Fan Assessment Numeration System (FANS) Design and Calibration Specifications

Richard S. Gates  
University of Kentucky

John D. Simmons  
United States Department of Agriculture

Kenneth D. Casey  
University of Kentucky

T. J. Greis  
University of Kentucky

Hongwei Xin  
Iowa State University, hxin@iastate.edu

See next page for additional authors

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Abstract
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Keywords
Airflow, Controlled Environment, Livestock Housing, Ventilation, Instrumentation

Disciplines
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Authors
Richard S. Gates, John D. Simmons, Kenneth D. Casey, T. J. Greis, Hongwei Xin, Eileen F. Wheeler, C. L. King, and J. R. Barnett

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R. S. Gates\textsuperscript{1}, J. D. Simmons\textsuperscript{2}, K. D. Casey\textsuperscript{1}, T. J. Greis\textsuperscript{1}, H. Xin\textsuperscript{3}, E. F. Wheeler\textsuperscript{4}, C. L. King\textsuperscript{1} and J. R. Barnett\textsuperscript{1}

\textsuperscript{1} Biosystems and Agricultural Engineering, University of Kentucky, Lexington KY 40546-0276
\textsuperscript{2} USDA ARS Poultry, POB 5367 Mississippi State MS 39762
\textsuperscript{3} Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa, 50011-3080
\textsuperscript{4} Agricultural and Biological Engineering, Pennsylvania State University, University Park, PA

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Abstract. A device for \textit{in-situ} fan airflow measurement, called the Fan Assessment Numeration System (FANS) device, previously developed and constructed at the USDA-ARS Southern Poultry Research Laboratory, was refined at University of Kentucky as part of a project for quantifying building emissions from poultry and livestock operations. The FANS incorporates an array of five propeller anemometers to perform a real-time traverse of the air flow entering fans of up to 137 cm (54 in) diameter. Details of the updated design, including hardware, software, and calibration methodology are presented. An error analysis of the flow rate, and calibration results from ten units recently manufactured, is provided. Sufficient details of fabrication and calibration are presented so that interested readers can replicate a FANS for their use. Full design details are provided at www.bae.uky.edu/IFAFS/FANS.

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Introduction

Gas and dust emission from poultry houses varies with season and weather patterns, management
practices, feeding practices, housing styles, and other factors. Little scientific-based data exists for
poultry house ammonia emissions for modern U.S. poultry facilities, including laying hen houses,
broiler chicken growout houses, and turkey production facilities (Bicudo et al., 2002). A project that
involves a comprehensive team of engineers and animal scientists was funded to systematically and
thoroughly obtain baseline data for ammonia emission from broiler and layer housing in the U.S.
(Gates et. al, 2001). The team will assess the effects of manure and litter management practices and
dietary manipulation as possible methods for reducing poultry house emissions.

Building emission rates are obtained as the product of two measurements: gas (or other)
concentration difference between discharge air and ambient air, and the ventilation rate.
Considerable attention has been paid to accurate and robust methods of NH$_3$ concentration
measurements and a number of different technologies exist (Agaro et al, 2001). A principal source of
uncertainty in measuring building emissions has to do with measurement of the building ventilation
rate. Estimating ventilation rate of a whole building is difficult even for mechanically ventilated
facilities because of the effects of time, harsh environment, incomplete or irregular maintenance,
dynamic and irregular wind effects, equipment switching during measurement, and other factors
such as construction methods. Standards and/or procedures for determination of fan performance
(AMCA, ASHRAE-HOF) and standards for laboratory airflow measurements (ASHRAE Standard
41.2) exist, but whole-building ventilation determination (with multiple inlets and outlets) is more
problematic. In part, the difficulty is due to a lack of a reference method to which alternate
measurements techniques can be compared and employed.

