# Vibroacoustic study of circular cylindrical tubes in roller coaster rails[1)]

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(Received: 17 November 2009; Revised: 25 September 2010; Accepted: 2 April 2011)

**Excessive noise generated by roller coasters during operation is a significant issue for amusement parks located near residential and business districts. Previous work showed that filling the rails with sand and pea gravel can provide noise reduction levels of up to 10 and 15 decibels. However, using damping materials may require additional support structures to accommodate the weight increase and, consequently, raise installation costs. This paper presents field results that characterize sound and vibration of roller coasters with different rail geometry and fill. Finite element modeling is used to compute the theoretical natural frequencies and mode shapes of a typical track section. Additionally, laboratory experimental results of lighter fill materials are presented. The results indicate that vermiculite provides similar, though less noise reduction than sand, but with a much lower additional weight. Furthermore, the handling and manufacturing characteristics are superior to the other materials investigated.** 

Primary subject classification: 13.4; Secondary subject classification: 47.3

## 1 INTRODUCTION

Noise from amusement parks is often perceived to be *annoying* to adjacent residential and business communities. The highest elevations along the track superstructure permit screams to propagate beyond the property while structural vibration intensifies the noise in the local sound field near the ride. While riders' screams may be the most consistent source of noise, mechanical and structural components substantially influence the noise level[1]. Although sounds are known to contribute to the exciting atmosphere of amusement parks[2], there has been recent interest in reducing the sounds radiated from roller coasters to address local community concerns[3].

As illustrated in Fig. 1, typical roller coaster track consists of a combination of hollow steel tubular shells including the running rail track, which the coaster wheels ride along, a larger tube known as the backbone, which provides structural support for the track and support beams. Few studies have addressed the noise generated from roller coasters in detail but much has been conducted on railroad freight trains. Though the supporting structures are not identical, railroad research provides a starting point. Thomspon concludes that rolling noise in freight train rails is caused by structural vibrations of the wheel, rail and supports induced by the combined surface roughness of the wheel and rail running surfaces[4,5]. The situation is worse in roller coasters than railroads since the coaster supporting structure usually has more hollow steel tube members with very little damping compared to wood ties in the ground for a railroad.

Several methods have been used to reduce the noise from of rail structures. Maes presents vibration dampers placed throughout the rail structure[6]. Vincent presents rolling noise control strategies including the application of viscoelastic damping material to the

*Fig. 1—Roller coaster track with circular backbone and rails.*

[1)] To comply with the conditions of a confidentiality agreement, this paper excludes specific information about amusement park operators and attractions.

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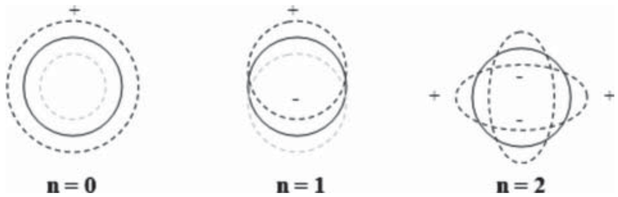



*Fig. 2—Cross section distortion for circumferential modes 1–3.*

wheels and or track[7]. Maes presents a tuned vibration absorber for railroad tracks[6]. Another method known as particle damping, also known as impact and acceleration damping has been used for several different applications to reduce vibrations[8]. Particle damping uses granular particles added to the structure to increase damping and thereby reduce the resonant amplitudes of the structure[9]. Recently this technique has been applied to roller coasters by adding sand to the interior of the backbone with good results. Menge[10] reports up to 10 dB sound reduction using sand fill and up to 15 dB using pea gravel in the rail and support structures but also notes that it increases the weight significantly. For roller coasters, this technique is preferable to other forms of passive damping such as the application of visoelastic material because particle damping does not affect the exterior aesthetics of the structure and because the particles are enclosed inside the tubes, they are less affected by environmental degradation over time. In addition, the cost and difficulty of filling the tubes with granular materials is lower.

