Considerations of External Noise and Vibration Factors in the Design of Sensitive Inpatient Facilities

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Abstract - To provide a better and wider range of healthcare services to the community, hospitals often require redevelopment, resulting in necessary expansion into an existing and quite often constrained building envelope. Due to limited space within the hospital complex, it is often the outcome that these expansions are constructed vertically, either above an existing clinical facility or above a mechanical plantroom. Additionally, the available spaces suitable for expansion may also conflict with existing helipads located on the rooftop. This presents noise and vibration isolation challenges in the design of sensitive inpatient facilities. Acoustic design of inpatient areas for hospitals requires careful consideration of transient or continuous noise and vibration factors that may be critical to patient diagnosis, comfort, and recovery. This paper explores the critical considerations of helicopter noise and mechanical plant vibrations in the design of inpatient areas within a hospital. These external factors pose challenges to patient comfort and recovery due to the vulnerable nature of the patient, necessitating effective design strategies to creating a calm and peaceful atmosphere conducive to patient healing and comfort. In this paper, we have assessed the helicopter noise, mechanical plant airborne and structure-borne noise in the design of an inpatient area, located above a mechanical plant room and adjacent to rooftop helipad. Helicopter take-offs and landings generate high-intensity noise levels, while mechanical plants contribute low-frequency noise and vibration that are potential risk factors for the design of comfortable critical-patient facilities. This paper reviews the current design guidelines and standards related to noise and vibration in healthcare facilities and discusses architectural and engineering solutions including façade design and vibration isolation as effective mitigation measures in a challenging noise and vibration environment.

1 INTRODUCTION

This paper discusses the essential factors related to helicopter noise and mechanical plant vibrations in the design of inpatient areas within a hospital setting. These external influences present significant challenges to patient comfort and recovery. Considering the wide spectrum of sensitivity requirements of patients in recovery the implementation of effective design strategies aimed at fostering a serene and tranquil environment that supports healing and comfort is paramount. The referenced project site is situated within a bustling hospital grounds in New South Wales. Among various potential sites for the establishment of a new inpatient facility for critically ill patients, the rooftop of an existing low-rise building was identified as the preferred location. The designated site can be described as a rectangular area measuring approximately 60 metres in length and 25 metres in width. This proposed development area is positioned above a substantial mechanical plant room, which houses HVAC systems, multiple substations, and generators. Numerous air handling units (AHUs) and other HVAC equipment are located along the perimeter of the site. Additionally, a helipad is situated on the rooftop of a nearby high-rise building connected to the core hospital complex. The combined plant and nearby airborne helicopter noise pattern provides additional complications to the acoustic design of the hospital inpatient areas, demanding meticulous attention to both transient and continuous noise and vibration factors, the control of which is vital to patient diagnosis, comfort, and recovery.

2 LITERATURE REVIEW

External noise intrusion factors in healthcare facilities have been researched at length, with little pragmatic or legislative acoustic/vibro-acoustic design control methods being implemented in the concept design phase despite the significant propensity to influence human health outcomes (Andrade, et al., 2021). The focus of this review is on the investigation of currently understood hospital design considerations in helicopter noise and mechanical noise and vibrations.

The use of helicopters within hospital boundaries is a complicated issue, with the detrimental impacts of periodic high level helicopter noise intrusions outweighed by the considerable benefit of expedited patient transfer. Modern therapeutic understanding is now highlighting the complex issues that a high ambient or background noise can impose upon the recovery path of patients (Waye & Ryherd, 2013; Hsu, Ryherd, Waye, & Ackerman, 2012). Further complications in modern hospital design consideration lie in the constrained boundary parameters of hospitals, which are most often constructed within urban or metropolitan settings and are seldom able to be expanded within the urban footprint. As patient and staffing needs increase, we see further expansion upwards, squeezing mechanical plant and helicopter infrastructure closer to sensitive noise receivers. There are multiple mechanical processes that contribute to helicopter noise emissions, which will vary depending on helicopter size and design intention. Leverton (2014) categorises primary helicopter noise sources as; “main rotor thickness/high speed impulsive (HIS) noise, main rotor blade/blade vortex interaction (BVI) noise, main rotor wake/tail rotor interaction (TRI) noise and tail rotor (TR) noise”. Measurements taken by James et. al. (2012) provides a LF_{max} sound pressure level range for the Bell 412 Helicopter performing various take-off and landing manoeuvres as 87dB to 97dB 100m from a helipad. Modelling conducted by James et. al. (2012) shows elevated sound power in the 63Hz – 125Hz frequency bands, often necessitating high performance insulated glazed units and bespoke façade constructions to adequately control intrusion.

