Isolation room exhaust fan noise in a hospital

Chad HIMMEL

1 JEAcoustics, USA

ABSTRACT
Healthcare facilities with airborne infection isolation rooms for patients will often use a central building exhaust system dedicated to maintain constant negative air pressure in each isolation room to reduce the spread of airborne infectious diseases from the patient to the rest of the hospital. Such isolation exhaust systems often use a redundant two-fan system to assure that at least one fan stays on while the other fan is shut down for maintenance or failure. This paper presents a case study of one hospital’s rooftop isolation exhaust two-fan system that produced excessive noise in patient areas located below. Several decisions in building design contributed to the noisy conditions, including equipment location, mechanical shaft size, and exhaust duct sizes and paths. In addition, variable frequency drive settings for the primary and backup exhaust fans contributed to noise produced. Indoor noise was reduced significantly using a combination of equipment drive settings along with insulated duct lagging enclosure. Comparative charts of noise and vibration levels will be presented to show criteria and facility performance before and after corrections, along with diagrams, photos and illustrations of noise control measures used. Theoretically predicted noise spectrum results using basic algorithms are compared with measured data.

Keywords: Lagging, Exhaust, Hospital  
I-INCE Classification of Subjects Numbers: 35.8, 51.1.5, 51.6

1. INTRODUCTION
Airborne infection isolation (AII) rooms are needed in hospitals to reduce the spread of airborne infectious diseases, such as tuberculosis. It is important that AII rooms maintain constant negative pressure such that when the room is used as designed, airborne particles generated in the room cannot escape to the corridor (1).

This paper presents a case in which rooftop isolation exhaust fans affected indoor noise quality in a 12-story hospital with excessive fan noise radiated from ductwork above patient room corridors on the top floor of the building. Results and analyses indicated significant noise reduction was possible with remedial changes to the fan speed settings and retrofit installation of insulated sheet duct lagging materials immediately above the affected corridor.

The hospital’s roof deck is a concrete pan-joist structure, with rigid polyisocyanurate insulation and roofing membrane topping, with a suspended acoustical tile ceiling grid above the corridor below. Initially, after construction was complete, noise and vibration levels in the patient room corridor below the isolation exhaust fans exceeded allowable tolerances for healthcare facilities. As a first corrective measure, exhaust fan speeds were adjusted while listening indoors to optimize the resulting noise level by ear. Adjusting the fan speeds did reduce noise levels significantly, but not enough to achieve the limits required for the hospital corridors according to standard design guidelines established by the Facilities Guidelines Institute (FGI) (2).

For further corrective measures, mass-loaded vinyl sheet duct lagging and insulation was added to enclose exhaust ducts immediately above the corridor. Following the fan speed adjustments and installation of duct lagging, the noise and vibration in the affected corridor near patient rooms achieved required criteria. Subsequently, new exhaust fans and ductwork have been added to the facility roof to provide additional redundancy, sharing exhaust air demands between the existing and new systems.

1 himmel<at>jeacoustics.com
2. ISOLATION ROOM EXHAUST SYSTEMS

2.1 Initial System Design and Planning

The design intent for the isolation patient room exhaust systems on this project was to have two exhaust fans located on the rooftop, 13 floors above ground level. A single exhaust duct riser connected to both fans would extend 12 floors down within a shaft, branching at lower floors as needed to reach ground floor AII patient rooms. One of the two identical fans (Fan A) would be on at all times, running at 85-95% of full capacity, while the second fan (Fan B) would remain off, maintained for use as a backup in the event of the primary fan’s failure. While there were two AII exhaust systems at the hospital, this paper focuses on just one of those two-fan systems. Table 1 summarizes fan information, and Figure 1 shows a photograph of the two fans.

Table 1 – Isolation exhaust fan information

<table>
<thead>
<tr>
<th>Make / Model</th>
<th>Drive Type</th>
<th>Wheel Type</th>
<th>Fan Wheel Diameter</th>
<th>Wheel RPM</th>
<th>Airflow Volume</th>
<th>Static Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loren Cook / CPS</td>
<td>Belt drive</td>
<td>Backward inclined</td>
<td>762 mm</td>
<td>1349</td>
<td>7780 L/s</td>
<td>947 Pa</td>
</tr>
</tbody>
</table>

Negative pressure isolation patient rooms would be as airtight as possible to prevent air from being pulled in through cracks and other gaps, and the rooms would achieve minimum pressure differential and air change rates, such as a negative pressure differential across the patient room door of 7.47 Pa of water column, 10-12 room air changes per hour, or similar goals according to standard design practices for AII spaces (3).