The purpose of this paper is to document the design and performance testing of a device for in situ
airflow determination, initially developed at the USDA Poultry Research Laboratory (Simmons and
Hannigan, 2000; Simmons et al, 1998a,b). The device, called a Fan Assessment Numeration System or FANS, can be used with in situ exhaust fans in poultry and livestock buildings. Each
exhaust fan can be calibrated individually with its exact equipment options such as shutters, louvers
and discharge cones. Once calibrated against building static pressure, real-time dynamic
measurements of building ventilation can be obtained from readings of fan activity and static
pressure. The FANS can serve as a field-based reference measurement technique so that other
methods of estimating mechanically ventilated building ventilation rates can be objectively evaluated
(e.g. using a CO$_2$ balance from livestock heat production relations, tracer methods, direct use of fan
curves, etc.).
**FANS Design Features and Details**

Design features, including CAD drawings and a bill of materials, are online and may be downloaded from the University of Kentucky Biosystems and Agricultural Engineering server: [http://www.bae.uky.edu/IFAFS/FANS](http://www.bae.uky.edu/IFAFS/FANS). Included are detailed design drawings of the frame, sheet metal layout, and anemometer rack and associated components in AutoCAD2000 format. Details of fabrication are provided in this paper to aid the interested reader.

**Fabrication**

The purpose of the following discussion on fabrication of the FANS is to give a general concept of the processes, equipment, materials, and parts necessary for someone to construct their own FANS. The FANS consists of three main components: body and frame; drive system; and anemometer/controls. To reduce weight and the effects of corrosion, the FANS unit is constructed almost entirely of lightweight aluminum and corrosion resistant stainless or zinc plated steel fasteners. The FANS unit is depicted in the photographs in Figure 1.

The frame is constructed from 25.4 mm (1 in) square tubing with a 1.6 mm (1/16 in) wall thickness. The entire frame system, consisting of top, bottom, and side modules that are independently fabricated, is welded. Vertical traverse of the anemometer rack is accomplished with linear bearings driven by screws that are connected with chain and run by a gear motor. Both top and bottom frame sections hold the drive assembly. The bottom frame section also has tubing for mounting the control box and motor mount. The top frame section has an additional tube and holes drilled for mounting the chain tensioner mount. The side frame sections are mirror images of one another, and have one vertical member with holes drilled every 50 mm (1.97 in) for fastening the linear bearing, and a 4.8 mm (3/16 in) aluminum plate drilled and tapped for attaching carry handles. These handles are a critical ergonomic improvement over the original design.

A smooth airflow entrance is created from a four-member section that is inset 75 mm (3 in) from the front of the frame. This section provides a rigid support for the sheet metal to wrap around and to aid in maintaining a smooth, low dynamic loss shape. Aluminum sheet metal 0.4547 mm (0.0179 in, 26 ga) covers the top, bottom, and two mirror imaged sides. All sheet metal sections are sheared to size, and finish fit using hand shears. To make the corners of the transition inlet, material is removed along two lines. During assembly, the side sections must be attached to the frame prior to the top and bottom sections. Either stainless steel rivets, or sheet metal screws, are used to fasten the sections to the frame using a 100 mm (4 in) spacing between fasteners.

The drive system consists of a commercially available linear actuator with attached motor and gearbox. The linear actuator is removed by cutting the drive shaft approximately 25 mm (1 in) from its protrusion from the gearbox, and discarded. Flats are filed on the remaining shaft for setscrews. The motor’s internal limit switch and associated small set of nylon gears are removed. The motor’s output shaft is joined to the vertically mounted precision drive screw via a flexible coupling. This drive screw turns a sprocket and chain at the inside of the top frame section; this chain turns the opposite drive screw to assure simultaneous vertical movement of both linear bearings. The sprockets, chain, and chain tensioner are mounted to the top frame.
Figure 1: FANS unit photographs. (a) recently built units (b) anemometer rack (c) electronics for controlling drive-train and acquiring anemometer signals (d) FANS unit in trailer for transport to site (d) calibration in the University of Illinois BESS Lab (e) calibration at BESS with fan in place.
section of the FANS. The linear bearings are parallel to both drive screws, and the linkage between
the drive screws, bearings, and anemometer rack is accomplished at “bearing plates” on each side.
These plates rigidly fasten to the anemometer bar, allowing for only in-plane movement of the
anemometer rack. The plate on one side also contacts top and bottom limit switches (DPDT) to stop
rack travel. The anemometer rack is constructed of 38 mm (1.5 in) aluminum tubing, with five holes
into which are welded the anemometer’s threaded adaptors. A slot on the top of the rack is also
milled to provide for the data cables connecting anemometers to the control box. Wire is routed from
the rack, held away from the threaded screw with a simple hook, and then routed behind a separate
shield made of thicker sheet metal (e.g. 1.5189 mm; 0.0598 in or 16 ga) and down to the data
acquisition box.

