Vibration Criterion Curves – Part 2: Application to Transients

Aaron Miller (1)

(1) Acoustic Studio, Sydney, Australia

Abstract – Part 1 of this paper explains the evolution of VC curves and summarises the most recent guidance. for medical and scientific research facilities containing sensitive equipment such as optical and electron microscopes that require a more stringent vibration criterion than human comfort thresholds, provided in the IEST’s Recommended Practice (RP) 201.1. Part 2 focusses on the specific challenge of applying VC curves to transient events.

The guidance summarised in Part 1 is clear about how ‘steady-state’ vibration should be assessed against VC curves but the question of how to quantify and assess the impact of transient vibration is particularly challenging and has not been fully resolved. In some cases, equipment suppliers and/or users can guide the assessment of transient vibration; however, in most cases, they cannot.

This paper draws on recent guidance to address the questions frequently faced by practitioners when attempting to assess transient vibration against VC curves in the absence of guidance from equipment suppliers and/or users, such as integration times, how one-third octave band levels should be derived, time weightings and applicable locations. It recommends a benchmarking approach to determine the disruption tolerance of existing sensitive equipment and processes, using statistical techniques. Collating these benchmarks across a wide cross-section of facilities and equipment may allow for disruption tolerance thresholds to be determined in the future.

1 INTRODUCTION

Part 1 of this paper explains the evolution of VC curves and summarises current guidance on interpretation and application of the curves to medical and scientific research facilities containing sensitive equipment such as optical and electron microscopes that require a more stringent vibration criterion than human comfort thresholds, drawing on the most recent guidance in the IEST’s Recommended Practice (RP) 201.1 (WG-NANO201, 2024).

This paper focusses on the specific challenge of applying VC curves to transient events, or ‘occasional disturbances’ referred to by (Amick et al., 2005) in situations where equipment sensitivity is prescribed in terms of VC curves but with no supporting commentary or guidance with respect to signal processing methods, or the importance that should be attributed to occasional disturbances. Advice should always be sought from equipment manufacturers and facility operators in the first instance, but this is often not available. (Amick et al., 2005) describe the challenge as follows:

> “In instances where the environment is impacted by occasional disturbances […], these may be evaluated in the “peak hold” or “maximum RMS” or “maximum hold” mode of the measuring system. If the disturbing event is long enough (i.e., “Quasi-static,” or steady-state during the averaging time, such as day vs. night comparisons), the linear average mode should be used. The importance attributed to these occasional events will depend upon the frequency of occurrence and other parameters relating to the vibration-sensitive process.”

The challenge of applying VC curves to transient events is noted in the ANC “Red Book” Measurement and Assessment of Groundborne Noise and Vibration (ANC, 2020), which is widely adopted in Australia, and notes that there is no definitive guidance on how to assess transient vibration against VC curves and recommends consideration of six questions. These are reproduced in Table 1 and are used in this paper as a framework for providing guidance based on (WG-NANO201, 2024) as well as other available sources. Some practical implications are also explored, where applicable.

Table 1 Questions from (ANC, 2020) and recommended approaches

Q1	Over what period of time is the rms velocity analysed?
A	An RMS integration time of 1s is recommended for monitoring. Average or peak-hold results for longer time periods can be derived from multiple 1s intervals. Assessment periods and monitoring durations depend on how the facility is used. This is discussed further in Section 2.
Q2	For transient events over a time period, should the average, worst case, or a percentile value be used?
A	A percentile approach is recommended, with consideration of disruption tolerance. See Section 3.
Q3	How should the 1/3 octave band levels be derived, using digital filters or by processing from narrow band FFT data?
A	Narrow band FFT data should only be used for stationary / steady signals, as discussed in Section 4.
Q4	What time weighting should be applied?
A	No time weighting is applicable, see Section 5.
Q5	At which location should the specifications be set?
A	Adjacent to the equipment where vibration amplitudes are expected to be highest, see Section 6.
Q6	Is the frequency spectrum evaluated for an event peak hold or maximum RMS value, linear average, the average spectrum for the highest overall magnitude of vibration etc.?
A	The answers to questions 1 and 2 address this.