Vibratory effects in healthcare can be generally grouped into two broad categories, human perception and structure-borne mechanical influence. Continuous vibration amplitude, or whole-body vibration, is felt on a level factors higher than the displacement velocity and acceleration required to detrimentally affect clinical equipment (Nash, 2008). Principally, it is found that the threshold of human vibration perception is higher than what is required to severely degrade scanning equipment accuracy, leading to the healthcare facility floor criteria presented by E., E., Ungar (2007). A study conducted in neonatal wards, and in agreement with ISO 2631-2 (International Organization for Standardization (ISO), 2003), discusses obtained global acceleration levels in incubators that exceed regulation criteria or are likely to generate acute health effects (Sequi-Canat et al., 2022). Iterative guidelines presented by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) post-1995 include vibration criteria curves intended to mimic the “human perceptual frequency response” (Nash, 2008) and are used to provide vibration isolation control for structurally borne emissions generated by mechanical plant and clinical equipment. Despite expansive research and commercial development in vibration isolation there is still very little documentation or regulatory procedure on the adverse health impacts on patients that continued mechanical, and structure borne vibration can impose (Zootjens & Cockings, 2014).

Community health guidelines published by the World Health Organization (World Health Organization, 1999) outline several physiological and physical effects caused by short term and continued exposure to impactful environmental noise, including, but not limited to, sleep disturbance, annoyance and stress related cardiovascular impacts. Helicopter generated noise is particularly problematic in this case, due to the mandatory proximity of the helipad, and the “quasi-impulsive” acoustic character generated by the rotational, mechanical and exhaust elements of the aircraft (Chyla & Bukula, 2019). Disturbed sleep can adversely affect health, recovery and recuperation time in convalescing patients, with impacts upon cardiovascular, cognitive, psychological and immune systems (Hillman, 2021). Control of unwanted noise intrusion and propagation in hospitals is of critical importance, though there are significant challenges in providing good acoustic control in areas requiring high cleanability or those used for differing activities of distinct sensitivity obligations (Clarke, 2011). Mitigating factors affecting external noise control within hospitals are varied and far-reaching, from mechanical and other service penetrations, infections insulation, high-load plant equipment installed on the rooftop (or within the structure) along with the significant vibration factors they represent (Clarke, 2011). A case study conducted by Evans J., B (2003) highlights the considerable acoustic, vibro-acoustic and structural load constraints and energy that MRI equipment displaces within a healthcare facility. Results presented in the study outline design considerations in achieving strict allowable floor criteria presented in manufacturer's technical documents (SIEMENS) including, structural stiffness and strength, and slab and continuous ambient resonant frequency.

3 ACOUSTIC AND VIBRATION DESIGN OBJECTIVES

3.1 Helicopter Noise Intrusion Criteria

Helicopter operations exhibit noise characteristics that are not comparable to those of fixed-wing aircraft during flyovers, displaying a collection of acoustic characters relating to blade rotation (tail and rotor), mechanical exhaust and body interactions emitted over multiple axes. Additionally, emergency medical helicopter operations are distinct from fixed-wing aircraft operations in periodicity and path, as they can take place at any hour, don't follow a strict flight pattern, and likely to operate in close proximity to hospital façades. Consequently, the criteria for managing noise associated with emergency medical helicopter operations differ from those applicable to fixed-wing aircraft (NSW Health - Engineering Services Guide 2022). The level of noise at a building façade due to helicopter take-off and landing operation will vary depending on the frequency of helicopter movement, duration and type of the event including landing, engine idle, engine shut down, engine start, take off etc. Therefore, a conservative or measured noise level should be used for acoustic design of the building. To provide an indoor acoustic comfort in relation to helicopter noise in Hospital building, NSW Health – Engineering Services Guide 2022 recommends the following internal noise level criteria to be considered for a new redevelopment, specially where helicopter movement is frequent.

