NELSON ACOUSTICS
POST OFFICE BOX 879, ELGIN, TX 78621
VOICE: 512.281.5535 FAX: 512.233.5276
E-MAIL: david@nelsonacoustical.com
noise and vibration control • sound quality • test facility design • seminars

FINAL REPORT

PROJECT 778: FOH FAN TESTING

2005 July 15

Performed By:

David Nelson, INCE Bd. Cert.
Nelson Acoustics

For:

Federal Occupational Health
On behalf of
NASA Glenn Research Center
Acoustical Testing Laboratory
21000 Brookpark Road
Cleveland OH 44135

1.0 PURPOSE AND SCOPE

Flow/Acoustic Tests were performed on 3 candidate fans using the NASA Automated Fan Plenum. The purpose of the tests was to exercise the plenum hardware and software, develop a preliminary test procedure, generate comparison data for quality assurance purposes (pending retests when the system is delivered to ATL), and provide some preliminary data on the effect of inlet conditions on flow delivery and noise emission.

The three fans selected were:

- EBM/Papst 8314/12: a 5-bladed, 80 mm diameter, 24V fan selected from the list of "approved" fans circulated by Eric Phillips of Boeing.
- EBM/Papst W2G115: a 7-bladed, 110mm diameter, 24V fan used in a payload tested at ATL
- EBM/Papst 612NHH: a 5-bladed, 60mm diameter, 12V fan under consideration for a payload.

All three fans were tested with unobstructed inlets and outlets. The 8314/12 fan was tested with several partially-obstructed inlet conditions:

- Straight inlet pipe, one duct diameter in length
- Straight inlet pipe, three duct diameters in lenth
- 50% diameter reduction (chamfered) at the inlet end of a straight inlet pipe, one duct diameter in length.
- 90º elbow (R/D = 1.5) at the inlet end of a straight inlet pipe, one duct diameter in length.

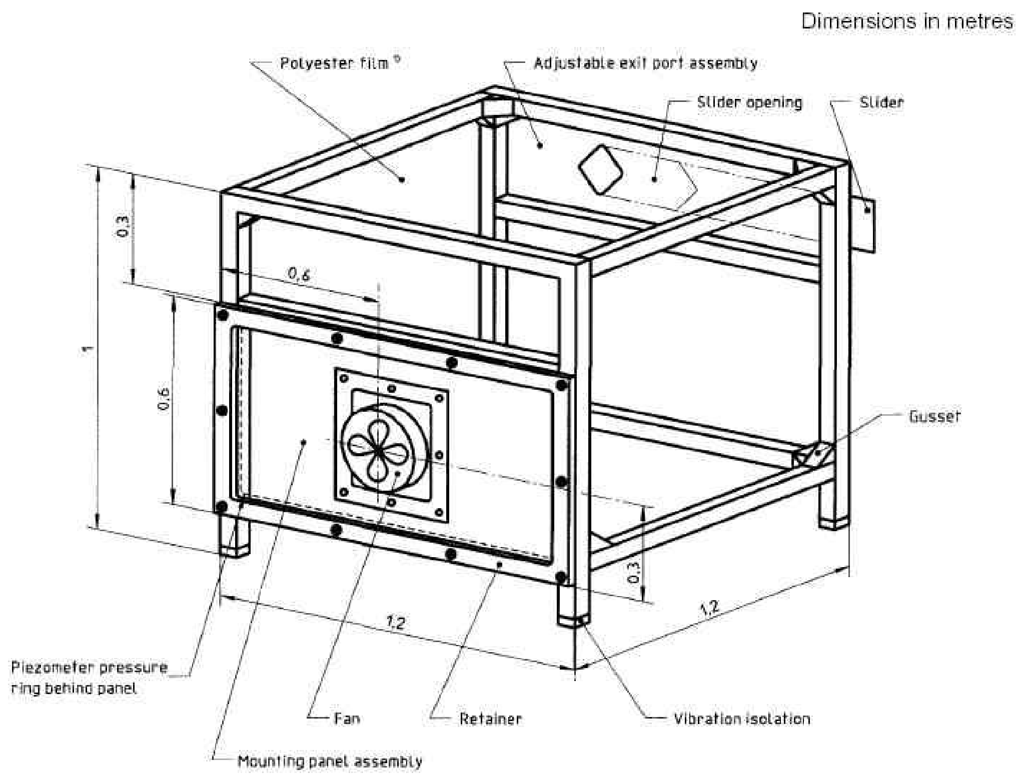
The air delivery of a fan *in situ* is determined by the point of intersection between the fan curve[1] for a given RPM and the system resistance curve[2]. The manufacturer's fan curve documents tests performed under ideal flow conditions that do not exist in the installed configuration. Fan curves of installed fans tend to differ markedly from the catalog information; the inlet ductwork in particular adds flow resistances and turbulence not present during catalog measurements.

The noise emission of a fan is influenced primarily by the flowrate, backpressure, proximity to a "sweet spot" characterized by the fan's peak static efficiency, and ductwork vortices and turbulence. For low-noise design work, one-third octave band sound power level readings under realistic loads and flow conditions are desired However, fan manufacturers typically measure the noise emission of the fan under more or less ideal inflow/outflow conditions at free air, and then only as an A-weighted sound pressure level 3 feet from the inlet. Thus catalog noise emission data is of limited value.

[1] The fan curve is the locus of pressure/flow combinations that a fan can deliver into various loads at a given rpm.
[2] The system curve is the locus of backpressures that a flow system presents for a range of flows.

2.0 TEST METHODS

The primary test method employed in this study is ISO 10302 "Acoustics — Measurement of airborne noise and structure-borne vibration of small air-moving devices". The test standard describes the construction and use of an acoustically-transparent fan discharge plenum with adjustable flow resistance (see illustration next page). The plenum permits straightforward measurement of discharge static pressure and sound power. During testing the flow is inferred from the static pressure within the plenum, based on *a priori* flow tests[3].



1) Covers all areas, including bottom, except mounting panel and exit port.

The fan plenum depicted above is a "full size" plenum that is intended for rather large fans. The plenum used for the current study was constructed at half scale and automated to facilitate more accurate measurements of smaller and medium-sized fans.

Sound power measurements were made in a reverberant chamber using in accordance with standard method ISO 3741 "Acoustics — Determination of sound power levels of

[3] Direct measurement of flow typically adds ductwork and/or fittings that may affect the noise emission and create additional uncontrolled backpressures. Hence the flow resistance of the plenum is fully characterized in advance.

noise sources using sound pressure — Precision methods for reverberation rooms", using the comparison method[4].

2.1 Method of Selection of test points/combinations.

Test points were selected on the assumption that the fan curves obtained at various voltages would collapse to a single non-dimensional curve (see "fan laws" discussion below). Therefore it is only necessary to get detailed information at one typical voltage.

The type of test to be performed is called a "full fan characterization" designed to assess the fan's performance across the entire fan curve. Test points are selected differently when comparing to a known system load or searching for a particular operating point (see the Test Procedure section following).

First the fan plenum was opened to free air (400 mm). Then the "Home" command was asserted. The slider position was noted for any of the following conditions:

- Static Pressure increases from zero to past 0.005 in H_2O.
- Rapid change in pressure
- Rapid change in noise emission

No fewer than 12 slider positions were selected with emphasis on the areas noted above. All tests were conducted at the nominal supply voltage of the fan.

2.2 Flow/Pressure Characterization of Plenum.

The static pressure P_S developed across the fan plenum is related to the flow through the plenum Q as $P_S = P_0(x)Q^2$ (where $P_0(x)$ is the pressure drop in inches of H_2O at a flowrate of 1 cfm) across a wide range of slider positions. One unique value of P_0 is associated with each slider position. Thus the resistance of a given system is simulated by moving to the slider position that produces the desired value of P_0.

This relationship can also be inverted in order to compute the flow from static pressure readings as $Q = Q_0(x)\, Ps^{½}$ (where $Q_0(x)$ is the flowrate produced at a static pressure of 1.0 inches H_2O for a given slider position x). One unique value of Q_0 is associated with each slider position.

The standard deviation of uncertainty of flow is approximately +/- 6% throughout the range.

