Testing to Determine Allowable Vibration Limits at a Natural-History Museum in the Netherlands

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Fig. 1. Typical natural-history objects mounted on a commercial vibration-testing table. All photographs by W. (Bill) Wei, unless otherwise noted.

Object testing is critical for the establishment of vibration limits and mitigation methods for a "building-bound" natural-history collection.

Over the past decades, the effect of vibrations on valuable objects of art and cultural heritage has become a continued source of concern for museum professionals and collection managers. This concern has its origins in the increased handling and transport of popular and valuable works of art when they are on loan to other institutions.[1] More recently, concern has expanded to include the effect of vibrations on entire collections as a result of activities in and around museums and other cultural and historic collections.[2] Many museums and historic sites organize activities such as Nights at the Museum, which include rock concerts to attract younger visitors. Furthermore, many institutions are conducting major construction work, renovating and modernizing their exhibition and/or storage facilities, or being confronted with major construction work in their immediate vicinity.

Construction work near entire cultural-heritage collections poses a broader, though no more or less important, problem compared to the transport of individual valuable objects. There has been much work conducted on the effect of vibrations on the condition of historic buildings in which many museums are housed. However, the collections themselves are almost never considered. Many museums want to remain open during construction work, and some museums have their storage facilities at the same location. One solution for reducing the effect of vibrations is to temporarily move objects a safe distance away from the source of the vibrations.[3] However, this approach is often not possible when it comes to entire collections and exhibits. Furthermore, monitoring can be conducted only on the building itself, near the work and near the objects considered fragile.

Fig. 2. Naturalis Biodiversity Center, Leiden, the Netherlands, and its collection storage tower. Photograph by Hay Kranen, Sept. 19, 2019, https://commons.wikimedia.org/wiki/File:Naturalis-Leiden-2019-1.jpg.

One such situation was experienced by Naturalis Biodiversity Center in Leiden, the Netherlands. Naturalis is home to the fifth-largest natural-history collection in the world, with over 40 million objects ranging from large insect, bird, animal, and skeleton collections to ancient flora and bottled specimens of all sizes (Fig. 1). The storage facilities are housed in a 20-story building constructed during a renovation project in 1990, which is attached to the natural-history museum and the center's offices and laboratories (Fig. 2). This physical attachment became a problem when the center conducted more major renovation work in 2017 and 2018. In order to support the redesigned buildings, a support beam had to be attached through the side of the tower on the fourth floor. A collection the size of Naturalis's could not be moved elsewhere, so there were obviously serious concerns about the effect of vibrations from this heavy construction on the wide variety of objects in the collection. Of particular concern was the movement ("wandering") of objects and possible damage to them due to the vibration of older metal shelving on the floors near where the beam would be attached. The question that arose was what vibration levels would be acceptable for the duration of the work.

In order to answer this question, information on allowable vibration levels was required for the types of objects found in the collection. Although there has been considerable research into protecting objects from vibrations (and shock loading) in the past, it has been only recently that research has been conducted to determine at what vibration levels and duration objects will sustain damage, however that may be defined.[4] The recommended vibration levels were based primarily on experience and monitoring but very little actual object testing. This could be considered surprising, given that one needs to know what an object can withstand in terms of vibration loading before methods to reduce their effects can be developed.

This lack of data is especially true of objects that had been of "less interest" in vibration research but are of equivalent (though not financial) value: natural-history objects. In order to determine the allowable limits for the Naturalis construction, a limited set of vibration tests was therefore conducted in order to obtain an impression of what could happen to representative natural-history objects under vibration loading of the building. Of particular interest were the movement of objects on shelves, the rotation of insects mounted on pins, the vibration behavior of objects including resonance, and the stage at which damage might occur. The results of this testing and their use during the construction work are reported in this paper.

