of samples in this distribution increases, the statistical confidence in estimating the distribution mean, or in this case the true ventilation rate, increases.

SUMMARY

A new sensor, composed entirely of electrical components, was developed to monitor the operation of agricultural fans, based on previous work that demonstrated the feasibility of determining fan operational status by vibration measurement. Laboratory testing showed that the sensor draws less than 1 mA during operation and has a negligible sensitivity reduction when exposed to high moisture conditions or extreme temperature conditions. The new sensor can be easily installed on any agricultural fan that has a hood or other mounting device that transmits vibration while the fan is running, and the sensitivity of the sensor can be adjusted upon installation. Field testing in both swine and poultry facilities demonstrated that the vibration sensor provided a stable response to vibration activity and accurately indicated the status of agricultural fans.

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