Electronics and software

A schematic of control functions is provided in Figure 2. The data acquisition is accomplished using
Anemometer2, written in VisualBasic. Solid state relays isolate the PC from AC power to the gear
motor. Digital inputs are used on one set of limit switch contacts to determine whether it is active.
The software main screen is shown in Figure 3. When acquiring data from the anemometers, a loop
is executed continuously as the rack travels from one limit switch to the other. For each of the 5
analog input channels in turn, 1000 samples are acquired at a rate of 10 kHz and averaged to obtain
a single velocity reading. The rack requires approximately 185 s to travel the full length of opening,
thus about 1775 averaged velocity readings (1000 points/average) distributed uniformly over the
opening are acquired during a traverse.

FANS Calibration Results

Component Error Analysis

A component error analysis was performed by students in the BAE 599 PC-Based Data Acquisition
and Control course (Fall, 2001), as per the IFAFS project proposal. A breakdown of errors
(expressed as mV or least significant bits [LSBs]), is provided below:

Data Acquisition Card: For this project, a 12-bit analog-to-digital converter\(^2\) (ADC) was set to a
bipolar $\pm 1.25V$ input range. The resolution (LSB) is thus 0.6 mV/bit, and integral and differential
linearity errors are each given as 1 LSB, and full-scale error is 0.5% (6.3 mV or 10.2 LSB). The
combined probable errors associated with ADC are thus:

$$\Delta \text{ADC} = \sqrt{1^2 + 1^2 + 12.5^2} \text{ mV} = 12.5 \text{ mV or 20.5 LSB}$$

Oversampling, i.e. the technique of using the mean of multiple AD conversions to estimate the “true”
voltage, will reduce full-scale error. In this application, we utilize 1000 samples per observation. The
resultant $\Delta \text{ADC}$ is 6.3 to 1.5 mV (10.3 to 2.4 LSB), respectively, for a 5 to 10-fold reduction in full-
scale error. Alternatively, an ADC with smaller uncertainties could be selected.

\(^2\) Keithley Instruments Inc, 28775 Aurora Rd, Cleveland OH 44139, Model Number KPCMCIA-12AI.
Wiring Logic Design for FANS system

Figure 2: Schematic of data acquisition and controls circuits.
Figure 3: FANS software for airflow measurements.

Figure 4: Expected flow error at maximum expected air velocity of 8 ms$^{-1}$.
Anemometer DC Generator: The manufacturer provides calibration equations for velocity as a function of either rpm or generated voltage:

\[
\text{Velocity (m/s)} = 0.018 \times \text{mV} = 0.005 \times \text{rpm}
\]

The anemometer generates a DC voltage proportional to propeller rotational velocity with accuracy within 1% of reading. The DC-generator is calibrated at 500 (±2) mV @1800-rpm (0.3 mV/rpm). Zero offset is negligible.

Anemometer accuracy is expressed by the manufacturer both as ± 2 mV, and also relative to readings. At a maximum expected velocity of 8 m·s\(^{-1}\) (1,575 fpm) the nominal rotational speed is 1600 ± 1 rpm (or 480 ± 4.8 mV), and the dc-generator calibration error is < 2 mV (7.3 LSB). Combined, the maximum total anemometer probable error is:

\[
\Delta \text{Anemometer} = \sqrt{4.8^2 + 2^2} \text{ mV} = 5.2 \text{ mV} \text{ or } 8.5 \text{ LSB}
\]

and the minimum error is simply 2 mV. Expressed in units of velocity, these are 0.09 and 0.02-m·s\(^{-1}\), respectively.