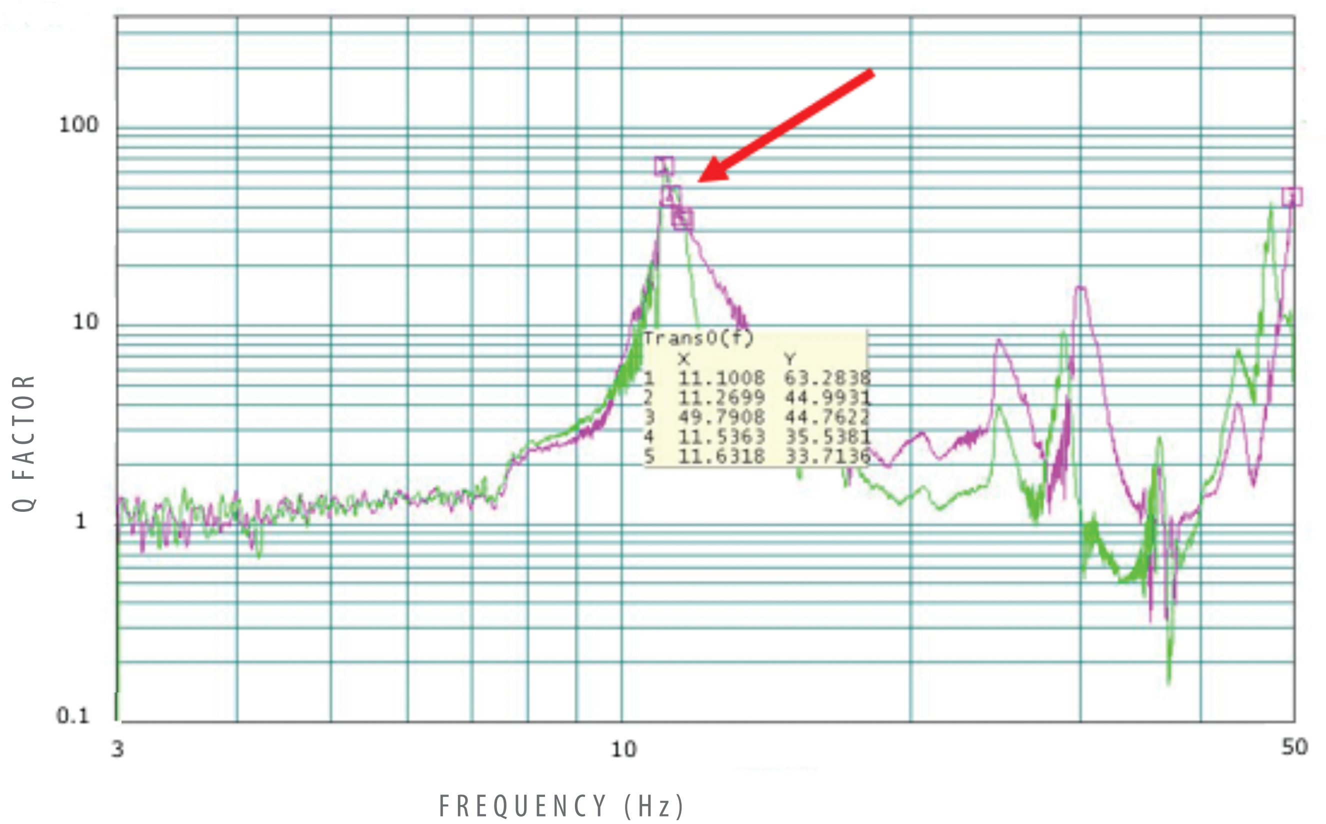
Experimental Procedure

Before continuing with this paper, it should be noted that the term "vibrations" used here refers to "high-frequency" (from roughly 2 or 3 to 100 Hertz [Hz] where 1 Hz is one cycle per second) cyclic loads, which can go on for long periods of time (minutes or days, weeks, or even years). In terms of construction work, this can include not only continuous vibrations caused by heavy truck traffic or heavy machinery but also those from lighter power tools used near objects of concern. Damage due to cyclic loading occurs cumulatively at stress levels below the material strength. It is virtually invisible at first, and final failure (however that is defined) occurs after a certain (large) number of cycles. Damage or failure will occur sooner (at a lower number of load cycles) for high levels of vibrations (cyclic loads) than for lower levels. The reader with an engineering background will recognize this failure process as "fatigue," which can be described with S-N (stress-number of cycles) curves or Wöhler diagrams.[5] The important concept to remember for this paper is that recommended vibration limits must be given as the combination of a vibration level with a duration.

Fig. 3. Objects on shelves for vibration testing.