2 TIME PERIODS OVER WHICH RMS VELOCITY IS ANALYSED

The question “Over what period of time is the rms velocity analysed?” can be interpreted in a variety of ways when considering transient events. This paper considers the four time periods described below:

- Integration time: the time period over which an RMS is calculated from the underlying waveform. The blue line in Figure 1 shows the RMS calculated using an integration time of 1s.
- Event duration: the time period over which a transient event occurs (or can be detected above ambient vibration). In Figure 1, the vibration event emerges above ambient vibration between approximately 4s and 28s, with an event duration of 24s.
- Task duration: the time period over which a task being performed by a piece of sensitive equipment might be susceptible to vibration impacts. For example, a scanning electron microscope may capture an image in a few seconds, or may perform a scan over several hours. This is discussed further in Section 2.3.
- Averaging time: the time period over which linear average or peak-hold results are calculated.
- Assessment period: the time period over which vibration is assessed. For example, the day and night periods described in (Amick et al., 2005) are assessment periods.
- Monitoring duration: the time period over which vibration is monitored. For example, the monitoring duration shown in Figure 1 is 35s and the monitoring duration shown in Figure 2 is 1 hour.

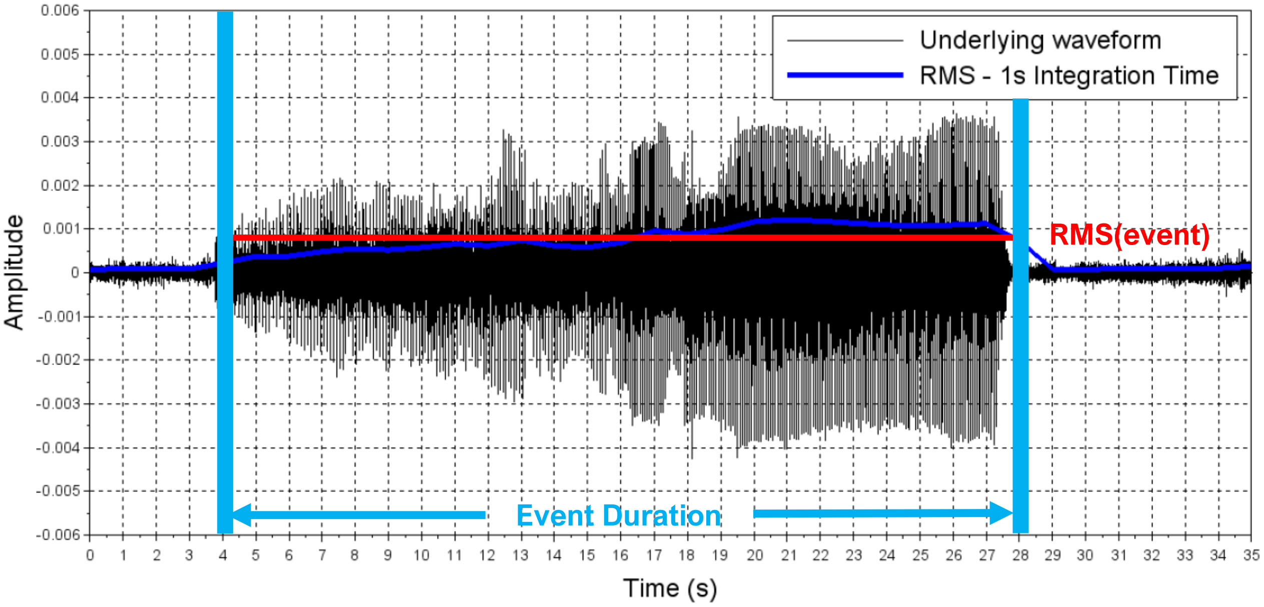

Figure 1 – An example transient vibration event. The RMS has been calculated from the underlying waveform using an integration time of 1s in blue. The RMS of the event has been calculated as the linear average of the 1s RMS values over the event duration in red.