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[4] In the comparison method, the relative sound power level of a source is determined by comparing the reverberant sound pressure level in a given environment to the sound pressure level produced by a calibrated reference sound source in the same environment.

2.3 Reduction to non-dimensional fan curve

Fans tend to follow well-known dimensional scaling laws that allow the performance of a fan to be defined in a general fashion for any speed or any scaled diameter (in our study, only the speed was varied). The fan laws are used to reduce the various fan curves for different speeds to one non-dimensional fan curve using the parameters ϕ for flow coefficient, ψ for pressure coefficient, λ for power coefficient, η for static efficiency, and N for rotational speed and D for impeller diameter.

$$\phi = Q / ND^3$$
$$\psi = P_S / \rho N^2 D^2$$
$$\lambda = W_{electric} / \rho N^3 D^5$$
$$\eta = QP_S / W_{electric} = \phi\psi / \lambda$$

For this study, flow and pressure data were first converted to consistent MKS units of [m^3/s] for flow and [Pa] for pressure[5].

A static efficiency curve is usually presented in conjunction with the non-dimensional curve. The point of maximum static efficiency is the flow state where the most flow work gets done for the least input power. In studies of larger scale fans, the power and efficiency is based on the brake horsepower so that mechanical and electrical losses are excluded. In this study, however, the electrical power is used and the efficiency so obtained combines aerodynamics and motor performance.

2.4 Estimation of pressure-flow using Fan Laws

Once the fan curve for a given fan design is known in non-dimensional terms, its performance can be estimated for any rotation rate and diameter by applying the fan laws "in reverse".

$$Q = \phi ND^3$$
$$P_S = \psi\rho N^2 D^2$$

For N is expressed in [Hz] and D in [m], values calculated in this study produce estimates of Q and P_S estimates with units of [m^3/s] and [Pa] respectively.

2.5 Reduction to non-dimensional system curves

For a turbulent flow system where $P_S=P_0Q^2$, a single non-dimensionalized system curve exists for each fan diameter independent of speed:

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[5] Note: 1 m^3/s = 2117 cfm, 1 in. H_2O = 248.8 Pa

$$\psi = \left(P_0 / \rho\right) D^4 \phi^2$$

The non-dimensionalized system curve can be plotted against the non-dimensional fan curve: the intersection of the curves defines the operating point (ϕ, ψ).

3.0 ACOUSTIC NOISE EMISSION

3.1 Reduction to nondimensional noise curve based on Fan Laws

Dimensional scaling laws for noise are not as well-behaved as those for flow. The fan laws are used to reduce the various fan noise curves for different speeds to one non-dimensional fan curve using the parameters L_W for one-third octave band sound power level, L_{WA} for overall A-weighted sound power level, K_W for one-third octave band specific sound power level, K_{WA} for overall A-weighted sound power level, and N for rotational speed and D for impeller diameter.

$$K_W(\phi) = 10\log(W_{acoustic} / QP_S{}^2) = L_W(\phi) - 10\log(QP_S{}^2)$$
$$K_{WA}(\phi) = \log(W_{acoustic,A} / QP_S{}^2) = L_{WA}(\phi) - \log(QP_S{}^2)$$

For this study, K_W data was referred to Q in [cfm] and P_S in [in. H_2O] for convenience. While octave band K_W values were expressed in dB, overall A-weighted noise emission data were expressed in bels [B] as is customary in the product noise emission community[6]. The values of K_W and K_{WA} typically vary with ϕ, reaching a minimum just "to the right" of maximum static efficiency.

The blade passage tone component is often handled separately from K_W estimates; this step has been omitted for the present.

3.2 Estimation of noise using nondimensional curves

Once the fan noise curves are known in non-dimensional terms, noise emission can be estimated for any rotation rate and diameter by applying the fan laws "in reverse".

$$Q = \phi N D^3$$
$$P_S = \psi \rho N^2 D^2$$
$$L_W = K_W(\phi) + 10\log(QP_S{}^2)$$
$$L_{WA} = K_{WA}(\phi) + \log(QP_S{}^2)$$

[6] 10 decibels, A-weighted, equal 1 bel.

For this study, N is expressed in [Hz] and D in [m]. Thus the Q and P_S values must be converted to [cfm] and [inches H_2O] before performing the L_W calculation.

Substitution for Q and P into the relationship for L_W leads to the commonly accepted "rule" that noise emission tracks *50 log N*. The difference in noise emission at two speeds, provided the flow coefficient ϕ has not changed, is therefore expected to be $50 \log N_1/N_2$. This factor may be applied to both overall A-weighted and octave band estimates.

4.0 8314/12 FAN

The fan was tested unobstructed ("Open") and with 4 partially obstructed cases:

- straight inlet pipe, one fan diameter in width and duct diameter in length ("1D")
- straight inlet pipe, one fan diameter in width and three duct diameters in length ("3D")
- 50% diameter reducer, followed by a straight inlet pipe, one fan diameter in width and one duct diameter in length ("1D + Reducer")
- 90º elbow (R/D = 1.5), followed by a straight inlet pipe, one fan diameter in width one duct diameter in length ("1D + Elbow").

Fan data was compared to catalog data. The catalog did not report the RPM of the fan during fan curve tests. The supply voltage range of the fan is reported as 12 to 28 V, with 24V nominal. All tests of this fan connected with this project were performed at 24V. Figure 1 shows all the results on one chart.

The catalog fan curve matches best when RPMs 15% greater than those observed at 24V. Therefore it appears the catalog fan curve was developed at a voltage greater than 24V. Figure 2 compares the measured unobstructed fan data with the catalog data based on a presumed RPM.

The introduction of a straight inlet pipe significantly reduced the pressure developed at lower flow coefficients. There was little difference between the 1x and 3x diameter lengths. From this it can be inferred that constriction at the fan inlet interferes with its ability to develop pressure at low flow rates (below ϕ=0.25). Above this flow rate the presence of the straight pipe inlet seemed to have little effect. From this it can be inferred that the obstruction causes inflow distortions rather than pressure drop effects: the latter would be expected to be strongest at highest flowrates. The breakpoint between the two regimes occurs near the maximum static efficiency (ϕ=0.20 to ϕ=0.30). Figure 3 compares the unobstructed results to those for one and three diameter lengths of straight pipe.

The introduction of the elbow at the upstream end of the 1D straight pipe seems to have had little effect. On the other hand, the diameter reduction exerted a significant effect particularly at higher flowrates. This is consistent with the influence of a significant flow-induced pressure drop. Figure 4 compares the unobstructed results to those for 1D, 1D+Reducer and 1D+Elbow.

Figures 5 through 8 show the corresponding effects of flow conditions on noise emission.

The unobstructed fan is quietest near flow coefficient ϕ=0.20. Addition of the straight inlet pipe moves the quietest point to near flow coefficient ϕ=0.30 and adds a "hump" near ϕ=0.20. It's interesting to note that the 1D case is actually quieter than the unobstructed case at high flow rates; perhaps a flow straightening effect is being observed. It's also interesting to note that the 3D case is 3 to 4 dB louder than the 1D case in spite of minimal change to the pressure/flow curves. Similarly, the presence of the elbow increased noise emission somewhat in spite of minimal effect on the pressure/flow curves. In fact, the increases due to the elbow and 3D inlet pipe are very similar. Addition of the reducer dramatically increases the noise emission and changes the pressure/flow curves as well.

So in summary it can be stated that two kinds of pressure/flow curve changes have been observed:

- those which introduce local flow distortions which primarily affect the lower flowrates (although they could in theory affect any or all flowrates), and
- those associated with upstream pressure drops which primarily the higher flowrates most strongly.

It has also been observed that significant changes in noise emission can occur even without a significant change in the pressure/flow curve. Thus it is not sufficient to search for changes in the pressure/flow curve as a means to anticipate changes in noise emission.