2.2 Built Conditions

During final design coordination, it was determined that there would not be enough space within the exhaust duct shaft, among other ducts also taking up space in that shaft, to carry the AII rooms’ exhaust riser directly to the roof. In a change, AII ducts, including the 1470 mm wide by 860 mm tall rectangular duct, would need to exit the shaft on the 12th floor, travel horizontally above the corridor ceiling a distance of about 3 m, then turn upward in a final vertical rise to penetrate the roof deck and split above the rooftop to connect separately to the two exhaust fans mounted there.
2.3 Sounding Alarms on the Ground Floor

Once the project was built and HVAC systems were fully operational, some isolation rooms exhibited low negative air pressure, and as a result, automatic negative air pressure detection systems were continuously in alarm with clearly audible sirens. It is not known to this author why the AII rooms did not achieve negative air pressure as designed. It is also not known what investigative or corrective measures may have been taken to identify or correct leakages or HVAC air balancing issues. There are many conditions that might compromise negative pressure room design, such as air leakage at patient room door bottoms, high volume delivery of supply air, building air fluctuations related to exterior doors or elevators, etc.
HVAC system operators adjusted the primary exhaust fan (Fan A) to its full capacity, or 100% speed setting, in an attempt to correct the pressure differential. Since at least one of the isolation rooms remained in alarm for pressure, the secondary fan (Fan B) was also turned on in order to generate enough negative pressure to silence the alarms. Operators found that the desired minimum negative pressure could be achieved with Fan A at 100% capacity and Fan B on at 60% of capacity.

Figure 4 – Twelfth floor corridor at the shaft

2.4 Fan Noise on the Top Floor

Once the negative air pressure alarms were silenced, loud fan noise and rumble was observed in areas of the corridor directly below the isolation exhaust fans. Using Loren Cook fan noise software (4) to estimate the source fan sound power levels, along with estimated noise losses due to duct fittings according to algorithms by ASHRAE (5) and comparisons with later measurements on site, the indoor noise spectrum received in the top floor corridor prior to noise mitigation is estimated below in Figure 5, compared with FGI allowable noise goals for hospital corridors, NC 45, RC 45(N) and 50 dBA (2).

Figure 5 – Estimated fan noise at the top floor corridor prior to noise mitigation
3. NOISE MITIGATION

3.1 Optimizing Fan Speeds

As a first corrective measure, building HVAC system technicians adjusted the exhaust fans’ speeds while listening indoors in the corridor to optimize the perceived noise levels. To ear, technicians determined the results sounded quietest with both fans running at 70%. Table 2 below summarizes the various exhaust system conditions and the measured (or estimated*) noise levels.

Table 2 – Isolation Exhaust Fan Speed Settings and Conditions

<table>
<thead>
<tr>
<th>Exhaust System Condition</th>
<th>Fan A</th>
<th>Fan B</th>
<th>Noise Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design phase intent</td>
<td>85-95%</td>
<td>0%</td>
<td>---</td>
</tr>
<tr>
<td>Post-occupancy, with alarms</td>
<td>100%</td>
<td>0-55%</td>
<td>---</td>
</tr>
<tr>
<td>Post-occupancy, no alarms</td>
<td>100%</td>
<td>60%</td>
<td>61 dBA*</td>
</tr>
<tr>
<td>With optimized fan speeds</td>
<td>70%</td>
<td>70%</td>
<td>55 dBA</td>
</tr>
<tr>
<td>With added duct lagging</td>
<td>70%</td>
<td>70%</td>
<td>50 dBA</td>
</tr>
</tbody>
</table>

*estimated

Figure 6 shows the indoor $L_{33}$ noise spectrum received in the top floor corridor after fan speeds were optimized for noise mitigation. All measurement results reported in this paper are based on $L_{33}$ statistical percentiles, including spectra shown in Figures 6, 7, 9 and 10.

3.2 Vibration

Prior to installation of duct lagging, surface vibration of lightweight wall and ceiling elements and ductwork was measured to evaluate whether interior noise may be induced or radiated by vibrating exhaust ducts or vibration transmitted by the exhaust fan housings supported at the roof. Observations on the roof indicated Fan A and B were floating freely on spring isolation mounts along with proper flexible duct connections and flexible electrical connections, shown in the photograph in Figure 1. Surface vibration measurements at the shaft wall in the corridor indicated that when Fan A and Fan B
were both turned off, low frequency vibration related to other vibration sources, such as other general exhaust fans on the roof, was present. Airborne noise radiated from vibrating lightweight structures can be estimated using data provided by Miller (6). Figure 7 shows an estimation of the airborne noise that would be radiated from the vibrating shaft walls with the isolation exhaust fans off as well as on, which would likely contribute to corridor noise regardless of noise mitigation applied to Fans A and B.

Figure 7 – Estimated noise radiated from vibrating shaft wall surfaces

3.3 Lagging Exhaust Ductwork

For further corrective measures, mass-loaded vinyl sheet duct lagging and insulation was added to enclose exhaust ducts immediately above the corridor, shown in Figure 8. Lagging materials were Sound Seal® model B-20 LAG/QFA-3, a composite material featuring a flexible 9.8 kg per square meter reinforced foil faced loaded vinyl noise barrier bonded to a 25 mm thick quilted fiberglass sound absorber, commonly used to wrap noisy pipes, ducts, valves, and fan housings.

Figure 8 – Exhaust duct before lagging (left) and after the lagging was applied (right)
Following the installation of the insulation and lagging, along with optimizing the fan speeds, the noise and vibration in the affected corridor near patient rooms achieved required criteria, shown in Figure 9.