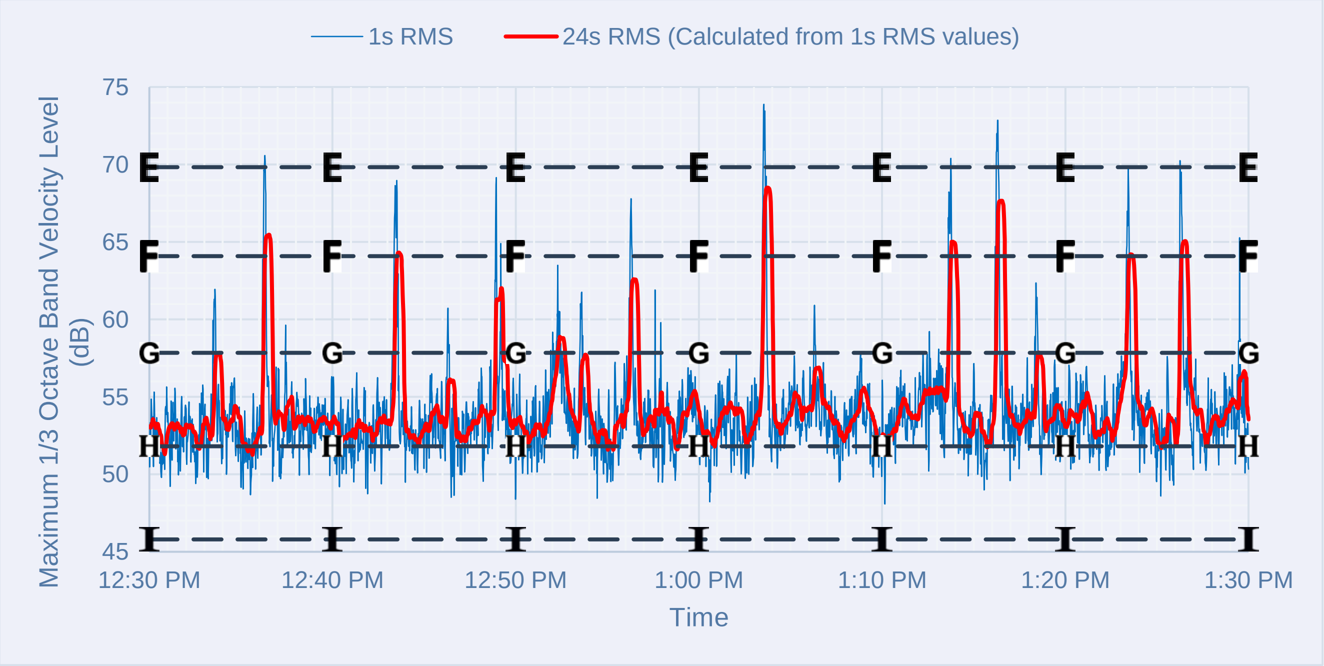

Figure 2 – An example of vibration monitoring with a one-hour monitoring duration, with VC curves shown as black dashed lines. The maximum one-third octave band RMS velocity has been calculated from the underlying waveform based on a 1s integration time (in blue). There are 9 events, each having an event duration of 24s. A running 24s RMS velocity, calculated by linearly averaging the 1s periods, is also shown in red.

2.1 Methods of Calculating RMS Velocity

Prior to discussing time periods, it is important to put these into context with respect to how the RMS velocity can be calculated. There are two equally valid methods of calculating the RMS velocity of a ‘disturbing event’ implied by (Amick et al., 2005):

Method 1: Use an integration time that is much shorter than the event duration. Then, set the averaging time to be the same as the event/task duration, and use linear averaging to calculate the RMS velocity.

Using Figure 1 as an example, the RMS velocity of the disturbing event could be calculated by taking the linear average of the 1s RMS values calculated between t = 4s and t = 28s – this is shown in red in Figure 1.

Method 2: Use an integration time that is roughly the same length as the event duration. Then set the averaging time to be longer than the event/task duration, and use peak-hold to calculate the RMS velocity.

Using Figure 2 as an example, the RMS velocities of the disturbing events (each with an event duration of 24s) could be calculated by taking the maximum values of the 24s RMS trace for each event. In this example, the averaging time over which the maximum values are obtained for each event is unimportant, provided that the maximum values remain attributable to the event. For instance, to calculate the peak-hold for the event at 1:13 pm in Figure 2, the averaging time should not include the events on either side at 1:03 pm or 1:16 pm, as these would change the maximum RMS for that event.

The commentary in (Amick et al., 2005) quoted in Section 1 assumes that Method 2 above is used for transient events, and Method 1 is used for steady-state vibrations; both methods implicitly incorporating an integration time that matches an event duration. This is why the linear average is specified by (Amick et al., 2005) for “day vs. night comparisons” - the integration time will inevitably be shorter than the assessment period, necessitating the use of linear averaging to calculate an RMS velocity over that assessment period. Similarly, the use of peak-hold for occasional disturbances, using the event duration as the integration time, matches the guidance in (WG-NANO201, 2024) that is summarised as follows in (Amick, 1997):

> “Vibrations from transient events, such as train passages, can be considered using time T that is less than or equal to the duration of the event.”