The roller coasters radiate noise from multiple sources, but predominantly from passengers, the vehicle wheels and the track structure. Only the noise from the track structure is affected by the use of particle damping. The challenge is then to identify the changes in the noise due only to the change in the fill material. In the case of most roller coasters where both the running and backbone rails are circular, the noise radiation is dominated by surface vibration from flexural or circumferential modes that develop in the radial direction. Furthermore, these modes are likely to be strongly affected by the application of particle damping due to the interaction of the fill material and the circular track walls.

Circular track rails can be characterized as cylindrical tubes with thin walls, where wall thickness is significantly less than the radius. Figure 2 represents the cross section distortion of the first three vibration modes of a cylinder[11]. As the structure vibrates, the interaction of the structure with air particles creates energy radiated into the environment and perceived as sound to the human ear. While coaster tracks also include flat support plates, the plate vibration is not likely to be affected by filling the tubes with material. The reader is referred to Refs. 12 and 13 for a description of the vibration characteristics of flat plates.

This study is focused on comparing and understanding the effect of different fill materials used for particle damping. In early construction of steel frame roller coasters particle damping was not used. Recently coasters have been constructed using sand as the fill material with good results. Because of the large scale of typical roller coasters, the quantity of fill materials is significant and adds cost for the fill material. More importantly, the added weight of the rail structure requires additional support structure, which can increase the cost substantially. Some tradeoffs may be made between the cost, weight and effectiveness of the fill material when selecting the best material for a roller coaster.

This paper investigates the use of vermiculite and perlite as alternative fill materials to sand. Because of the large scale of a roller coaster, a full-scale comparison was not possible. Field measurements were conducted to collect qualitative data and to understand damping effect of sand on the sound and vibration levels. A finite element model was then used to examine the modal response of one of the coaster structures without the particle damping. Finally, the comparison of different fill materials was conducted in a laboratory using a hollow circular steel tube similar in cross section to the backbone of one of the coasters measured in the field. Different fill materials were used and modal testing was conducted to measure the changes in damping. In addition to reducing the scale and cost, this method was used in an effort to eliminate the many environmental and other compounding factors in the field that would make the comparison impossible. Although a direct, quantitative comparison cannot be made between the lab and field measurements, the performance of the fill materials is clearly illustrated and shows that vermiculite is a possible alternative to sand due to its good damping performance and significantly lower weight.

## 2 FIELD MEASUREMENTS

Field pass-by measurements were conducted to qualitatively compare the sound and vibration characteristics of two roller coaster tracks with no fill and one existing roller coaster with sand fill, see Table 1. The objective was to obtain a qualitative comparison to help guide a controlled study of fill materials in a laboratory environment.

The track of Coaster A included two circular (running) rails with a rectangular, sand-filled backbone rail. The track for Coaster B included two circular rails with a circular backbone rail without material fill. The

*Table 1—Roller coaster description.*

| Coaster | Backbone | Fill | Wheel type |
|---|---|---|---|
| A | Rectangular | Sand | Polyurethane/nylon |
| B | Circular | None | Polyurethane/nylon |
| C | Rectangular | None | Nylon |

track for Coaster C contained two circular rails with a rectangular backbone rail without material fill. The testing was performed during non-operational hours to eliminate screaming and minimize the influence of other noise sources inside the park. Ideally, to complete the study a circular track with fill would have been included; however, no such track was available for testing. The three tracks do allow for comparison of rectangular fill to rectangular with no fill and rectangular no fill to circular no fill. It was important to include the circular cross section because the lab based fill material comparison was conducted on a circular cross section.

It should also be noted that coasters A and B had polyurethane/nylon wheels and coaster C had only nylon wheels. Clearly, the wheel material affects the noise generated on the structure making quantitative comparisons between coasters difficult. Again, it must be noted that the objective was to qualitatively characterize the amplitudes and frequencies of mechanical vibration and the sound levels, and understand the effect of sand fill in the rail structure.