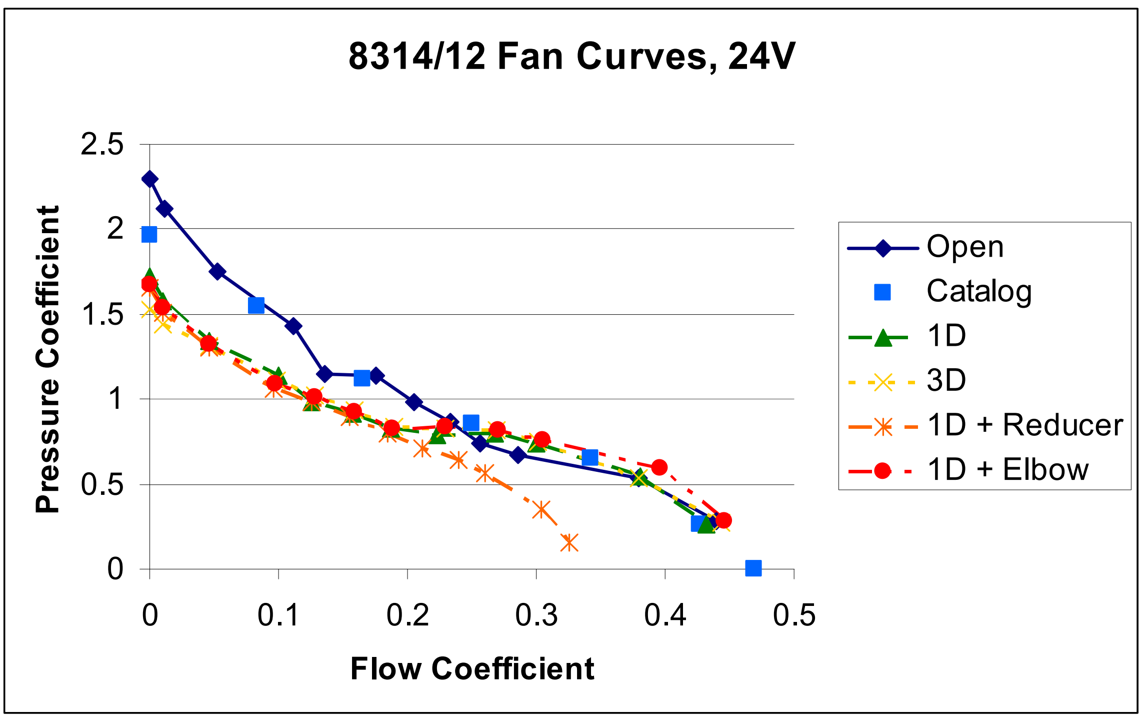


Figure 1: All 5 conditions plus catalog data

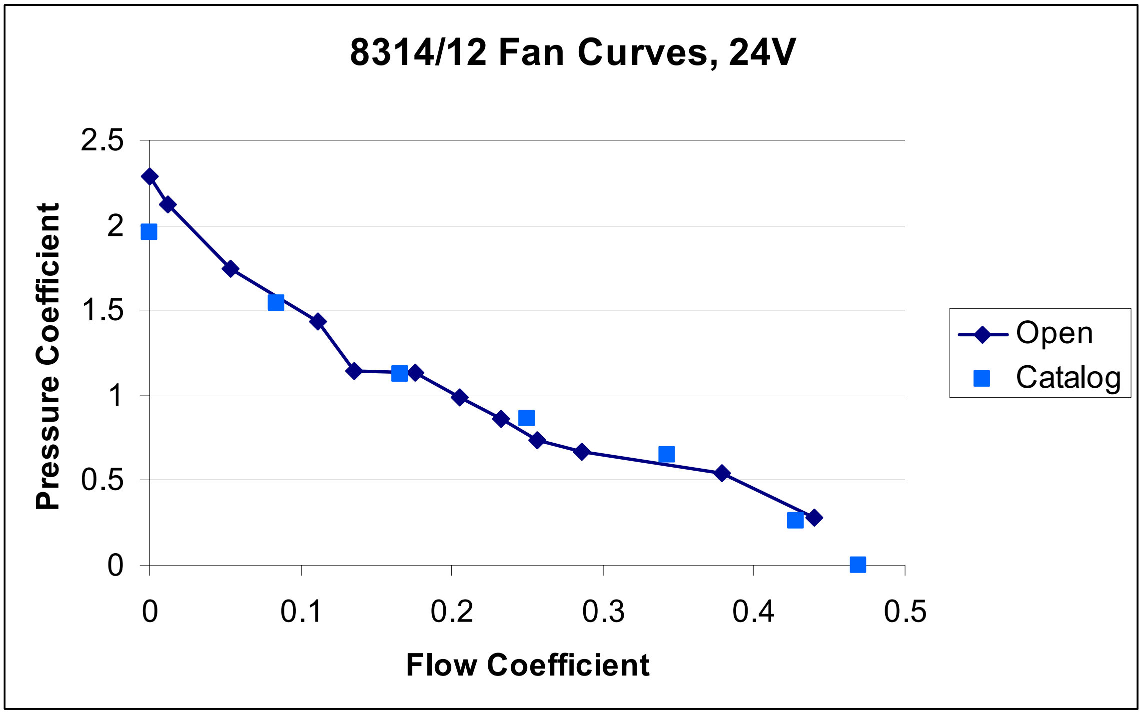


Figure 2: Comparison to Catalog Flow Data

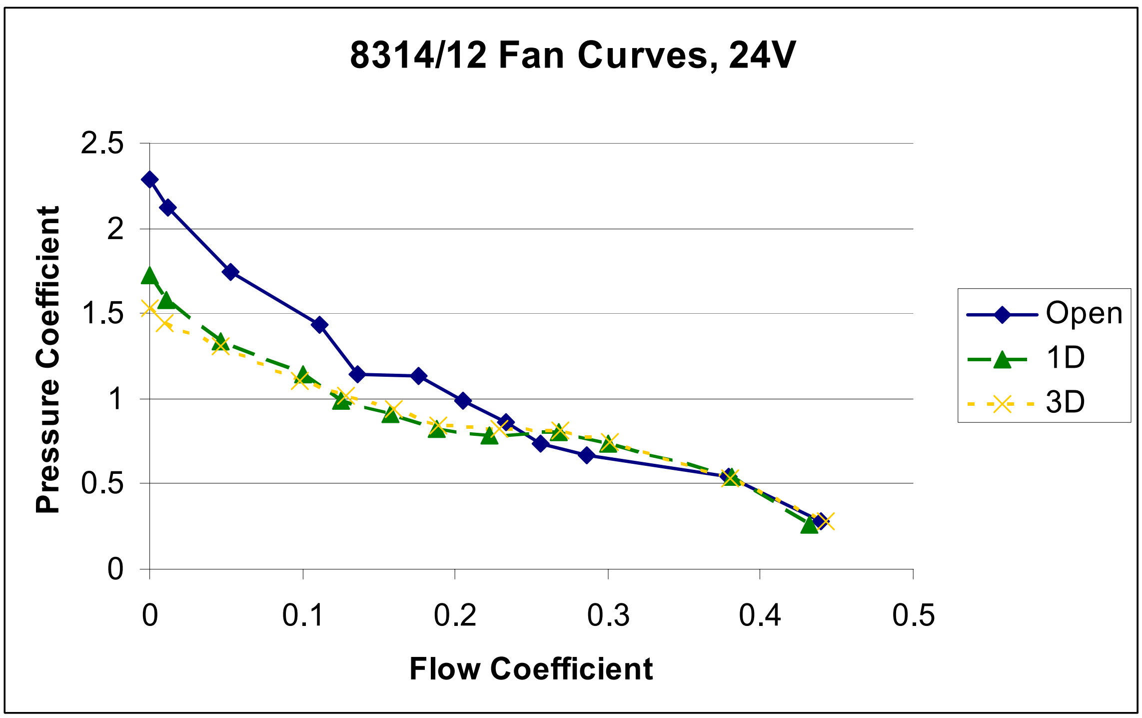


Figure 3: Effect of Straight Inlet Ducts on Flow

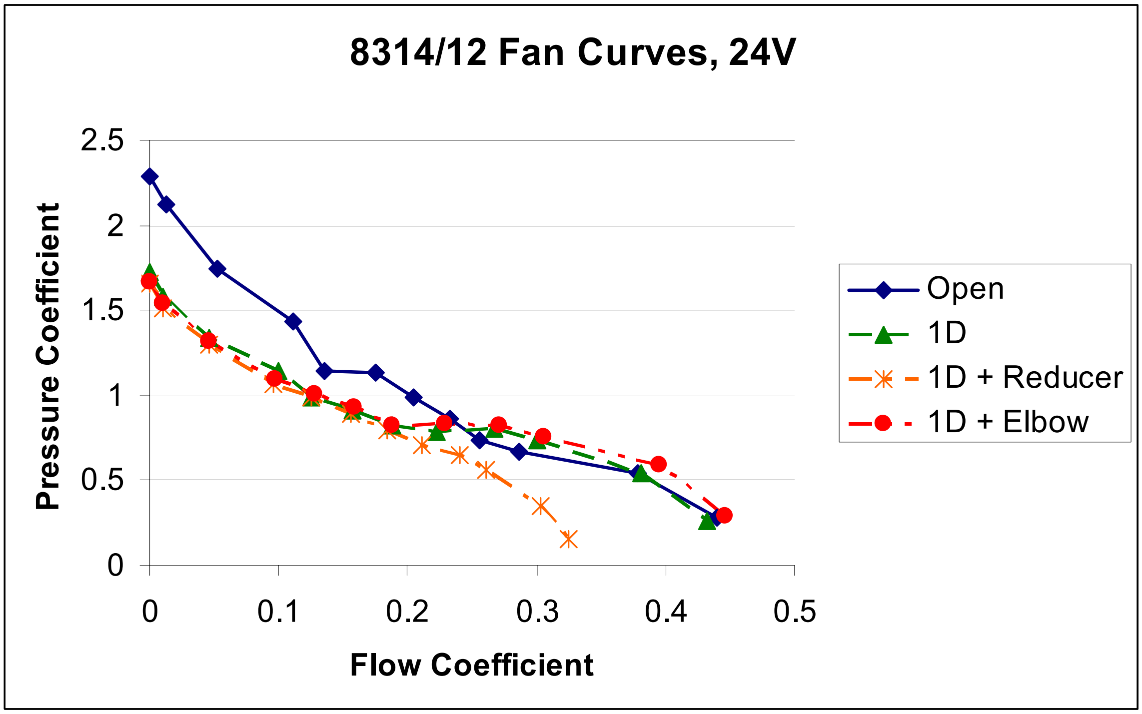


Figure 4: Effect of Reducer and Elbow on Flow

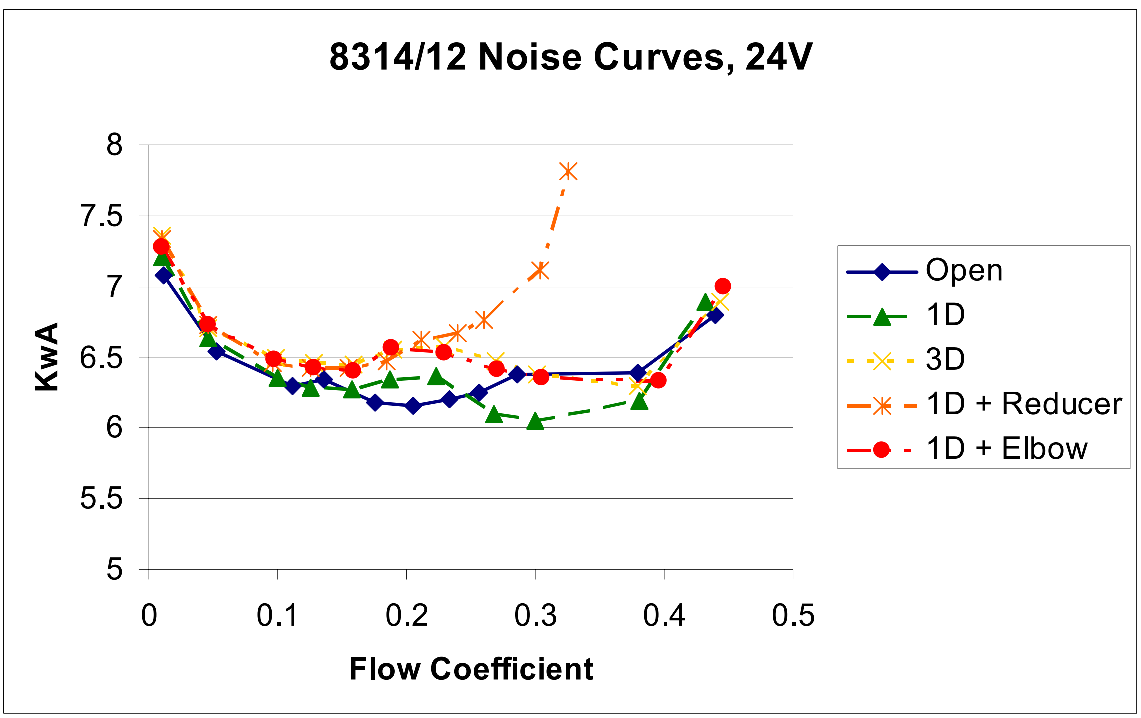


Figure 5 Noise Curves for all 5 cases

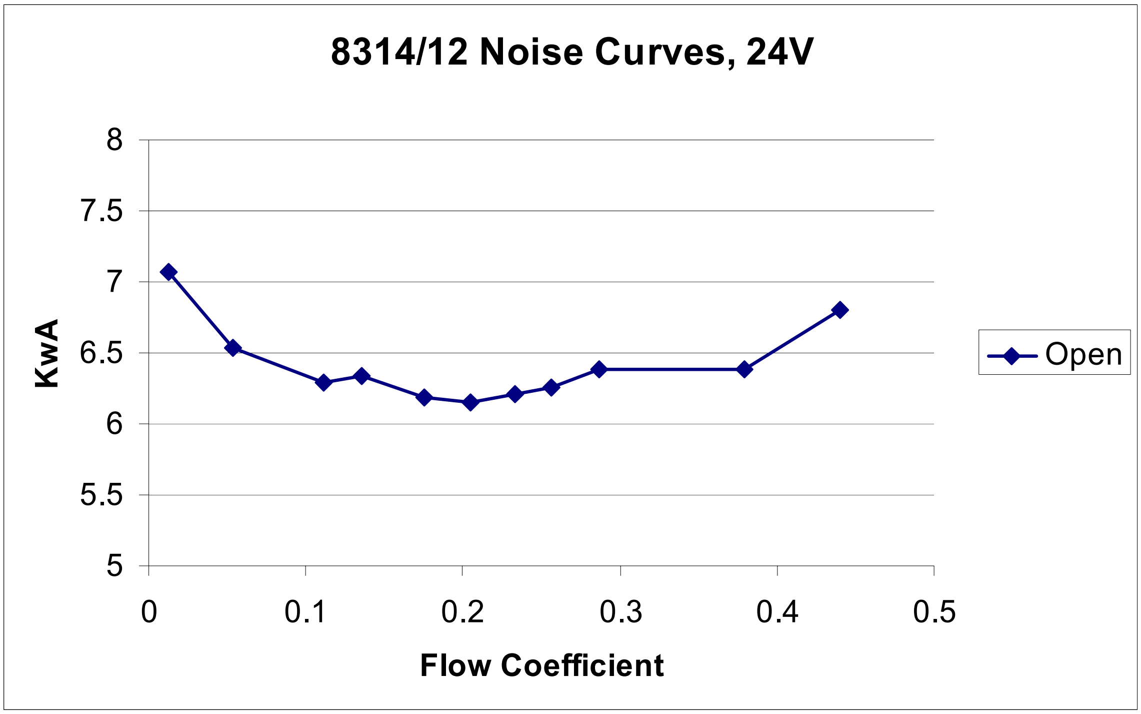