Fig. 4. Metal shelving from Naturalis being placed on the vibration table. The shelving is not fixed to the vibration table, but side beams prevent it from wandering.

Fig. 5. Plot of Q factor versus frequency for shelves 3 and 5. The main resonance peak for both shelves is 11 Hz (red arrow).



Vibration-testing objectives. Vibration testing was conducted on typical objects provided by Naturalis. They included mounted birds and rodents, bird skeletons, mounted insects, bottled biological samples, two crystalline mineral samples, and a large fossilized tree branch with a powdery surface (see Figs. 1 and 3). Small, empty, plastic specimen boxes commonly used for storage were also tested, stacked two to three high (Fig. 3). The objective of the testing was to provide an indication of the input levels caused by the construction work that would not result in wandering of or damage to the objects in the vicinity. This information was used to determine vibration limits for the construction work.

Vibration-testing setup. Vibration testing was conducted on a commercial vibration-testing table operated by Sebert Trillingstechniek, B.V. The situation in the storage facility was simulated by placing typical shelving from Naturalis on the vibration table (Fig. 4). The shelves were not fixed to the vibration table, simulating the many freestanding shelves in the facility. However, metal side beams were placed against the feet to prevent the shelves themselves from wandering during testing.

The vibration behavior of the shelving with and without the objects was monitored using vibration sensors (accelerometers) attached to the center of shelves 3, 4, and 5, counting from the top. All vibration levels were measured in terms of peak particle velocity (PPV).

The resonance behavior of the objects themselves and the effect of vibrations on their condition were studied by placing them directly on the vibration table. As with the shelves, they were not fixed to the table. They were tested on pieces of white paper that were taped to the table to prevent them from wandering and to collect any material that might be lost.

Vibration-testing protocols. Vibration testing was conducted for the worst-case situation where objects would be in resonance. An object resonates at a particular frequency (resonant or eigen frequency) at an amplitude much higher than the input level of vibration. The resonant frequency is determined by comparing the vibration level of an object with that of the incoming vibrations as a function of frequency. This comparison is expressed in the form of Q factors, where

$$Q = \frac{\textit{vibration at a given sensor location}}{\textit{incoming vibration level}}$$

The resonant frequency is that at which the Q factor peaks; see, for example, Figure 5. This frequency is determined not only by the material properties of a particular object but also by its size, geometry, and weight. At resonance, the object would thus be expected to experience damage sooner than at the input vibration level.

Based on this concept of resonance, vibration testing was conducted in the following steps:

1. The resonance behavior of the shelves was determined first without, and then with, objects. This was performed by exposing the shelving to steadily decreasing input vibration frequencies from 50 to 3 Hz. This is the range of vibrations most critical when it comes to fatigue damage of objects due to vibrations. The input vibration level was kept constant at 2 mm/sec.
2. The resonant frequencies of the objects on the shelves were then determined, again decreasing the input frequency from 50 to 3 Hz. Because vibration sensors could not be attached to the objects, the frequencies at which particular objects began to resonate and/or wander were determined by eye with the help of members of Naturalis's collections-care staff.
3. Based on the results of the first two tests, the shelves with objects were vibrated at two frequencies close to those that were observed by the collections-care staff as having caused resonance of most of the objects. The vibration level at those frequencies was raised starting from 0.5 mm/sec. The vibration level at which particular objects began to wander was noted. This was found to be between 1.5 and 2 mm/sec.
4. The shelves with objects were then vibrated at the two frequencies at a level of 2 mm/sec for several minutes to provide an indication of the longer-term wandering behavior of the objects.
5. After tests one through four, the objects were checked for damage, or more precisely, the area on the shelves around the objects was checked for particles that fell from the objects. The objects were then vibrated directly on the vibration table in order to determine their resonant frequencies and to ascertain whether any further damage occurred for the short period of the tests.