Following the procedure outlined in Menge[10,14], a calibrated Extech Type II integrating sound level meter was positioned 15 meters from the centerline of the track and captured train pass-by events with averaged A-weighted third octave spectra. Vibration measurements were simultaneously acquired by mounting Endevco 63B-100-2 tri-axial accelerometers at two locations on the track structure as far from vertical supports as possible and recording averaged third octave spectra using an LDS Focus signal analyzer.

Figure 3 displays the A-weighted sound pressure level over a frequency span of 10–10,000 Hz and the overall levels for the pass-by events. At frequencies between 50 and 250 Hz, the sound levels were similar which may suggest that sound is somewhat independent of rail geometry (for the same fill type) in this range. At frequencies greater than 250 Hz, Coasters A and B had similar levels including overall sound levels of 82 and 80 dBA, respectively. However, Coaster C recorded sound levels up to 23 dB higher in this region and an overall level over 100 dBA. The graph further indicates that each coaster emitted its highest levels within the region of 200 to 500 Hz, which is consistent with Menge[10].

Figure 4 shows a comparison of acceleration levels from the accelerometers located on the structure. The acceleration levels of Coaster A are relatively flat across the frequency spectrum. At low frequencies, Coaster C exhibited lower levels than Coasters A and B. Above 80 Hz, Coaster C had higher levels than Coaster B and nearly twice the level of Coaster A. In general, the vibration levels of Coasters B and C, which contained no damping fill, were significantly higher.

The acceleration spectra show a similar qualitative shape as the sound spectra. For example, the highest levels appear between 200 to 500 Hz with significant attenuation at lower frequencies. This suggests that a

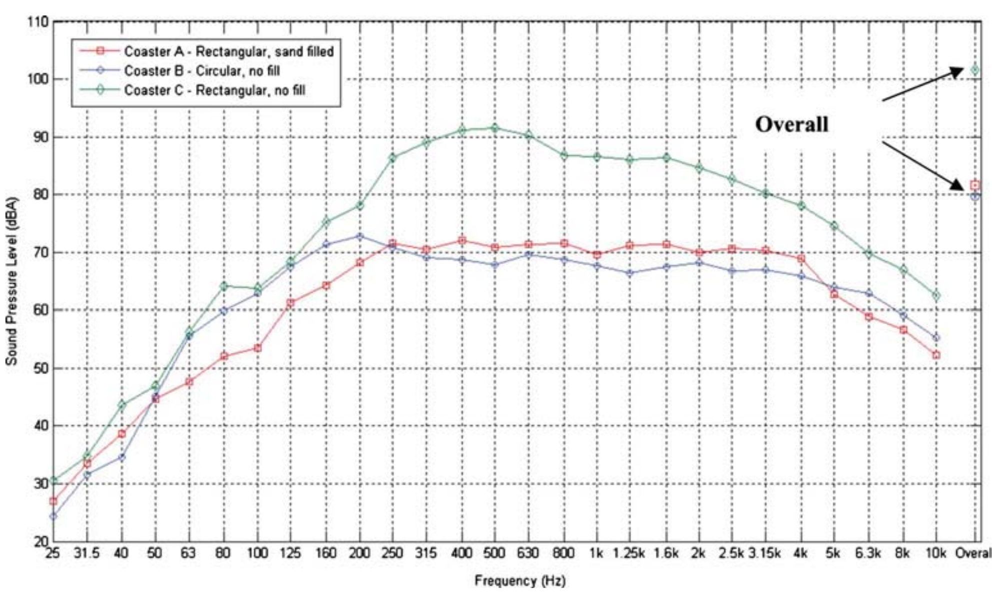



*Fig. 3—A-weighted acoustic pass-by spectra comparison at* 15 m.