![Figure 9 – Measured fan noise at the top floor corridor following fan speed optimization and lagging](image)

### 3.4 Theory

Theory related to duct breakout sound transmission is based on experimental data provided by ASHRAE for sheet metal ductwork. The Transmission Loss, $TL_{out}$, of ductwork is normalized for duct breakout transmission and is independent of duct size or surface area (5) as follows. At frequencies below the cross-over frequency, $f_{cr}$, the quantity $TL_{out}$ is calculated by Equation 1:

$$TL_{out} = 10\log(f * m^2 / (a + b)) - 13 \quad f < f_{cr}$$

(1)

where

$$f_{cr} = 612 / (a/b)^{0.5}$$

(2)

$f = $ band center frequency, Hz  
$m = $ mass/unit area, kg/m²  
$a = $ larger duct cross-section dimension  
$b = $ smaller duct cross-section dimension

At frequencies above $f_{cr}$ and below half the critical frequency, $f_c$:

$$TL_{out} = 20\log(f * m) - 45 \quad f_{cr} < f < f_c / 2$$

(3)

(Limited to 45dB).

Laboratory testing of the acoustical performance of duct lagging can be performed according to procedures in ASTM E1222 (7). Figure 10 shows a comparison of measured insertion loss of the lagging, compared with lab tested insertion loss for a similar lagging and insulation product by the same manufacturer (8), having half the weight per unit area applied to piping, and with lab tested
insertion loss for a similar lagging product with and without insulation by a different manufacturer (9), again having half the weight per unit area applied to 20-gauge ductwork, and the estimated insertion loss using ASHRAE methods and Equations 1 and 3. In Figure 10, the measured insertion loss above 1000 Hz appears to have been limited by the presence of airborne airflow noise and diffuser-generated noise present in the corridor.

Different duct sizes are likely to have different optimal acoustical solutions. Jacketing and insulation have a greater impact on containing noise on smaller ducts than larger ducts. Data and subsequent modeling of data suggest that jacket mass or insulation thickness must increase as duct size increases. With lagging systems, increasing insulation thickness improves the insertion loss performance. Increasing jacket weight also has an improving influence on insertion loss (10). Research on the insertion loss of pipe lagging has produced simplistic analytic models, which generally do not yield useful results as vital parameters such as modes of pipe vibration, curvature, etc. are not taken into consideration (11). Although rigorous analytical and predictive methods do exist (12, 13), they were not used in this evaluation as they have been developed more for piping than ductwork, and are also known not to predict the insertion loss associated with pipe lagging with complete accuracy (11).

Figure 10 – Comparison of measured and estimated insertion loss of duct lagging
4. FINAL REMARKS

Results in Figure 10 indicate that the octave band average insertion loss values of duct lagging materials wrapped around sheet metal ductwork when estimated using ASHRAE methods, do not match very well with field measured octave band insertion losses, particularly not at frequencies below the cross-over frequency, which was 543 Hz in this case. On the other hand, Figure 10 hints of the possibility that insertion loss values of duct lagging tested in general accordance with the American Society for Testing and Materials designation ASTM E1222 could match reasonably well with field measured octave band insertion losses, particularly if lab testing was conducted with the same or similar lagging system applied to ductwork (not piping) having similar gauge, size and shape as was present in field or designed conditions. Octave band or one-third octave transmission loss values tested according to ASTM E90 would not indicate, and would likely far exceed, a lagging material’s actual insertion loss performance when applied in the field to ductwork. A simplified algorithm based approach to predicting spectrum insertion loss for duct lagging would be desirable. Perhaps an insertion loss estimate based on double panel sound transmission loss estimations (14,15) could be compared with lab tested results ASTM E1222 to develop a new method.

In this case, fan speed adjustments were utilized along with retrofit duct lagging to successfully mitigate an unanticipated fan noise problem. For similar installations, building designers and acoustical consultants could expect to utilize similar methods to reduce noise following building construction and occupancy. However, results could be limited by noise radiated from vibrating walls or ceilings attached to ductwork. A proper design with exhaust ducts fully enclosed in a shaft sized large enough to contain ductwork and provide separation from occupied spaces would likely eliminate any need for retrofit lagging for added containment.

In the final assessment of this case, HVAC operators believe that an exhaust system utilizing multiple fans running at partial capacity should be more reliable than a system that relies on one fan running at full capacity, while other fans are off or idle, as the idle fans might not be properly lubricated and ready to run when they are needed. Thus, a secondary benefit was discovered in this case, and additional fans running at partial capacity were eventually added to make the system more robust and redundant overall.

Designers of isolation patient room exhaust systems may not be able to accurately predict all variables that could affect final negative pressure in their isolation rooms. Some variables, like door undercuts, are beyond the control of the mechanical designer. It is necessary, therefore, to anticipate that fan speed adjustments may be needed in the design and installation of isolation room exhaust fan systems in hospital buildings. A design that does not allow for post-construction fan speed adjustments to satisfy minimum negative pressure requirements in isolation rooms can introduce significant, unwanted noise and vibration impacts elsewhere in the facility.

ACKNOWLEDGEMENTS

The author wishes to thank the medical center for their permission and generous assistance in the development of this manuscript.

REFERENCES