Table 1 NSW Health – Engineering Services Guide 2022 Helicopter noise intrusion criteria

Space Use	Recommended Internal Noise Levels, LAmax dB(A)
Private Offices, Meeting Rooms	70
Open Plan Office	75
Corridors and Lobbies, Reception and Waiting areas	80
Consulting rooms, Interview and Counselling Rooms	65
Single Patient Bedroom	68
Multi Bedroom	68
Cafeteria/Dining	80

It is important that façade design should be developed carefully providing a balance between the control helicopter noise and the ambient noise at the project site, such that the façade is not overdesigned and it does not leave the patient having a feeling of isolation during typical time of the day without helicopter. As noted by James et el. (2012) facade design to control incident helicopter noise levels will most likely over-perform against more common yet quieter external events such as road traffic, thus removing a potentially useful source of sound masking and may adversely affect the indoor soundscape. The paper concluded that setting a maximum limit of LA_{max} 65dB for control of helicopter noise is considered appropriate for wards and sensitive spaces. The acoustic criteria provided in NSW Health – Engineering Services Guide 2022 are found consistent with this recommendations.

3.2 Building Vibration Criteria

Human response to floor vibration motion is a complex phenomenon, the wide variations in vibration tolerance and accordingly the acceptance criteria for human comfort are difficult to define and quantify. Acceptable level of human exposure to vibration are primarily dependent on functional use of the occupied space (e.g., office, residential, operating theatre, hospital bedrooms and sensitive equipment area etc.) and the character of the vibration (e.g., continuous or intermittent). In addition, specific values are also dependent on social and cultural factors, psychological attitudes, expected interference with privacy, and ultimately the individual’s perceptibility.

Structural vibration from plant rooms, below the inpatient facility has the potential to adversely affect critically ill patients in the hospital. Therefore, the new building structure must be designed to achieve appropriate levels of low frequency noise and vibration to minimise such adverse effects. ISO 10137 and AS ISO 2631 provides recommendations on the evaluation of serviceability against vibrations of buildings, and walkways within buildings or connecting them or outside of buildings. A base curve marks the threshold of human perception and is defined in one-third octave bands from 1 Hz to 80 Hz. Vibration levels below the base curves typically do not result in adverse comments or complaints from occupants. The vibration criteria for different occupancy types are obtained by multiplying the base curve by a factor. Multiplying factors for different occupation types are listed in Table 2.

Table 2 Multiplying factors for satisfactory magnitudes of building vibration

Room Type	Multiplying Factor (R)	
	Continuous or Intermittent Vibration	Impulsive Vibration excitation with several occurrences per day
Critical working areas (for example some hospital operating-theatres, some precision laboratories)	1.0	1.0
Residential	2.0 to 4.0 (Day)	30 to 90 (Day)
	1.4 (Night)	1.4 to 20 (Night)

The ASHRAE curves include workshop, office, residential, operating room and VC curves for sensitive equipment. Velocity vibration criteria curves (RMS) defined in one-third octave frequency bands range 8 to 80 Hz are shown in Table 3. Guidelines for human comfort for continuous and impulsive vibration within a building are provided by NSW Department of Environment and Conservation (DECC) – Assessing Vibration: A technical guide (February 2006), as presented in Table 4 below. Intermittent vibration is assessed using “vibration dose” which relates vibration magnitude to exposure time. Guidelines for human comfort for intermittent vibration are also provided by NSW DECC, as presented in Table 5 below.