Velocity Error: The maximum probable error of a velocity reading is the combination of ADC and maximum anemometer errors. At 8 m·s\(^{-1}\), this is:

\[
\Delta \text{Velocity} = \sqrt{12.5^2 + 5.2^2} \text{ mV} = 13.5 \text{ mV} \text{ or } 22.2 \text{ LSB} \quad (0.24 \text{ms}^{-1})
\]

Total Error: The expected error of the flow measurement system can be estimated from the component errors above, using the following relation between airflow rate and measured velocity:

\[
\text{Flow (m}^3\cdot\text{h}^{-1}) = \text{Velocity} \times \text{Area}
\]

where Velocity is obtained from the anemometer via ADC, and Area is obtained from shop drawings. The nominal area of the FANS inlet is 1.664 m\(^2\) (d=1.290 m ±1.6 mm square) with error on the order of 2d·Δd = 0.004 m\(^2\). An estimate of maximum probable uncertainty in flow measurement can be obtained from the maximum expected velocity through the FANS unit, i.e. 8 m·s\(^{-1}\). This is equivalent to a nominal airflow rate through the FANS of 10.3 m\(^3\)·s\(^{-1}\) (24,750 cfm). Maximum probable uncertainty at this rate is obtained from a component error analysis:

\[
\Delta \text{Flow} = \sqrt{\left(\frac{\partial \text{Flow}}{\partial \text{Velocity}} \Delta \text{Velocity}\right)^2 + \left(\frac{\partial \text{Flow}}{\partial \text{Area}} \Delta \text{Area}\right)^2}
\]

or:
\[ \Delta \text{Flow} = \sqrt{(\text{Area} \cdot \Delta \text{Velocity})^2 + (\text{Velocity} \cdot \Delta \text{Area})^2} \]

\[ = \sqrt{(1.290 \cdot 0.24)^2 + (8 \cdot 0.004)^2} = 0.31 \text{ m}^3 \cdot \text{s}^{-1} \ (743 \text{ cfm}) \]

This probable error is about 3% of the flow reading, assuming the worst-case full-scale ADC error of 0.5%.

Figure 4 demonstrates probable error as a function of flow, as affected by oversampling. The effect of flow rate is relatively small. The full-scale ADC error is shown to be critical, and warrants careful selection of ADC. It should be pointed out that increasing the number of bits of the ADC has negligible improvement on the RMS error of airflow rate. However, as is shown in the following section, calibration can reduce the uncertainty further.

**Laboratory Calibration of FANS**

Ten newly constructed FANS were individually calibrated at the University of Illinois BESS fan test facility (http://www.age.uiuc.edu/bee/research/research.htm). Figure 5 is a graph of measured vs. “true” airflow calibration curves for all 10 of these units.

Two slightly different means of expressing the calibration equations are possible: regression of measured \( y \) vs. reference airflow rate \( x \) as obtained (i.e. of the form: \( y=a+bx \)); or inclusion of a zero flow reading, then subtracting this offset from each measured reading and regressing the result (i.e. of the form: \( y-y_0 = bx \)). Expressed in these two ways, the calibration equation for the 10 FANS units together was determined as follows (numbers in parentheses are standard errors of regression coefficients):

FANS Flow = 1.015(\( \pm \)0.0009)\cdot Flow – 190 (\( \pm \)17)  [units are cfm]

FANS Flow – \( y_0 \) = 0.988(\( \pm \)0.0003)\cdot Flow;

\( y_0 \) depends on each device, 10-unit average = –93 cfm.

Airflow rate from a given FANS unit is obtained by inversion of the calibration equation:

FLOW = (FANS Flow + 190)/1.015 = 187 + 0.985\cdot FANS Flow

FLOW = (FANS Flow – \( y_0 \))/1.011 = 0.989\cdot (FANS Flow – \( y_0 \))
Regression slopes obtained from calibration of individual units were remarkably similar; it is thus recommended that a given unit can be used with either of the two equations above. The second relation, i.e. subtraction of any zero-flow offset, has the convenience of occasionally determining whether drift in zero offset has occurred by a simple check with no airflow during use.