Train passby vibrations in Australia are often measured and predicted in terms of a slow-response Lmax, to facilitate predictions of ground-borne noise in accordance with the NSW Rail Infrastructure Noise Guideline (NSW Environment Protection Authority, 2013) as described in (Duschlbauer et al., 2024)[1]. Slow-response Lmax spectra can also be used for calculating eVDVs for the purposes of assessing human comfort (Miller et al., 2021), and aligns with the procedure for determining vibration impacts from the FTA manual (Federal Transit Administration, 2018). It is therefore also widely adopted for the assessment of vibrations against the VC curves (see (CBD and South East Light Rail Project, 2013) for an example). This approach differs from both methods described above, and effectively uses an integration time that is much shorter than the event duration to calculate a peak-hold spectrum.

2.2 Integration Times

The RMS velocity of steady-state vibrations over an entire assessment period is insensitive to integration time, as Method 1 requires the use of an integration time that is much shorter than the assessment period. Conversely, peak-hold values for transient events can be very sensitive to integration time (as shown in Figure 2, where the 1s RMS values for each transient event are roughly 5-6 dB higher than the 24s RMS values). There are two potential issues regarding the adoption of a 1s integration time when using peak-hold to calculate the RMS velocities of transient events:

---

[1] The RING is also often adopted in other states like Victoria and Western Australia in the absence of local or national guidance, and is borrowed from heavily in other states with prescribed ground-borne noise limits like South Australia and Queensland (see (Miller et al., 2024) for further details).

- A 1s integration time would be suitable for very short-term events like door slams, or gymnasium weight drops (as described in (Parker, 2021)) but would be too short to adopt as an event duration for longer events like train passbys[2], as it may result in the RMS velocities from these events being overestimated.
- In many circumstances, a 1s integration time might be unnecessarily conservative as an assumed task duration. This is discussed further in Section 2.3.

This paper recommends the adoption of 1s integration times for monitoring, and for calculating RMS velocities using Method 1 in Section 2.1, for the following additional reasons:

- It is noted in (WG-NANO201, 2024) that consideration of very short integration times is not practical without a detailed understanding of the item of sensitive equipment. It also reflects the commentary in (Amick, 1997) regarding response associated with events of very short duration:

  > "… many believe that rms averaging provides a more appropriate representation of how a tool will respond in most cases, depending on the averaging time involved. In one particular case … the client's project director … insisted that instantaneous representation *not* be used, because his studies had indicated that vibrations must be of significant amplitude when "integrated over a period of at least one second" (which corresponds to an rms averaging time T of one second) in order to affect his apparatus."

1s is therefore considered to be the minimum appropriate integration time. It is also the shortest integration time capability that is commonly available for one-third octave band analysers[3].

- It also allows for calculation of event RMS velocities using Method 2 described in Section 2.1, through post-processing. If necessary, 1s integration times can be combined into longer integration times, using Method 1. An example of this is shown in Figure 2, where the 1s integration times have been combined into 24s integration times in post-processing by taking a linear average over an averaging time of 24s.
- It can assist in determining appropriate event durations for various types of transient events. It also allows for any extraneous vibrations[4] (or the transient events themselves, if they are already present in the monitoring and it is desired to quantify the environment in their absence) to be removed precisely.

As noted above, it is appropriate to use a 1s integration time for short-term events (i.e less than 2s in duration), and to evaluate these using peak-hold over some averaging time. In this circumstance, the averaging time used should be sufficiently long to account for the response time of the one-third octave band filters to impulsive events, particularly at low frequencies (Mercer, 2013). This also applies to task durations (described in Section 2.3) of less than 2s.

2.3 Event Durations and Task Durations

The commentary and examples in Section 2.1 primarily consider the event duration. This is appropriate in circumstances where the event duration is shorter than the task duration. There may also be circumstances where the task duration is shorter than the event duration – in these circumstances, it would be appropriate to use the

---

[2] It might be appropriate for train passbys that produce large instantaneous vibration levels, such as over joints.