Table 3 Acceptable vibration dose values for intermittent vibration

Location	Assessment Period	8 to 80Hz Curve mm/s
Residential	Day – or Night time	0.140
Hospital operating rooms and critical work areas	All	0.102

Table 4 Preferred and maximum weighted values for continuous and impulsive vibration (Z Axis) (NSW DECC)

Location	Assessment Period	RMS velocity (mm/s)		RMS acceleration (m/s2)		Peak velocity (mm/s)	
		Preferred	Maximum	Preferred	Maximum	Preferred	Maximum
Continuous Vibration							
Residences	Day	0.20	0.40	0.010	0.020	0.28	0.56
	Night time	0.14	0.28	0.007	0.014	0.20	0.40
Impulsive Vibration							
Residences	Day	6.0	12.0	0.30	0.60	8.6	17.0

Location	Assessment Period	RMS velocity (mm/s)		RMS acceleration (m/s2)		Peak velocity (mm/s)	
	Night time	2.0	4.0	0.10	0.20	2.8	5.6

Table 5 Acceptable vibration dose values for intermittent vibration

Location	Vibration Dose Values (m/s1.75)			
	Daytime (7am – 10pm)		Night-time (10pm – 7am)	
	Preferred	Maximum	Preferred	Maximum
Critical Areas, hospital operating theatres and precision laboratories where operations are occurring	0.1	0.2	0.1	0.2
Residences	0.2	0.4	0.13	0.26

4 FIELD MEASUREMENTS

The ambient noise environment at the project site was dominated by existing mechanical plant surrounding the building and the large mechanical plantroom located on the Level 4 of the building (just below the roof slab of the subject site). Therefore, noise and vibration measurement were crucial to understand the existing noise and vibration environment and consider these factors in building design. Attended noise and vibration measurements were conducted at various locations around the project site to determine the ambient noise profile and impacts to the development via airborne & vibration sources.

4.1 Mechanical Plant Noise Level

A total of 15 measurements were conducted at different locations, along the perimeter of the project site. Each measurement was conducted for a period of 15-minutes. Noise levels at different locations ranges between 61 and 73 dB(A) and is dominant by mechanical ventilation noise. The octave band noise spectrum of the measured data shows that the dominant frequency of noise contribution is between 63Hz to 1KHz. Noted that the attended noise measurements were mostly dominated by HVAC plant and equipment noise, no helicopter noise was measured during attended measurements. Unattended background noise monitoring was conducted (at the centre of the proposed site) for a period of 7 days to establish existing background noise levels at the development site. Measured noise data was processed in accordance with Noise Policy for Industry 2017 to establish the Rating Background Level (RBL). It was obvious from the measurements that both the background and ambient noise levels were dominated by HVAC plant noise and are approximately same throughout day, evening or night at the measurement location (58 to 60 dB(A)).

4.2 Helicopter Noise Level

For patient transfer, emergency helicopters would be flying frequently (at least one helicopter per day) over the proposed inpatient facility. Although, the helipad is located approximately 40m above the project site on the rooftop of adjacent building, the helicopter take-off and landing noise is likely to cause significant impact on the façade of the proposed development. Based on the helicopter movement log during the measurement period, the following noise level of the Airbus H145 twin-engine rotorcraft helicopter was measured during the unattended noise measurement period.

Table 6 Measured Helicopter noise level at the proposed development site (L_{max})

Noise Source	Octave – Band Centre Frequencies (Hz) Sound Power Level, dB									Total, dB(A)
	31.5	63	125	250	500	1000	2000	4000	8000	
Helicopter Noise	98	98	99	102	100	95	89	83	92	101

4.3 Vibration Measurements

Attended structural vibration measurements were conducted at various locations of the project site (roof slab of mechanical plant room) to assess the existing structure-borne noise and vibration. Measured acceleration and velocity vibration data were recorded over a representative time. Seismic accelerometers were mounted to the existing concrete floor above the plant room at different locations. A summary of the measured vibration levels at some critical locations are provided in Figure 1 to Figure 3 below.

According to the vibration results presented above, the vertical responses confirm a frequency peak at 26Hz, 50Hz, 100Hz, 150Hz and 250Hz which is related to the operational frequency of the rotating mechanical services such as such as generators, pumps and AHUs, just located in the plant room below. The one-third octave band velocity levels are presented in Figure 1 showing an exceedance at approximately 80-100 Hz at Location 1.