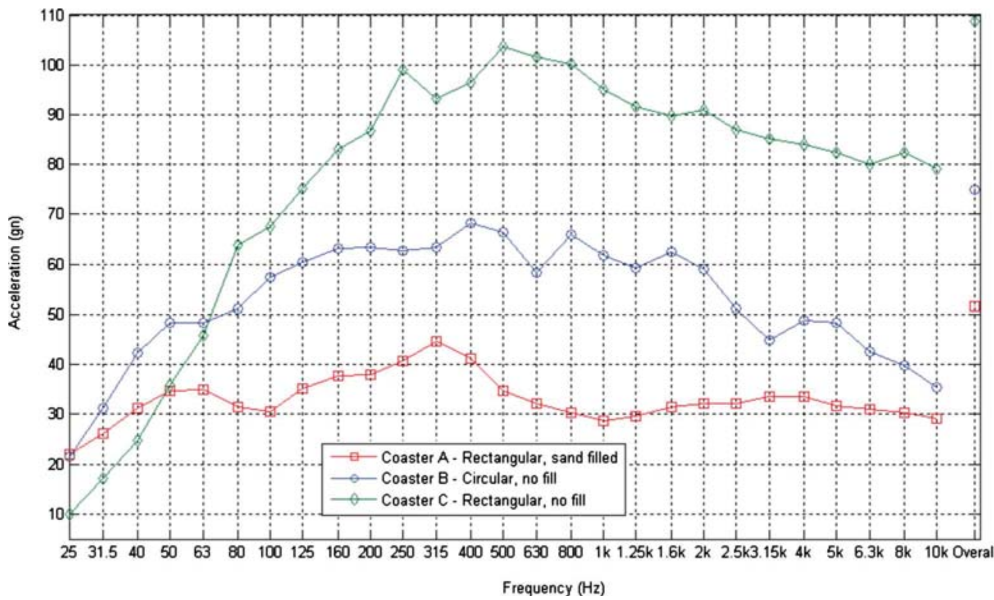



*Fig. 4—The acceleration levels for three coasters.*

significant component of the sound radiation is due to the mechanical vibration of the track.

The comparison of the rectangular backbone with and without fill indicates that the sand fill reduces the overall vibration levels significantly. In addition, a comparison of circular compared to rectangular backbone, both with no fill indicates that the circular backbone exhibits lower levels. In conclusion, Coaster C, rectangular with no fill exhibited the highest levels of all. It should be noted that some of the high levels exhibited in Coaster C were likely due to the stiffer nylon car wheels as compared to softer polyurethane/nylon for Coasters A and B and no method was found to account for the different wheel types in the field tests.

The overall conclusions from the field tests were that the sand fill clearly has a significant impact on the vibration and noise levels radiated from a coaster, circular backbone exhibited less noise than rectangular, the prominent sound levels occur above 250 Hz, and that the mechanical vibration of the rail structure are an important source of the sound radiation.

## 3 FINITE ELEMENT MODEL

A finite element (FE) model of a 30-foot track section was generated for this study. The purpose of the FE model was to help identify the mode shapes and frequencies that are typical of these structures without fill material. Ideally, a full modal analysis could be done experimentally instead, but this was not feasible due to the large scale, complex geometry and safety issues of a full-scale roller coaster.

A thirty-foot track section of a standing coaster track with similar geometry to Coaster B was modeled using three-dimensional finite elements shells. Modal analysis was performed and resonant frequencies and mode shapes were calculated. The modal response of the

*Fig. 5—Bending and torsion modes: top 1st bending mode* (19 Hz)*, 2nd from top second bending mode* (49 Hz)*, 3rd: first torsion mode* (20 Hz)*, 4th: second torsion mode* (46 Hz).


*Fig. 6—Rail translation modes.*

structure is very complex with hundreds of modes in the spectrum of interest. The results shown below are a sample of typical mode shapes and frequencies. Figure 5 shows the first two bending and torsion modes for the track section. The frequencies are all below 50 Hz. These modes may be affected by the particle damping but since the frequencies are so low they do not contribute to the audible noise.

Figure 6 shows three modes where the rails translate in the direction of the track. These modes are not expected to radiate significant noise since the deformation is not normal to the surface of the rail body.