Figure 6: Noise Curve for unobstructed case

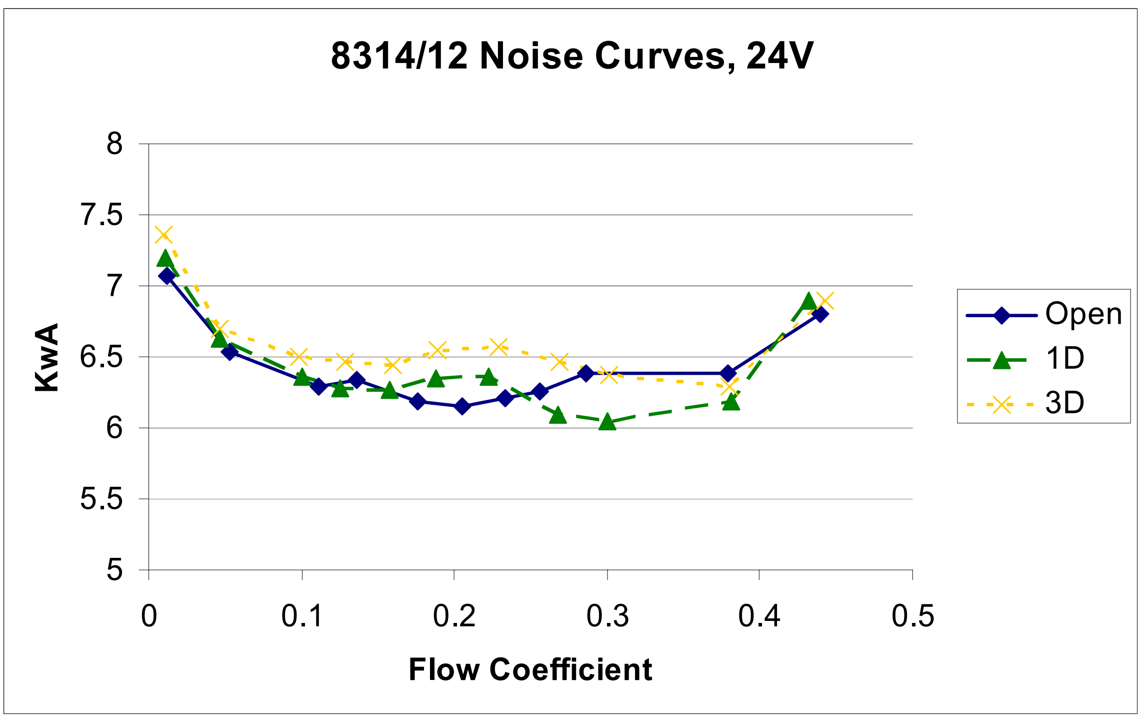


Figure 7: Effect of Straight Inlet Pipe on Noise Emission

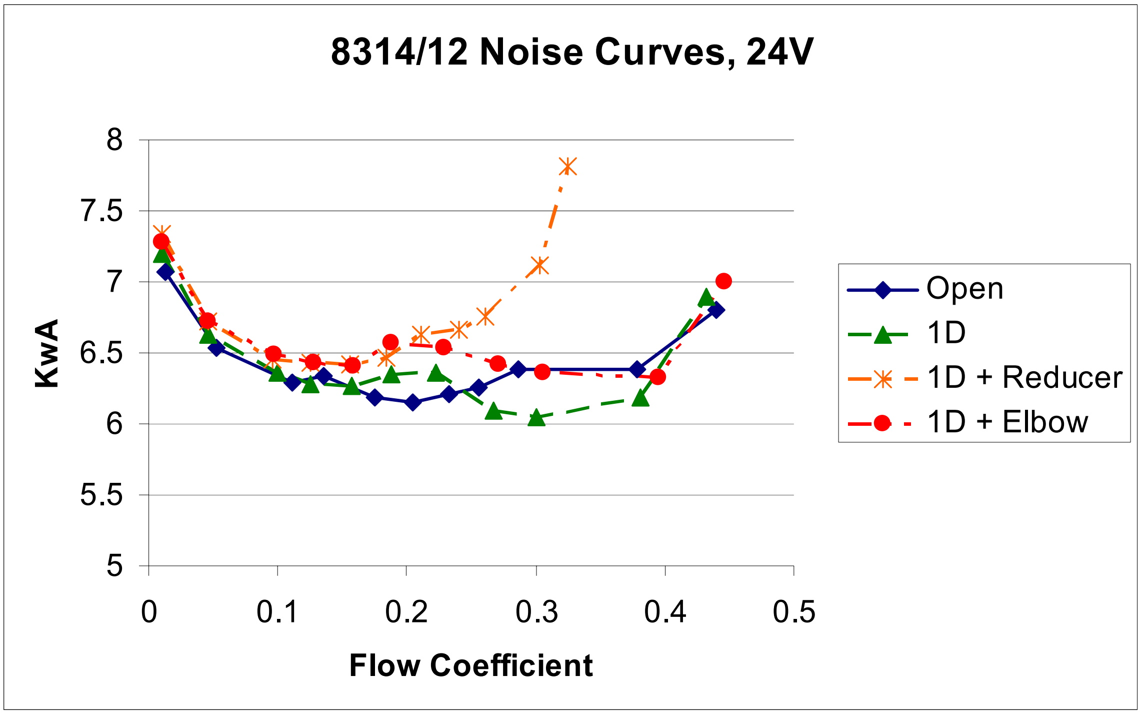


Figure 8: Effect of Reducer and Elbow on Noise Emission

5.0 W2G115 FAN

The precise model designation of the fan is W2G115-AE31-15. The model does not appear in current EBM catalogs but is present in older ones. The fan was tested under unobstructed conditions at 24V and compared to 24V catalog data. The pressure/flow data lines up very well without any adjustment (see Figure 9).

Lowest noise emission was observed near $\phi = 0.65$ (see Figure 10), which coincides with the point of maximum static efficiency for the unobstructed fan. The "spike" near $\phi = 0.45$ represents a significant increase in noise output that occurs as the flow regime in the fan changes, perhaps as fan blades "stall". This kind of sudden change in noise emission is characteristic of axial flow fans.