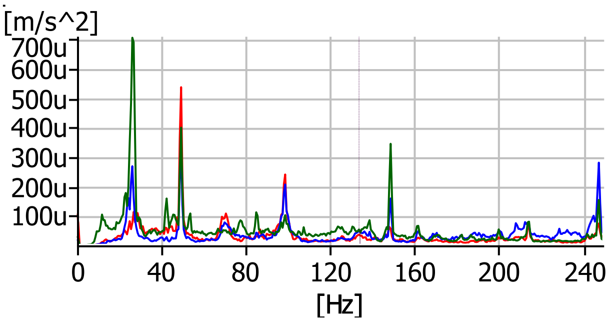

Figure 1 FFT acceleration spectrum at Locations 1 to 3

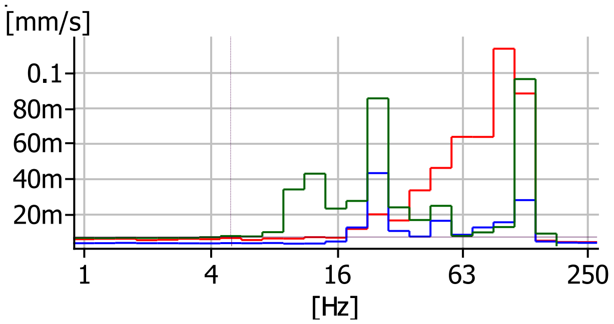

Figure 2 One-third octave band velocity spectrum

In parallel with the vibration measurements, the structural audio of the existing concrete floor was also recorded, confirming that the concrete floor radiates low frequency noise due to the plantroom below. It was therefore considered that there is a potential risk of structure-borne low frequency noise that may impact the proposed development area and would require adequate structural isolation of the new sleeping areas in order to mitigate external vibration ingress.