Figure 7 shows a mode where the connecting plates deform but the backbone and rails do not. While this and similar modes are expected to radiate significant noise, they are not expected to be affected by particle damping in the backbone.

Figure 8 shows three modes where the backbone exhibits circumferential deformation. The top case shows the n=2 mode has a frequency of 212 Hz. In this mode, the walls of the backbone oscillate in and out and will radiate significant noise due to the higher radiation efficiency of these modes. It is expected that this mode will be significantly affected by the particle damping which will in turn reduce the noise radiated. The middle and bottom modes in Fig. 8 exhibit circumferential deformation of higher orders with frequencies of 308 Hz and 1874 Hz. These modes are expected to radiate significant noise in the audible range because the deformation is normal to the surface of the backbone. In addition, it is expected that the particle

*Fig. 7—Connecting plate deformation mode (755 Hz).*

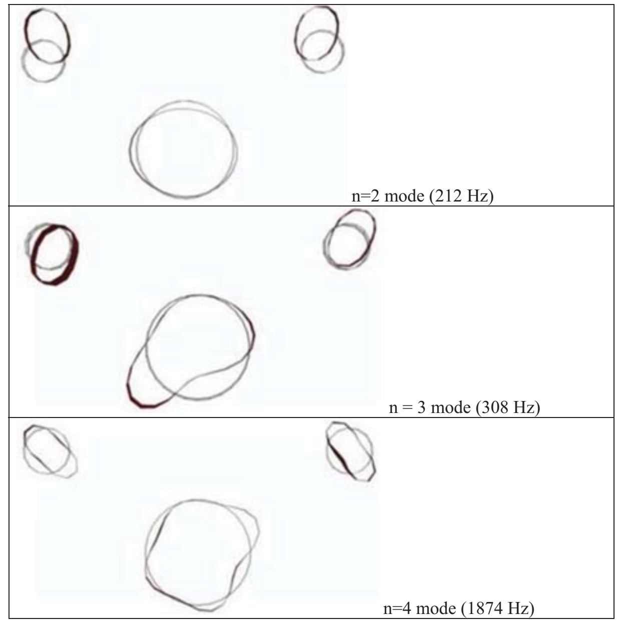



*Fig. 8—Backbone circumferential modes including* n=2, n=3 *and* n=4 *modes.*

damping will be effective in reducing the noise for these modes.

The conclusion of the finite element model analysis indicates that the modes that exhibit circumferential deformation are primarily in the audible range. Particle damping is expected to damp these modes considerably and hopefully be effective in reducing the overall noise radiated by the structure.

## 4 FILL MATERIAL STUDY

With an understanding of the characteristics of a real roller coaster in the field and the theoretical behavior from the finite element model, the next step was to compare the effect of using different fill material in a controlled lab experiment. The damping materials were selected based on performance include weight, noise reduction, heat resistance and handling characteristics. The materials tested in this study were sand, vermiculite, and perlite.

Testing a full-scale track section was prohibitively difficult due to the size constraints and the costs of assembling and filling such a large structure with the fill material. Therefore it was determined that the fill material study would be conducted on a single hollow steel circular cylindrical tube that is similar in dimension to the backbone of Coaster B. In addition, a length of 30 inches would capture the cross section modes. A 30.75 inch length of steel tube with outer diameter 5.56 inches and wall thickness 0.375 inches was mounted using elastic bands to simulate free-free boundary conditions as shown in Fig. 9.

An impact modal analysis test was administered

*Fig. 9—Impact hammer, accelerometer and steel tube used in experimental measurements.*

with a fixed-point response on the beam and a roving impact force using thirty-seven data points. Because sound radiation is dependent on radial motion, only the acceleration in the perpendicular to the beam (normal direction) was included in the results.

The data from experimental testing was imported into the STAR Modal software and the responses were plotted across a frequency spectrum of 10–10,000 Hz. A curve-fit of the frequency response functions (FRFs) at each resonant frequency was used to estimate the damping ratios of each resonant peak. Damping ratios were calculated for each mode by averaging the damping ratios over each measurement point for each mode. This procedure was repeated to compare the mechanical vibration of three different fill materials.