[3] Many sound level meters that also provide vibration meter capability are limited to recording LZeq one-third octave band spectra at 1s intervals or longer.

[4] Extraneous vibrations in this paper refer to vibrations created by performing the measurements, such as vibrations associated with the field technician operating the measurement equipment, or the settling of digital filters. This does not include things like door slams that would occur as part of normal operations of the facility.

task duration instead. If Method 1 is used to evaluate RMS, the averaging time would be set to the task duration. If Method 2 is used to evaluate RMS, the integration time would be set to the task duration.

For example, a scanning electron microscope may capture an image in four seconds. If the event duration is 24s (like in Figure 1), it would be more appropriate to evaluate the RMS velocity over the four seconds in which the image is captured (i.e the task duration) – the other 20s are not relevant.

The same scanning electron microscope, used in a different mode of operation, might also capture an image over several hours. A vibration event occurring over four seconds (or less) might therefore only affect one pixel[5] of thousands or millions, or ruin the image entirely. Such information is rarely forthcoming from equipment manufacturers and facility users, which can make it difficult to determine what an appropriate task duration might be. This difficulty often results in the task duration being conservatively assumed to be 1s with the intention of protecting against short-term events.

(WG-NANO201, 2024) suggests that where there is no information available, that a task duration of 30s is not unreasonable. It also comments that equipment sensitivity might be a function of time, and that particular tasks might be less sensitive to very short duration inputs compared to sustained inputs of the same level. This suggests that adopting a 1s task duration (that would then control the calculation of RMS velocities) might be unnecessarily conservative in many circumstances.

2.4 Assessment periods

In the authors' experience, many medical centres and imaging facilities will only operate during standard business hours on weekdays. Conversely high technology facilities can be used 24 hours per day, and may get used for different activities during the night-time and on weekends, compared to weekdays when the facilities and supporting buildings are generally more occupied. It might therefore be appropriate to have the following four assessment periods, where operations (or ambient vibrations) are known to differ between these periods: weekday – daytime, weekday – night-time, weekend – daytime and weekend – night-time[6]. The precise assessment periods should be facility specific and guided by monitoring where available.

2.5 Monitoring duration

Monitoring of ambient vibrations should cover at least one of each relevant assessment period in its entirety – this is discussed further in Section 3.1. When quantifying transient events (as described in Section 3.2), monitoring only needs to occur for sufficient time to characterise that event type: for instance if a transient event occurs many times per day, then one or two hours of monitoring might be sufficient. Conversely, an infrequently occurring event might require one or more assessment periods to characterise. More guidance regarding monitoring durations is provided in (WG-NANO201, 2024) and (Amick & Gendreau, 2005).

3 ASSESSING TRANSIENT EVENTS AGAINST VC CURVES

On face value, comparing vibration from transient events to VC curves is straightforward:

- Evaluate the RMS velocities using either Method 1 or Method 2 described in Section 2.1, and compare these to the VC curves. Using the 24s RMS values in Figure 2 as an example, there are three transient

---

[5] The term 'pixel' here is used as an analogy, where the output of the machine might be visualised as an image. This terms might not describe the outputs of these machines with technical precision.

[6] It is common practice in NSW to have a separate evening period in the context of environmental noise. It is recommended that such an evening period is incorporated into a daytime or night-time period as appropriate, unless there is a compelling reason to have a separate evening period.

events that clearly exceed VC-F and four more that marginally exceed VC-F, but are within the 1 dB range of tolerance described in (Amick et al., 2005):

> "It is generally accepted that vibration measurements are accurate and repeatable only within about 1 or 2 decibels (12% or 26%), so an overly strict interpretation of a comparison with the criteria is not encouraged."

- Determine how often this event occurs. Using Figure 2 as an example, there are 3 events that clearly exceed VC-F, and 9 events that clearly exceed VC-G. Each event is 24s in duration. This would mean that VC-F is exceeded for 72s every hour (or 2% of the time), and VC-G is exceeded for 216s every hour (or 6% of the time). An alternative way of expressing this is over a daytime assessment period of 15 hours: VC-F is exceeded 45 times per day, and VC-G is exceeded 135 times per day.

If the prescribed VC curve for the equipment is VC-E or higher, then the transient events (applying an event duration of 24s, and ignoring task duration) would be deemed to be compliant with the criterion. Where this becomes tricky however, is if the prescribed VC curve is VC-F or VC-G. As noted in (Amick et al., 2005): "The importance attributed to these occasional events will depend upon the frequency of occurrence and other parameters relating to the vibration-sensitive process."