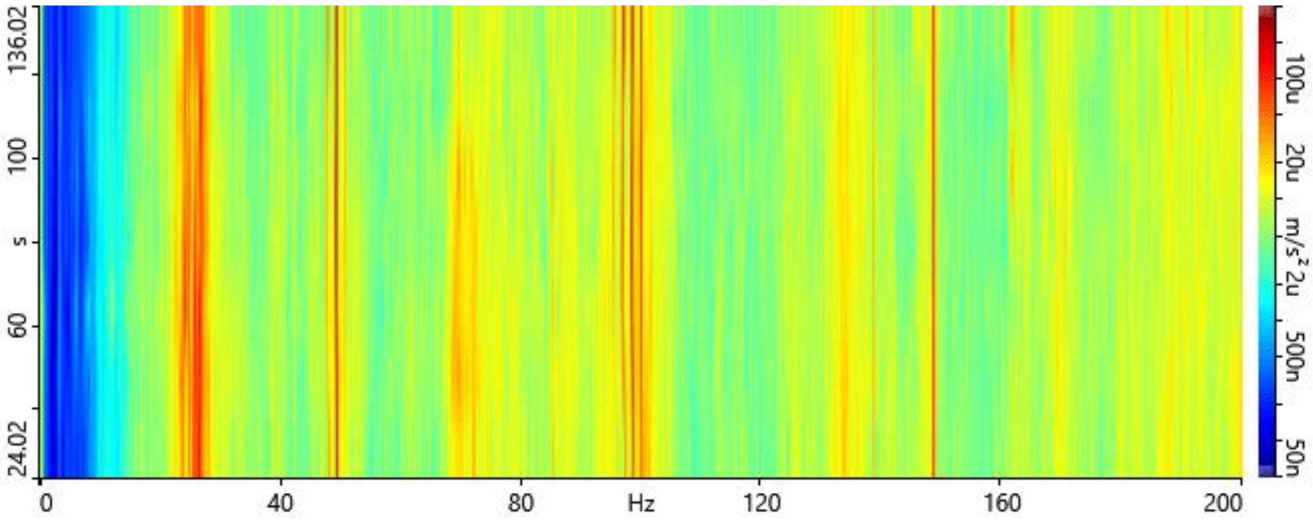

Figure 3 – FFT Auto spectrum Vs Time

5 ACOUSTICS AND VIBRATION DESIGN CONSIDERATIONS

5.1 Acoustic Design of Building Façade

Due to the high ambient noise level which is dominated by low frequency mechanical plant noise throughout the day and night and significant helicopter noise level, it is important that the façade is designed such that it not only reduces the overall noise level, but the low frequency external noise level is also considerably reduced with appropriate design and selection of building materials. Due to cost effectiveness, construction time, efficiency of construction and sustainability considerations, lightweight construction is often preferred which are not great in providing sufficient noise reduction in low frequency. In such case, a cavity wall or roof ceiling and double-glazed unit system is often recommended. For external door, hinge door is preferred in such environment and sliding door is better be avoided. To achieve the internal noise level specifications for the building, minimum acoustic rating of the external glazed window/partition should be approximately R_w+C_{tr} 38 to 40 dB which could be achieved through a double-glazed system comprising of Viridian 10mm VFloat, 16mm air gap and 10.5mm VLam Hush Glass or equivalent specification. External walls and roof-ceiling assembly should have a minimum specification of R_w+C_{tr} 45 to 50 dB. To achieve a higher rating of the roof-ceiling assembly, it is recommended that the roof-ceiling assembly should be of double cavity system.

5.2 Floor Vibration Isolation

Mechanical plant and equipment generate low frequency noise and vibration which could be transmitted through the structure from level below. Considerable resonance effects may take place in the higher storeys, specially slabs and walls are frequently excited to near resonance. The fundamental frequency of these elements lies between 10 and 25Hz and are particularly sensitive to this excitation.

To minimise structure-borne noise and vibration into the proposed structure, located just above the plant room, a base isolation system could become a practical strategy for vibration isolation. Therefore, it is recommended to decouple the existing concrete columns or other structural connection from the proposed lightweight floor using an elastomeric point bearing solution such as polyurethane or natural rubber. Alternatively, a lightweight floating floor implementing steel spring isolators between both structures could potentially reduce the risk of structural vibration transmission.

Basically, the isolation system introduces a layer of low stiffness pad between the proposed floor and the existing columns or concrete floor. These types of systems are also very effective solutions in reducing the perturbancy frequencies generated by building services such as generators, chillers, pumps, AHUs etc. The elastic properties of the vibration isolation elements are therefore of crucial significance to determine the effectiveness of vibration isolation in the low-mid frequency ranges. The isolation system should be sized to adequately support the weight of the new building structure at each grid location to avoid lateral movements to achieve desired bearing pressures. The choice of the type of system will require a careful study during the design detail stages.

It is critical to ensure that the only physical contact with the new building structure is via the elastomeric bearing or steel springs, i.e., there must be no rigid connection between both structures. The proposed isolation system with elastic point bearings should achieve 8-11Hz natural frequency by suitable choice of material and dimensions, while using steel springs should achieve 4-7Hz natural frequency. The use of stainless-steel plates underneath of the elastic point bearings are used to better distribute the forces within the point bearings. Additionally, this also increases the performance of the point bearings since the full extent of the shape-factor of the material can be utilized.

6 CONCLUDING REMARKS

Noise and vibration significantly influence the design of hospital facilities. This paper examines the essential factors related to helicopter noise and mechanical plant vibrations in the design of inpatient areas within a hospital setting. The noise generated by helicopters from a nearby helipad was identified as having high-intensity levels, presenting considerable challenges for façade design, particularly in areas where large glazing is intended to enhance the connection between outdoor and indoor environments for the benefit of patient well-being and recovery. It is imperative to carefully consider the selection of glazing materials and the management of high-magnitude, low-frequency helicopter noise, which can be challenging without sufficient data on helicopter movement noise. Additionally, structure-borne low frequency from mechanical equipment within the building were observed to have frequency peaks at 26Hz, 100Hz, 150Hz, and 250Hz, corresponding to the operational frequencies of rotating mechanical systems. The low-frequency noise generated by these mechanical systems in healthcare facilities is often underestimated. Analysis of recorded vibration signals indicates that the concrete flooring transmits low-frequency noise resulting from mechanical vibrations originating from the plant room below. Consequently, there exists a potential risk of structure-borne and low-frequency noise, necessitating appropriate structural isolation measures to ensure patient comfort. In conclusion, external acoustic and vibration elements can present considerable obstacles to patient comfort and recovery if not adequately addressed during the design process. It is essential to conduct thorough data analysis and implement effective design strategies to recognize significant noise and vibration effects, subsequently mitigating them to foster a supportive auditory environment conducive to patient healing and comfort.

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