Results

The results of the resonance testing of the shelves are shown in Table 1. A typical plot of Q factor versus frequency is shown in Figure 5 for shelves 3 and 5 without objects. The main resonant frequency for both shelves is 11 Hz, and there are secondary resonant peaks at 25, 30, and 50 Hz. The resonance behavior of all three shelves was similar, as shown in Table 1. The empty shelves showed a main resonant frequency of 11 Hz, which was up to 60 times the input level (Q factor of 60). Resonant frequencies were also observed at 25, 30, and 50 Hz, with the Q factor at 50 Hz also being fairly high (Q factor of 40). The shelves with objects on them resonated at similar frequencies but with lower Q factors. The main resonant frequency was slightly lower (8 to 9 Hz) than that for the empty shelves with Q factors up to 25.

The resonance behavior of the objects on the shelves is summarized in Table 2. There was considerable scatter in resonant frequencies for the different objects, and not all objects wandered at the 2 mm/sec input vibration level. The lightweight, empty specimen boxes wandered during the resonance testing, and several boxes fell off the stacks. However, a heavy bottle with a biological specimen also wandered. One small bird actually fell over, while others barely vibrated visibly. In spite of these differences, two ranges of resonant frequencies could actually be distinguished for all

Table 1. Resonant Frequencies of Shelving without and with Objects.

	Frequency (Hz)	Maximum amplification/Q factor
Empty shelves		
Main frequency	11	60
Other frequencies	25	9
	30	18
	50	40
Shelves with objects		
Main frequency	8–9	25
Other frequencies	25	5
	30	5
	50	5

Table 2. Summary of Resonance Behavior of Objects on Shelves (2 mm/sec input level).

Objects	Frequencies <10 Hz	Frequencies >30 Hz
Birds	Parts vibrate strongly	Parts vibrate visibly; small bird falls over
Bottles with fluid and biological specimens	Long cylindrical container begins to rock	Begin to wander
Minerals	No activity	Vibrates visibly
Plastic specimen boxes	Parts vibrate strongly	Begin to wander; some eventually fall off stack
Mounted rat	Rocks back and forth	Parts vibrate
Tree branch	Rocks lightly back and forth	No activity

Table 3. Effect of Input Vibration Level on Objects on Shelves.

Vibration level (mm/sec)	Frequency (Hz)	Object behavior
0.5	34	One bird turning on its stand
1.0	30–40	Plastic specimen boxes vibrate
	6–11	Plastic boxes and long cylindrical container visibly vibrate
1.5	32	Plastic boxes, smaller bottles, and long cylinder wander
	6–11	Birds turn on stands; plastic boxes and tall cylinder wander
2.0	various 6–32	All objects rocking; most wandering

objects: those roughly under 10 Hz and those above 30 Hz. These ranges correspond to the range of resonant frequencies found for the shelving with objects, as seen in Table 1.

Testing at various vibration levels in the two frequency ranges showed that some objects, the plastic specimen boxes, and some of the bottles began to wander at input vibration levels of 1.5 mm/sec but then stopped (Table 3). At 2 mm/sec, all of the objects except the mounted rat and the tree branch had wandered to a new position on the shelves.

A comparison of the vibration behavior of some of the objects on the shelves and on the vibration table itself is shown in Table 4. It can be seen that the objects show less vibration on the table at an input level of 2 mm/sec than on the shelves. Some objects vibrated at frequencies similar to those observed on the shelves, but most vibrated only very slightly. Of particular interest, in fact, is that strong resonance as seen on the shelves did not occur directly on the table until input levels close to 20 mm/sec, as seen in Table 5.

Discussion

The results of the vibration testing show that the objects on the shelves began to resonate and wander at input vibration levels of 1.5 to 2 mm/sec (Tables 2 and 3). Based on the measurements of the vibrations of the shelves themselves, the objects were actually wandering at levels much higher, between 15 and 40 mm/sec. When the objects were tested directly on the vibration table, resonance and wandering were not visible until input levels of 20 Hz. The resonant frequencies observed for the objects on the vibration table were similar to, but not always the same, as those measured for the shelves. This combination of results indicates that the resonance and wandering behavior of the objects on the shelves is determined in large part by the resonance of the shelves themselves.

The amplification of the input vibrations by the shelf construction resulted in significant wandering of objects on the shelves, including small specimen

Table 4. Comparison of Vibration Behavior of Objects on the Shelves and Directly on the Vibration Table (at 2 mm/sec input level).