For example, if a piece of sensitive equipment performs a task for 30s at a time, and it is operated roughly at 10-15 minute intervals, then it is very unlikely that the transient events shown in Figure 2 will interfere with these tasks, and VC-F being exceeded 2% of the time might be perfectly acceptable. On the other hand, if the sensitive equipment performs a task for 15 minutes at a time, and a 24s excursion above VC-F could ruin the task, then the transient events shown in Figure 2 would be unacceptable. The first example suggests the task is entirely tolerant of disruption from the transient events, whereas the second example suggests the task is not tolerant to disruption from the transient events at all. In many cases, this information regarding disruption tolerance is often not forthcoming, and a determination of compliance is unable to be made with any certainty.

This would also be further complicated if the task duration became controlling, such as conservatively assuming a task duration of 1s. Looking at the 1s RMS values from Figure 2, VC-E is also clearly exceeded on two occasions. If the prescribed VC curve for the equipment is VC-E, the disruption tolerance of the equipment again needs to be considered.

This raises two key questions, in the absence of supporting information:

1. What is the disruption tolerance for these items of equipment?
2. What is the appropriate task duration? Is a 1s task duration unnecessarily conservative?

The following methodology is recommended that can provide some insight into both of these questions. It comprises two stages: benchmarking the disruption tolerance of the equipment, and assessing future transient events against those benchmarks. Benchmarking the disruption tolerance involves measuring and quantifying the existing vibrations that facilities and items of sensitive equipment are exposed to. The general premise is that if a prescribed VC curve is exceeded some percentage of the time, and the facility users can tolerate those disruptions – then that disruption tolerance becomes the benchmark against which the future transient events are then assessed. This disruption tolerance will depend on the event duration / task duration used, and it is therefore prudent to benchmark the disruption tolerance (and subsequently assess the future transient events) against all of the event durations / task durations that might be applicable.

3.1 Benchmarking of disruption tolerance of sensitive equipment

The following methodology is recommended for benchmarking the disruption tolerance:

- One-third octave spectra are measured at 1s intervals over at least one of each relevant assessment period in its entirety[7], further details are provided in Section 4. 1s intervals are recommended for the reasons described in Section 2.2.
- Any periods containing extraneous vibrations are removed, and detailed notes should be kept around the types of events that occur at certain times, to facilitate the interpretation of the percentile spectra[8].
- Percentile spectra are calculated for each applicable event duration and task duration, and for each relevant assessment period. Using Figure 2 as an example, percentile spectra could be calculated using 1s intervals and 24s intervals.
- The percentile spectra should then be used to determine how often the various VC curves are exceeded, in the absence of the transient events. This could be presented along the lines of: “VC-A is exceeded 0.1% of the weekday, VC-B is exceeded 0.5% of the weekday” etc. These would then become the benchmarks for disruption tolerance. These benchmarks will of course be different for each applicable event duration / task duration.

Additional detail and guidance regarding percentile spectra is also provided in (WG-NANO201, 2024) and (Amick et al., 2005).

This approach will not necessarily quantitatively capture all of the relevant details of the existing vibrations, particularly items that might be very relevant such as whether an existing source is intermittent throughout the monitoring period or continuous for a fraction of it, and whether the users were able to partially or completely tolerate that extent of disruption. It is important that details such as these are also captured qualitatively.

It is also important to differentiate between disruption tolerance benchmarks and disruption tolerance thresholds. For instance, a facility user might be satisfied with a disruption tolerance benchmarked at 2%, and dissatisfied with a disruption tolerance benchmarked at 10%. The disruption tolerance threshold, at which the perception of the facility users changes from being satisfied to dissatisfied, might be anywhere in this range. Qualitative user feedback may assist in understanding the likely disruption tolerance threshold.

3.2 Assess future transient events against the benchmarks for disruption tolerance

The RMS velocities of the future transient events and how often they occur would be calculated as described in Section 3. The acceptability of the future transient events would then be determined based on whether they exceed the prescribed VC curve for the equipment (and, where appropriate, the less stringent VC curves[9]) more frequently than the benchmarks for disruption tolerance. The intervals used in the ambient vibration percentile spectra should match the task / event durations of the transient events.