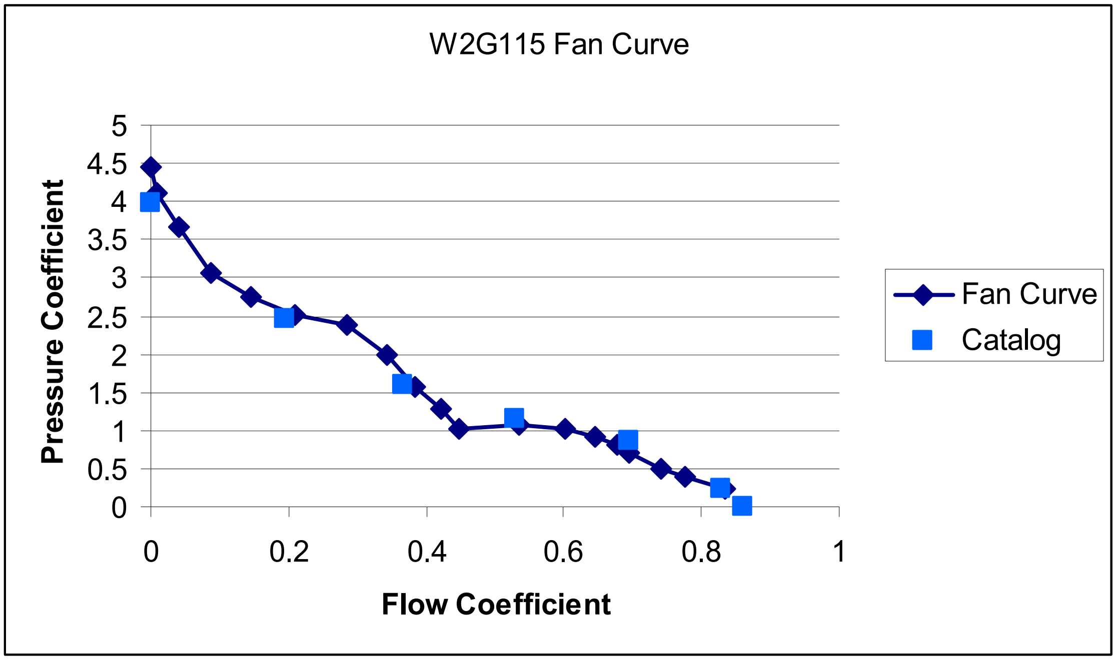


Figure 9: Pressure/Flow curve for unobstructed W2G115

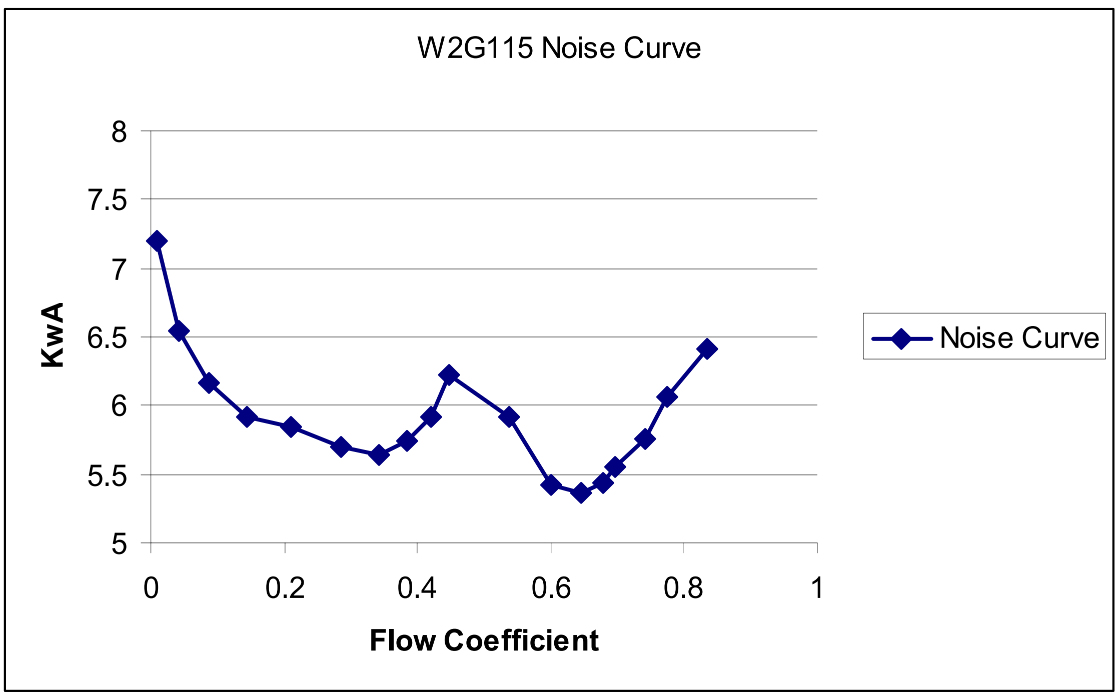


Figure 10: Noise Emission curve for unobstructed W2G115

6.0 612NHH FAN

The fan was tested under unobstructed conditions at 12V and compared to catalog data. The catalog fan curve matches best when RPMs 10% greater than those observed at 12V. Therefore it appears the catalog fan curve was developed at a voltage greater than 12V, probably 15V (top of catalog voltage range). Figure 11 compares the measured unobstructed fan data with the catalog data based on the presumed RPM.

This fan spins at very high RPM (near 6000). It delivers about the same free-air flow (33 cfm) as the 8314/12 (32 cfm) but is physically smaller, indicating the quantities ND^3 are similar for the two fans. It delivers much higher pressures than the 8314/12. In spite of the diameter difference being made up with speed, the actual noise emission for both fans was similar (L_{WA} ~ 50 to 56).

Lowest noise emission was observed near $\phi = 0.50$ (see Figure 12), which coincides with the point of maximum static efficiency for the unobstructed fan. The "spike" near $\phi = 0.35$ represents a significant increase in noise output that occurs as the flow regime in the fan changes, perhaps as fan blades "stall". This kind of sudden change in noise emission is characteristic of axial flow fans.