Objects	Behavior on shelf (Hz)		Behavior on table	
Bird (large)	6–8 26 45	Rocking Wandering Resonance	8–9	Resonance
Bird skeleton	26	Wandering	19, 27	Light resonance
Long cylindrical container	8–11 32	Rocking Wandering	—	No activity
Mineral	27	Wandering	—	Light vibration
Mounted rat	8 17–20	Rocking Parts vibrate	4–22	Light resonance
Tree branch	16	Rocking	13	Slight vibration

Table 5. Effect of Table Vibration Level (mm/sec) on Resonance of Objects.

Objects	2	5	10	20
Birds	Light	Parts of birds	Strong	Strong, wandering
Bird skeleton	Light	Light	Beak	Strong
Insects in case	No activity	Labels vibrate	Labels vibrate	Insects vibrate
Long cylinder	No activity	Medium	Medium	Strong
Mineral	No activity	Light rocking	No activity	No activity
Mounted rat	Light	No activity	Medium	Rocking
Tree branch	Light rocking	Light rocking, loss of bits of dust	Loss of bits of dust	Continuous loss of dust

boxes falling off of stacks of such boxes. However, no damage was found for the objects during the various tests, except for a small loss of "dust" particles from a large historical tree branch and from minerals that lay in direct contact with the vibration table.

Based on these results, an input vibration limit of 1.5 to 2 mm/sec was recommended for the duration of the construction work measured on the floor of the storage facility next to the shelving units. This is in line with the 2 mm/sec limit that has been suggested for input vibrations in museums and other collections for single events, such as a rock concert or construction project.[6] Based on many years of practical experience, this is a level at which no damage has ever been reported. This is not to say that there is no risk of damage, given that cultural-heritage objects are essentially unique and for which the material history may be unknown. However, the risk for damage to an object below these input vibration levels for one event can be considered to be very low. The possibility of resonance was not specifically addressed in that published limit, but given that it is a building input limit for an entire collection in a museum or other institution, possible resonance effects are implicitly covered.

It is noted that the 2 mm/sec limit is the vibration level measured on the building structure itself, and when possible, near sensitive objects. This limit is lower than limits suggested for older and historic buildings; see for example, the German DIN 4150-3 standards or less conservative United States standards. This illustrates the importance of taking valuable objects and collections into consideration when planning construction work in or near museums.

For the Naturalis situation, this 1.5–2 mm/sec limit could be considered to be conservative as it is based on the worst-case scenario that all objects will vibrate continuously at resonance for the duration of the construction work. However, this scenario is unlikely, given that such work contains a whole spectrum of frequencies, and work is never continuous in the way it is during vibration testing. However, there is no such thing as no risk. It was thus recommended that the position and condition of the objects be monitored during construction, especially if vibration levels were measured continuously at the limit levels for more than a few seconds.

A number of additional practical recommendations were made, though with a collection as large as that of Naturalis, it was not possible to carry them out in the short time period available. For future reference, the following measures could be taken for natural-history objects in such construction/vibration situations:

- Place sensitive objects on nonreactive padding to prevent them from wandering or block them from moving using museum putty. Note that padding should not be too soft nor too thick to avoid the danger of a top-heavy object toppling over.
- Use shelving with raised edges, or line the edges of shelves to stop objects from wandering off the shelves.
- Avoid the stacking of (light) objects or specimen boxes.
- Make sure that all labels are attached to their objects.
- Place additional weight on shelves with light objects (such as birds and bird skeletons) to reduce the effect of the resonance of the shelves themselves. Similarly, light objects could be placed in more solid cabinets, which do not resonate as strongly for the short periods of construction.

The last recommendation is based on the point made earlier—that resonance behavior depends on a number of factors, essentially on system behavior. Collections that are bound to the building respond not only as individual objects but also in combination with their location.

Naturalis staff reported that the placing of the support beam through the wall of the storage tower was conducted without damage or wandering of the objects. Although vibration levels were not actually monitored, the construction company proceeded with much caution, taking more time than normal to ensure that there was no damage to the collection. This case was a good example of how to protect collections by determining vibration limits through object testing, even though limited in this case. Similar limits and monitoring philosophies have been successfully applied to works of art that are part of church interiors and to exhibitions "bound" to museums.[7]

It is therefore recommended that much more testing on objects be conducted to obtain more S-N data on objects as described above. After all, vibration limits and other mitigation techniques for collections in buildings and also during transport can be developed only in a reliable and cost-effective manner with such object-based testing. It is noted that these recommendations do not cover questions about long-term vibrations, that is, over periods of years due to daily occurrences around the collection. Research is also being conducted in this area, but a discussion of this issue is beyond the scope of this article.