The standard error of regression provides a simple estimate of measurement precision for comparison to the theoretical value obtained from a component error analysis in the previous section. For the second regression equation, the standard error $\text{Se} = 83$ cfm and the estimated imprecision in a measure is thus $\text{Se}/b = 83/1.011 = 82$ cfm. The range in $\text{Se}/b$ for the 10 units was 42 – 168 cfm. In terms of 36 or 48 in (91 or 122 cm) diameter ventilation fans (nominally 10,000 or 20,000 cfm, 4.7 or 9.4 $\text{m}^3\text{s}^{-1}$) the mean imprecision is thus 0.8% and 0.4% of reading, respectively; error from simply neglecting the calibration equation amounts to 216 and 432 cfm (2.2%, 1.1% of reading), respectively, for these 2 fan sizes.

Figure 5: Composite graph illustrating the uniformity of measurement between 10 different FANS units. Reference flow obtained from standard flow nozzle equations for the nozzles in the BESS Lab (Univ. of IL) from manometer readings of pressure drop.
Comparison between Component Error Analysis and Calibration

From the preceding two sections, actual performance of the FANS device is shown to be better than the probable performance as predicted from the component error analysis. Thus, when characterizing the FANS unit performance, the recommended method is to use representative statistical values from the calibration.

FANS Unit Flow Penalty

Use of the FANS device upstream of a ventilation fan adds some pressure drop for the fan to work against and hence may reduce fan airflow rate. The reduction depends on the FANS system curve and performance curve of the particular ventilation fan being used.

Two propeller fans have been tested using the FANS unit and the BESS fan test facility to gain some insight into the penalty imposed. The FANS unit was positioned upstream of the fan in the test wind tunnel. The effect of the FANS unit on fan performance is graphically illustrated in Figure 6. The first fan (48” Chore-Time model 46868-4842) exhibited a 2-3% reduction in airflow rate for static pressures up to 0.15 in.W.C. (38 Pa) and a rapid increase at higher static pressures. The second fan (50” Multifan model MF50P-C-M) exhibited significant flow loss, with an increasing reduction in airflow rate from 5% at free air up to 10% at 0.15 in.W.C. (38 Pa) and then decreasing to 5% at 0.24 in.W.C. (61 Pa) before again increasing at higher static pressures.

Since most ventilation fans are used at lower pressures, the flow penalty can be considered relatively minor for the first fan but not negligible for the second fan. Thus it is necessary to assess individual fan models with the FANS system in a test chamber for accurate determination of the FANS penalty. From Table 1, there is no obvious difference in discharge dimensions between the two fans. Future work should be focused on developing which fan design factors are important in this regard. It appears that testing of a wider range of fan sizes and of fans differing in their performance characteristics is needed to establish the range of expected performance penalties. To establish the penalty explicitly for a given fan will require that it be independently assessed.

<table>
<thead>
<tr>
<th>Intake Dimension &amp; Area</th>
<th>Discharge Dimension Area</th>
<th>Discharge Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>WxH, (cm x cm, m²)</td>
<td>WxH or diameter (cm x cm, m²)</td>
<td>(%)</td>
</tr>
<tr>
<td>FANS Unit</td>
<td>145 x 145, 2.096</td>
<td>128.9 x 128.9, 1.664</td>
</tr>
<tr>
<td>Fan 1</td>
<td>138 x 139, 1.913</td>
<td>123.7 dia., 1.202</td>
</tr>
<tr>
<td>Fan 2</td>
<td>145 x 142, 2.116</td>
<td>128.5 dia., 1.297</td>
</tr>
</tbody>
</table>
Figure 6. Effect of FANS unit on fan performance. Top (penalty %), bottom (penalty flow).
Summary
Details of design, fabrication and performance of a device to measure airflow rate through propeller fans in-situ were presented. Drawings and CAD files are available at http://www.bae.uky.edu/IFAFS/FANS. Ten of the FANS units were fabricated and calibrated. The units predicted airflow rate within 1%, and after calibration had an imprecision of 42-168 cfm over the 10 units. Fan performance with and without the FANS unit attached was highly dependent on the particular fan model; one fan demonstrated a minimal 2-3% penalty over the range of static pressure commonly encountered in poultry and livestock facilities, but another fan demonstrated up to 15% penalty at 38 Pa (0.15 in W.C.).

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References