In addition, the sound from impact strikes was captured for a time interval of one second using A-weighting. A Gras microphone was positioned 1.5 feet from the centerline of the tube at a height of 4.75 feet from the ground. Both third octave and impact force to sound level frequency response functions were computed. Using a specially constructed pendulum-hammer tool, a repeatable impact load of 900 lbf was applied near the middle of the specimen.

Figures 10 and 11 show the mechanical vibration and acoustic response to an impact strike near the center of the beam for perlite fill. Similar results were found for each measurement point and using each different fill material. A total of 148 sets of data were collected in all. Figure 10 shows one typical vibration response with acceleration on the vertical axis in a linear scale (to emphasize the resonant peak locations). Narrow band spectrum was used to accurately locate the resonant peak frequencies so that they could be related to the mode shapes and the sound radiation.

The plot indicates that while surface vibration spans the audio-frequency range, the most significant noise emission is restricted to frequencies between 1000 and 3000 Hz. Resonance frequencies appear at 1210 Hz, 1420 Hz, 1540 Hz, and 2700 Hz.

Figure 11 shows the microphone audio spectrum for the same measurement point with acoustic pressure in a linear scale on the vertical axis (to emphasize the peak frequencies). This figure illustrates which modes result in the highest sound levels. Table 2 displays the mode shapes that characterize the sound of the impact and compared vibration damping of the four material scenarios. The first column illustrates the mode shape, the second column lists the predicted resonant frequency from theory[13] followed by the measured resonant frequency. The fourth column lists each differ-