Conclusions

This vibration-testing project was carried out in order to determine allowable vibration limits (in terms of level and duration) for short-term, heavy construction work in the storage facilities of Naturalis Biodiversity Center in Leiden, the Netherlands. Resonance tests and tests for wandering and eventual damage were conducted on various kinds of natural-history objects provided by Naturalis. Testing was conducted on a commercial vibration-testing table and included testing of objects on typical freestanding metal shelving used in the storage facilities near the construction work and directly on the vibration table.

The results of the experiments showed that object wandering and resonance were amplified due to the resonance of the shelves themselves. This led to the recommendation that vibrations coming into the shelving at floor level should not exceed 1.5 to 2 mm/sec during the period of the construction work of concern. The condition and location of the objects nearby should also be monitored, especially if the limit level was maintained for more than several seconds at a time. By following these limits and action plan, no damage or wandering of the objects was noted during construction. It is recommended that more object testing be conducted for all types of cultural-heritage objects in order to better develop vibration limits and/or other damping systems for vibrations during construction work near collections that cannot be relocated, as well for other situations where vibrations are of concern.

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Notes

1. Sarah Staniforth, "The Testing of Packing Cases for the Transport of Paintings," in *ICOM-CC 7th Triennial Meeting Preprints, Copenhagen, 10–14 September 1984* (Paris: ICOM, 1984), B4.12.1–B4.12.6. Marion F. Mecklenburg, ed., *Art in Transit: Studies in the Transport of Paintings* (Washington, D.C.: National Gallery of Art, 1991). David Saunders, "Monitoring Shock and Vibration during the Transportation of Paintings," *National Gallery Technical Bulletin* 19 (1998): 64–73. David Saunders, "The Effect of Painting Orientation during Air Transportation," in *ICOM-CC 14th Triennial Meeting Preprints, The Hague, 12–16 September 2005*, vol. 2 (Paris: ICOM, 2005), 700–707.

2. William Wei, Netta Krumperman, and Nicole Delissen, "Design of a Vibration Damping System for Sculpture Pedestals: An Integral Object-Based Approach," in *ICOM-CC 16th Triennial Meeting Preprints, Lisbon, Portugal, 19–23 September 2011* (Paris: ICOM, 2011), paper 1519. Arne P. Johnson, W. Robert Hannen, and Frank Zucarri, "Vibration Control during Museum Construction Projects," *Journal of the American Institute for Conservation* 52, no. 1 (2013): 30–47. Andrew W. Smyth et al., "Vibration Mitigation and Monitoring: A Case Study of Construction in a Museum," *Journal of the American Institute for Conservation* 55, no. 1 (2016): 32–55.

3. Johnson, Hannen, and Zucarri, 30–47. Andrew W. Smyth et al., 32–55.

4. Wei, Krumperman, and Delissen, paper 1519. William Wei, Leila Sauvage, and Jenny Wölk, "Baseline Limits for Allowable Vibrations for Objects," in *Preprints of the 17th ICOM-CC Triennial Meeting, Melbourne, 15–19 September 2014* (Paris: ICOM, 2014), paper 1516.

5. For a quick review of the concept and its application for objects of art and cultural heritage, see Wei, Krumperman, and Delissen, paper 1519; Wei, Sauvage, and Wölk, paper 1516; and William D. Callister and David G. Rethwisch, *Materials Science and Engineering*, 8th ed. (Hoboken, N.J.: John Wiley & Sons, Inc., 2011), 255–259.

6. Wei, Sauvage, and Wölk, paper 1516.

7. Wei, Sauvage, and Wölk, paper 1516. William Wei, Siobhan Watts, Tracey Seddon, and David Crombie, "Protecting Museum Collections from Vibrations Due to Construction: Vibration Statistics, Limits, Flexibility and Cooperation," *Studies in Conservation* 63, no. S1 (2018): S293–S300.

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