For instance, if the prescribed criterion is VC-F, and the future transient events exceed VC-F for 2% of the daytime period, but the disruption tolerance has already been benchmarked as exceeding VC-F for 5% of the daytime period, then the future transient events would likely be acceptable. However, if the disruption tolerance has been

---

[7] (Gendreau & Amick, 2005) suggests sampling periods of 30 minutes for calculating percentiles while (WG-NANO201, 2024) suggests a typical 8-hour workday. This conflicts with many other standards which suggest three or more assessment periods. Some judgement should be applied depending on the observed or likely variability of vibration within the space.

[8] In addition to future transient events, it is also possible to assess transient events that already exist, if these transient events are also excluded from the measurements used to perform the benchmarking of the disruption tolerance.

[9] Using Figure 2 as an example - if the prescribed VC curve is VC-F, for instance, it might be appropriate to compare the future transient event using a 1s equipment duration to the disruption tolerances for both the VC-E and VC-F curves.

benchmarked to only exceed VC-F for 0.1% of the daytime period or not at all, it then presents a risk that the disruption tolerance threshold might be exceeded.

Benchmarking of individual pieces of sensitive equipment will only be relevant to that particular item of equipment in that facility. However, if enough equipment / facilities can be benchmarked, then some trends may be able to be observed, that could then potentially be used to quantify likely disruption tolerance thresholds. A consistent adoption of 1s intervals for benchmarking will assist in collating these trends; this will be discussed further in a future publication.

4 DERIVATION OF ONE-THIRD OCTAVE BAND LEVELS

(WG-NANO201, 2024) clarifies explicitly how the one-third octave levels should be derived. This can be summarised as follows:

- One-third octave band spectra for transient events should be quantified directly from time-domain input using digital (or analog) filters.
- Processing a one-third octave spectrum from a narrow-band spectrum is permissible for steady-state environments.

This is because there are errors associated with converting between the different bandwidths: these are quite small for steady-state signals, but can be significant for transient signals.

5 TIME WEIGHTING

Since vibration is often quantified in terms of slow-response Lmax (as described in Section 2.1), it is an intuitive assumption that an exponential time-weighting filter (such as slow-response) might be applicable in the context of VC curves.

AS/NZS IEC 61672.1:2019 defines the time-weighted sound level, which is calculated on the basis of the "root-mean-square sound pressure being obtained with a standard frequency weighting and standard time weighting". This differs from the specific definition of RMS in (WG-NANO201, 2024), which does not include frequency weighting or time weighting and aligns with how RMS is defined in (Amick, 1997), from which the equation for RMS amplitude is reproduced below:

$$rms\ amplitude = v_{rms} = \left[\frac{1}{T}\int_0^T x^2(t)\ dt\right]^{1/2} \tag{1}$$

(Amick, 1997) also notes that "If the average is taken over a significant time period, then it is quite common to refer to this as the *equivalent* level, Leq". This definition ultimately matches the definition of "equivalent continuous sound level" from AS/NZS IEC 61672.1:2019 (when expressed in linear units (i.e mm/s) rather than decibels), which explicitly precludes the involvement of time weighting. Finally, in the context of integration times longer than 1s, the inclusion of a time-weighting would be nonsensical. Therefore, in summary, no time weighting should be applied.

6 APPLICABLE LOCATION

(WG-NANO201, 2024) indicates the equipment criteria applies to "a floor or site", and the criteria takes into account the fact that certain types of equipment are supplied by the manufacturer with built-in vibration isolation. It is therefore clear that vibration should be assessed on the floor, rather than on the equipment itself, which may be isolated from (or may amplify) the underlying floor vibrations.

Otherwise, (WG-NANO201, 2024) only provides brief guidance regarding measurement locations for existing equipment. Some additional clarity that aligns with (WG-NANO201, 2024) is provided in (Gendreau & Amick, 2005) who state that “the vibration environment may be characterized at the location of a tool using vibration data measured only at that location (or multiple locations within the footprint of that tool)”.

In the absence of specific manufacturer requirements, vibration would ideally be evaluated at each foot of the tool, or at multiple locations immediate adjacent to its footprint, and the maximum spectrum evaluated. In practice however this is not economical; it is recommended that monitoring occur at one location immediately adjacent to the footprint where vibration amplitudes are expected to be highest (i.e close to midbay) and evaluated at this location.