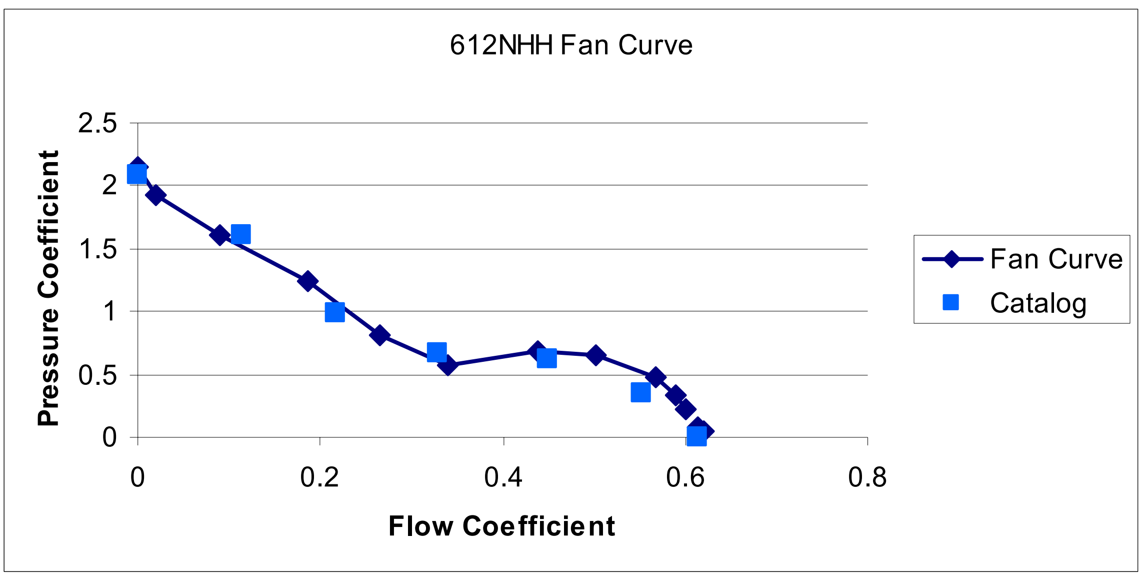


Figure 11: Pressure/Flow curve for unobstructed fan

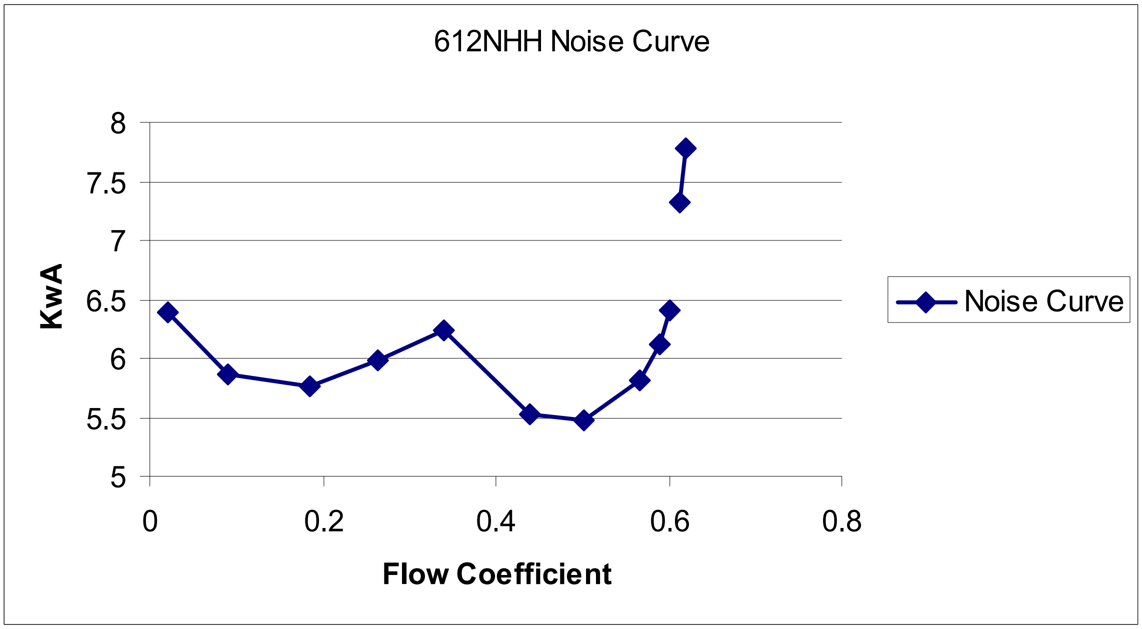
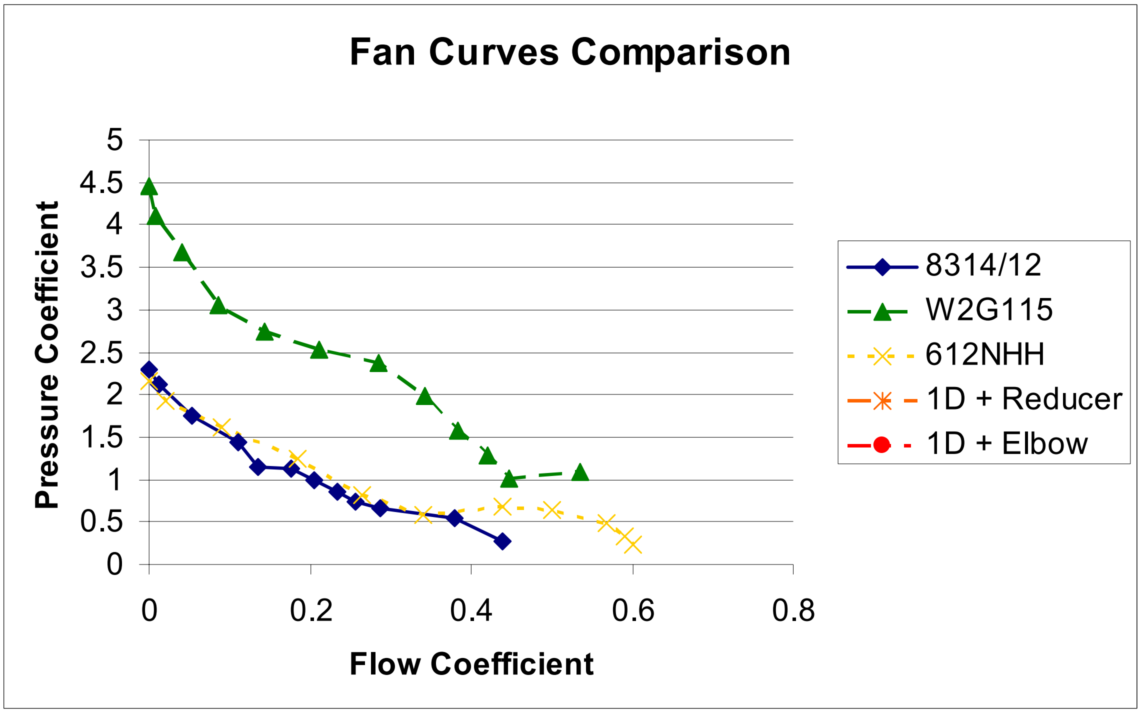


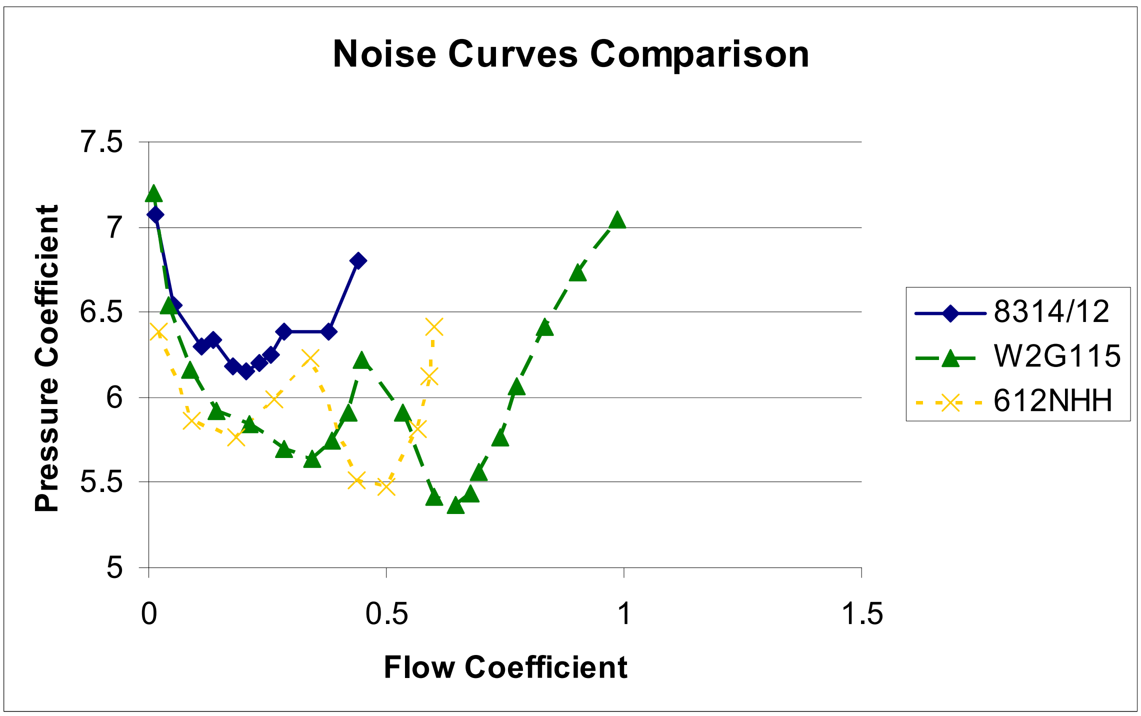
Figure 12: Noise Emission Curve for unobstructed fan

7.0 FAN TO FAN COMPARISON

The fans are of different design and are of different sizes. Figure 13, however, shows that the two smaller fans function very similarly and would be expected to deliver approximately the same flow into a given load. The W2G115 is a much more robust fan and delivers more pressure and flow due to its greater size and power consumption.

Figure 14 shows that the 8314/12 is the “noisiest” fan of the group, about 3 dBA louder than 612NHH on a non-dimensional basis. The W2G115 is about 2 dBA quieter still. “Spikes” are readily apparent on all but the 8314/12.


Fan Curves Comparison
Pressure Coefficient
Flow Coefficient
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
0.2
0.4
0.6
0.8
8314/12
W2G115
612NHH
1D + Reducer
1D + Elbow


Noise Curves Comparison
Pressure Coefficient
Flow Coefficient
5
5.5
6
6.5
7
7.5
0
0.5
1
1.5
8314/12
W2G115
612NHH

8.0 PRELIMINARY TEST PROCEDURE

8.1 Setting Up the Plenum

Set up the automatic test plenum in the test chamber. Make all wiring connections.

Install a fan in the test plenum. Disconnect power by pulling the banana plug from the binding posts.

Affix a piece of "cat's eye" to the impeller on the side facing the tachometer sensor.

Verify that the tachometer sensor reads the motions of the impeller. Spin the impeller by hand: the green light on the sensor flickers each time the cat's eye passes the beam. Verify that the tachometer display gives a reading while doing this.

Zero the pressure sensor by depressing the small button on its face.

Power up the plenum and controllable power supply.

Set the power supply for a supply voltage appropriate to the fan under test.

Connect power using the banana plug and the binding posts.

8.2 Setting Up the Computer

Install the data acquisition and DIO boards in the computer or outboard chassis.

Power up the computer

Using NI Measurement and Automation Explorer, exercise the boards using the test panels.

For the DAQ board, verify that a non-zero voltage is present on channels 0 and 1.

For the DIO board, first verify that input bits 2 and 3 (from the right) are high (red). The Input bank should be 0. Then set the output bank to 4. Set all bits high (by checking the boxes) and depress "Write Output". Then uncheck bit 6 (second from left) and depress "Write Output" again. The slider should proceed to "Home". Check bit 6 again and depress "Write Output" again. Uncheck bits 1 and 4 (to make the address 9). Depress Write Output. Then uncheck bit 7 (on the left) and depress Write Output. The slider should immediately move to 256 mm position.

Reassign the device numbers if necessary. If using the software in conjunction with SPS/MCE, the 455x boards serving the microphones require consecutive numbers beginning with 1. Number the DAQ and DIO board any number thereafter which is not consecutive with the 455x board numbers. For example, with (3) 455x boards, the audio boards would be Devices 1,2 and 3, and the numbers for the DAQ and DIO boards should be 5 or greater. These device numbers are changed by right-clicking on the board in MAX, then selecting Properties.

8.3 Setting up the Software

Copy the plenum software from the compact disk to the computer. Use Operating System tools to remove the Read Only tags on all files in the software folder.

Enter the startup voltage and voltage limit in the default configuration file Defaults.txt.

Enter the warning position in the default configuration file Defaults.txt. If you try to close the slider beyond the warning position using the software, a dialog box will ask you to verify that nothing is in the way as the slider closes.

Enter the device numbers in the default configuration file Defaults.txt. The PressTach Device is the Data Acquisition card (6023E), and the DIO Device is the DIO Card (6527).

Enter the default CSV filename in the last line.

```
Startup Voltage = 12.0
Voltage Limit = 12.0
Warning Position [mm] = 50.0
PressTach Device Number = 10
DIO Device Number = 11
C:\Documents and Settings
```

8.4 Selecting Test Paradigm

Three test paradigms are possible:

a. Full characterization of fan. The intent is to determine the fan's capabilities across a wide range of operating conditions. This is typically done from the viewpoint of documenting the fan for a wide range of as yet unknown loads and flow requirements. The voltage is fixed and the slider position varies. Tests may optionally be repeated at other voltages, although experience shows that the non-dimensionalized results are likely to be similar.

b. Performance test against known load. The intent is to determine the fan's capabilities under known loading conditions, usually representing a known system for which the fan is a candidate. This is typically done from the viewpoint of a known load and flow requirement, as when a chassis has already been designed and candidate fans are being tested for suitability. The slider position is fixed and the voltage varies.

c. Search for known flow or pressure. This is typically done from the viewpoint of the fan being a strong candidate along with a known load requirement. The supply voltage and slider position are varied under control of the user to reach a known pressure or flow.

Each paradigm represents a different approach, but the software supports all three.

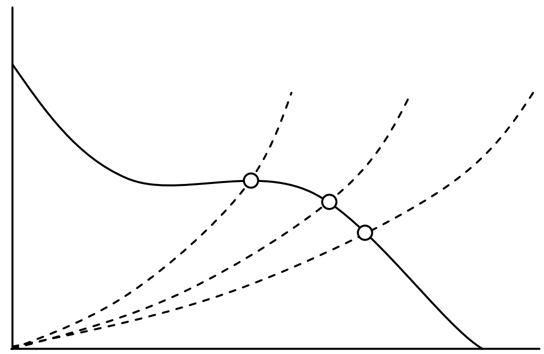
8.5 Selecting Operating Points

Full characterization

First open the fan plenum to free air (400 mm). Then assert the "Home" command. Note the slider position for any of the following conditions:

- Static Pressure increases moving up from zero to pass 0.005 in H_2O.
- Rapid change in pressure
- Rapid change in noise emission

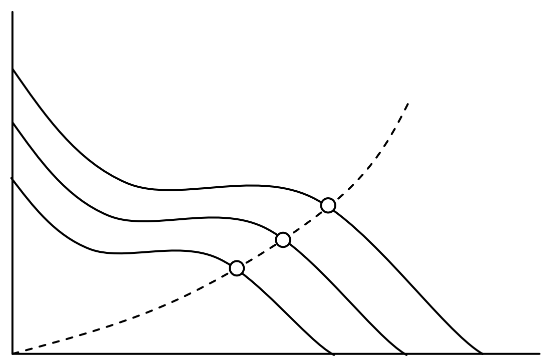
No fewer than 12 slider positions should be selected with emphasis on the areas noted above. If more detail is required to isolate points of interest, use the "Bump" commands to adjust the position of the slider. All tests should be conducted at the nominal supply voltage for the fan.



Known Load

Use the System Characteristic method of positioning the slider. Select the desired flow and pressure drop corresponding to desired performance in the known system.

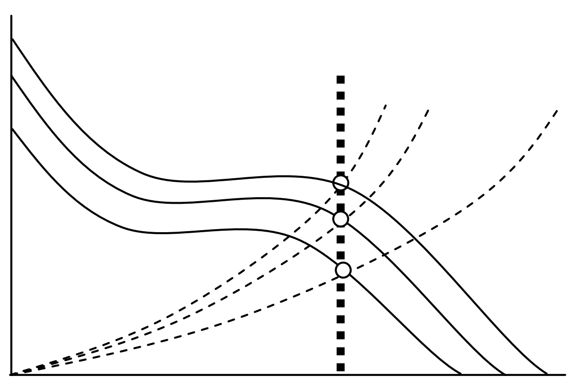
Adjust the fan to the top of its permissible supply voltage range. Make an initial determination if the fan delivers the desired flow. Vary the supply voltage until the desired flow is achieved. Select this slider position as a test point. Then select at least 5 others that cover the range of permissible supply voltages.



Target Flow or Pressure

Set the supply voltage at the high end of the permissible range for the fan.

If working towards a known flow requirement, open the slider to free air (400 mm). For small fans, the indicated flowrate will be a bit unstable because the pressure is very low. Close the slider gradually using the Bump commands. For small fans, the indicated flowrate may decrease a bit and then increase when a sufficient amount of pressure develops



(usually on the order of 0.005 inH_2O). Close the slider until the desired flowrate is reached. Record this as the first test point[7]. At this point the option exists to select a number of slider positions as test points and vary the voltages to achieve the desired flow, or to select a number of voltages as test points and vary the slider positions. Either approach is valid.

If working towards a known pressure requirement, begin with the slider in the Home position (0 mm). Open the slider gradually until the desired pressure is reached. Record this as the first test point. At this point the option exists to select a number of slider positions as test points and vary the voltages to achieve the desired flow, or to select a number of voltages as test points and vary the slider positions. Either approach is valid.

8.6 Performing the Tests

The Automated Fan Plenum Software must be open (not necessarily running, but open in memory) in LabVIEW before running Sound Power Software, because SPS takes control of the LabVIEW windows and prevents another VI being opened while it is running.

The Automated Fan Plenum Software runs in a separate window from SPS/MCE. It can be accessed either by Alt-Tab or by placing it off to the side in a dual monitor configuration.

The fan plenum should be placed within the 10-mic hemi-spherical grid. The fan should be located as near the center of the grid as possible.

Configure and calibrate SPS in accordance with existing procedures.

Set the fan and test plenum to one of the test points selected above. Wait for the indicated parameters pressure to settle (the pressure is usually the slowest). Save the flow parameters by depressing the “Write to CSV” button. If desired, depress the “Read CSV” button to display the most recently updated CSV contents. Then return to SPS perform the acoustic measurements in MCE. Optionally, make a WAV file recording or examine high-resolution FFT data. Return to SPS from MCE. At this point it is advantageous to set the fan plenum for the next test point so that the plenum can be settling while data is exported. Returning once more to SPS, save the MEA file and export the XLS file.

Iterate this process until all test points have been completed.

[7] It may be more advantageous to select all the test points and then formally test, but it many cases it may be best to simply run the tests as the operating points are found.

9.0 CONCLUSION

The ability to rapidly and simultaneously characterize fans for flow and acoustics is critical to proper low-noise design of fan-cooled or fan-assisted devices. In conjunction with parallel analysis of multiple microphone channels, the automation method described in this project reduces the time to characterize a single fan/flow configuration from a full day to less than one hour. Finally, exploration of noise emission and pressure/flow delivery across a variety of inlet and outlet configurations is crucial to a systematic engineering understanding of the factors affecting noise emission from installed fans.

This report documents the successful technical advances (some long overdue) achieved during this project:

- Successful implementation of an automated test plenum under software control.
- Demonstration of integrated flow/acoustic testing under realistic load and flow conditions.
- Documentation of the fan curves and noise emission of three fans typical of spaceflight applications.
- Documentation of the effect of four inlet conditions.
- Observation that even straight inlet ductwork may cause flow distortions which affect the pressure/flow curve at low flowrates.
- Observation that inlet obstructions may cause added pressure drop which affects the higher flowrates most strongly.
- Observation that significant changes in noise emission need not be accompanied by significant changes in the pressure/flow curve.
- Development of a preliminary test procedure for use at ATL.