7 CONCLUSION

Some of the questions raised in the ANC “Red Book” (ANC, 2020) regarding evaluating transient vibrations against the VC curves are able to be resolved following the publication of (WG-NANO201, 2024), such as how the one-third octave band levels can be derived, and whether time weightings are applicable. However, not all questions were able to be resolved entirely. Two aspects of assessing transient vibrations against the VC curves remain unresolved:

- The disruption tolerances of various items of sensitive equipment (i.e how often can a prescribed VC curve be exceeded), and
- The time period over which specific tasks might be susceptible to vibration impacts (i.e the task duration).

It is therefore proposed that the disruption tolerances are benchmarked using appropriate task and event durations, in the form of percentile spectra. If enough equipment / facilities can be benchmarked, then some trends may be able to be observed, that could then potentially be used to quantify likely disruption tolerance thresholds.

REFERENCES

Amick, H. (1997, September/October). On Generic Vibration Criteria for Advanced Technology Facilities with a Tutorial on Vibration Data Representation. *Journal of the Institute of Environmental Sciences, XL*(5), 35-44. Retrieved from https://colingordon.com/research/on-generic-vibration-criteria-for-advanced-technology-facilities-with-a-tutorial-on-vibration-data-representation/

Amick, H., & Gendreau, M. (2005, March). Considerations regarding the appropriate timing for advanced technology facility vibration surveys. *Cleanroom Section*(25). Retrieved from https://colingordon.com/research/considerations-regarding-the-appropriate-timing-for-advanced-technology-facility-vibration-surveys/

Amick, H., Gendreau, M., Busch, T., & Gordon, C. (2005). Evolving criteria for research facilities: I - Vibration. *Proceedings of SPIE Conference 5933: Buildings for Nanoscale Research and Beyond.* San Diego, CA. doi:https://doi.org/10.1117/12.617970

ANC. (2020). *Measurement & Assessment of Groundborne Noise & Vibration* (Third ed.). Lavenham, Suffolk, UK: Association of Noise Consultants.

CBD and South East Light Rail Project. (2013). *Environmental Impact Statement - Volume 6 Technical Papers - Technical Paper 11: Noise and Vibration Impact Assessment.*

Duschlbauer, D., Allan, M., & Nelson, J. (2024). Statistical Properties of Train Vibration Spectra for Ground-Borne Noise Assessments. *Acoustics Australia*. doi: https://doi.org/10.1007/s40857-024-00334-y

Federal Transit Administration. (2018). *Transit Noise and Vibration Impact Assessment Manual Report N0. 0123.* Washington, D.C. Retrieved from https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/118131/transit-noise-and-vibration-impact-assessment-manual-fta-report-no-0123_0.pdf

Gendreau, M., & Amick, H. (2005). Maturation of the Vibration Environment in Advanced Technology Facilities. *Journal of the IEST, 48*(1). Retrieved from https://colingordon.com/research/maturation-of-the-vibration-environment-in-advanced-technology-facilities-4/

Mercer, C. (2013, January 28). *Reference frequency for third octave filters.* Retrieved from Prosig Blog: https://blog.prosig.com/2013/01/28/reference-frequency-for-third-octave-filters/

Miller, A., Hanson, D., & Menon, V. (2024). Railway Ground-Borne Noise in Terrace Houses: A Case Study. *Acoustics 2024.* Gold Coast, QLD, Australia.

Miller, A., McMahon, J., & Duschlbauer, D. (2021). Examining the use of eVDVs for rail vibration in NSW. *Acoustics 2021.* Wollongong, NSW, Australia.

NSW Environment Protection Authority. (2013). *Rail Infrastructure Noise Guideline.*

Parker, A. (2021). Gymnasium vibration isolation within a sensitive medical research building. *Proceedings of Acoustics 2021.* Wollongong, NSW, Australia.

Standards Australia. (2019). *AS/NZS IEC 61672.1:2019 Electroacoustics - Sound Level Meters - Specifications.*

WG-NANO201. (2024). *IEST-RP-NANO201.1 Measuring and Reporting Vibrations in Advanced-Technology Facilities.* Schaumburg, IL, USA: Institute of Environmental Sciences and Technology. Retrieved from https://www.iest.org/Standards-RPs/Recommended-Practices/IEST-RP-NANO201