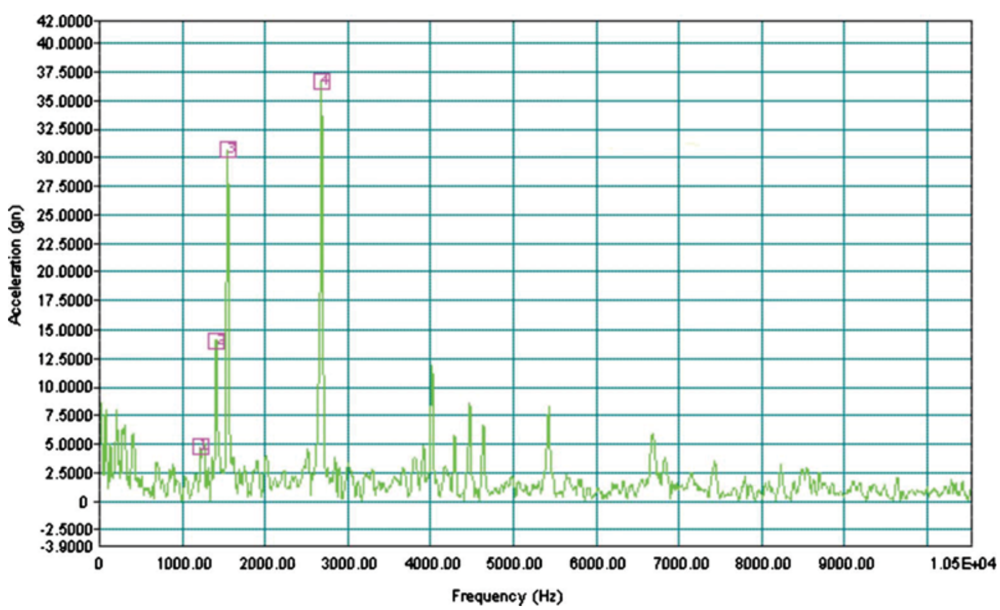



*Fig. 10—Typical vibration spectrum for tube with perlite fill.*

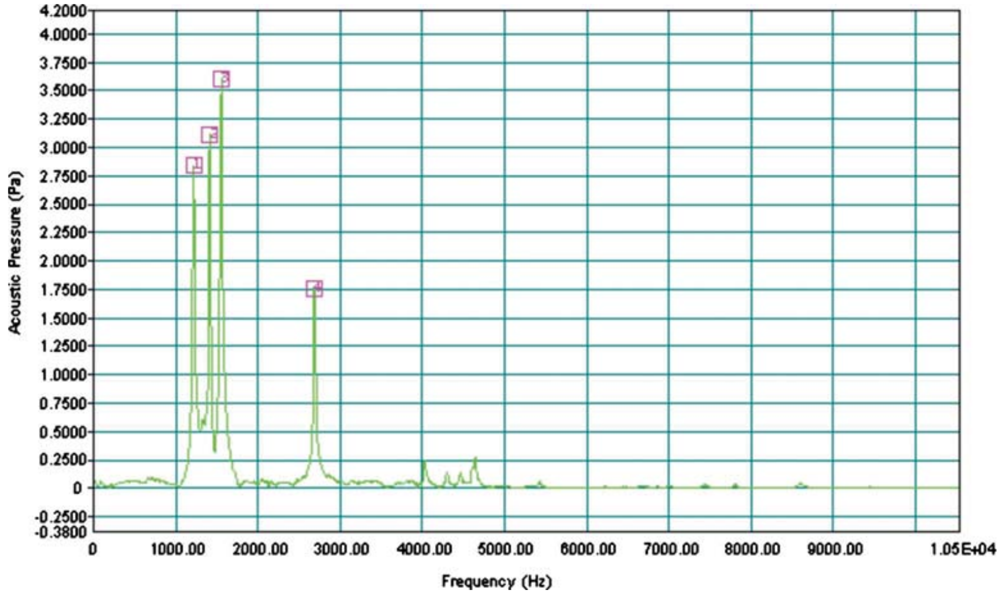


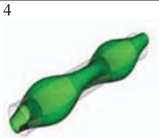

*Fig. 11—Typical audible spectrum for tube with perlite fill.*

ent fill material followed by the damping ratio estimated from the measured resonant peak.

Figure 12 compares the noise reduction for three materials compared with the no-fill case. The noise reduction was computed by comparing the sound levels between the no-fill and each different fill material using third octave band spectra. While sand showed a reduction up to 10 dB, vermiculite and perlite show a reduction of between 4 to 6 dB below 2000 Hz. The noise reduction was less effective above 2000 Hz for all fill materials.

The noise reduction of sand in the laboratory tube experiment is consistent with the results found by Menge with full-scale sand filled coaster rails[10]. This agreement validates the experimental method used in this study and supports the contention that the noise reduction results from the tube experiment will extend to full-scale coaster rails for the other fill materials as well. Therefore, the conclusions indicate that perlite and vermiculite are a suitable fill material as compared to sand for full-scale coaster rails. In addition to the noise reduction performance, the weight, durability and manufacturing characteristics of the fill materials must also be considered. The weight of the test specimen with and without the fill material was measured and the percent increase in weight for the different materials is shown in Table 3. Sand increases the weight of the section by 53% while perlite and vermiculite have

*Table 2—Hollow tube modal analysis.*

| Mode | Predicted Frequency (Hz) | Measured Resonant Frequency (Hz) | Fill Material | Measured Damping Ratio |
|---|---|---|---|---|
| 1  | 1180.6 | 1210 | No Fill<br>Sand<br>Vermiculite<br>Perlite | 0.0097<br>0.0200<br>0.0105<br>0.0121 |
| 2  | 1413 | 1410 | No Fill<br>Sand<br>Vermiculite<br>Perlite | 0.0012<br>0.0159<br>0.0118<br>0.0122 |
| 3  | 1540 | 1534 | No Fill<br>Sand<br>Vermiculite<br>Perlite | 0.0082<br>0.0119<br>0.0130<br>0.0117 |
| 4  | 2680 | 2929 | No Fill<br>Sand<br>Vermiculite<br>Perlite | 0.0064<br>0.0087<br>0.0048<br>0.0047 |

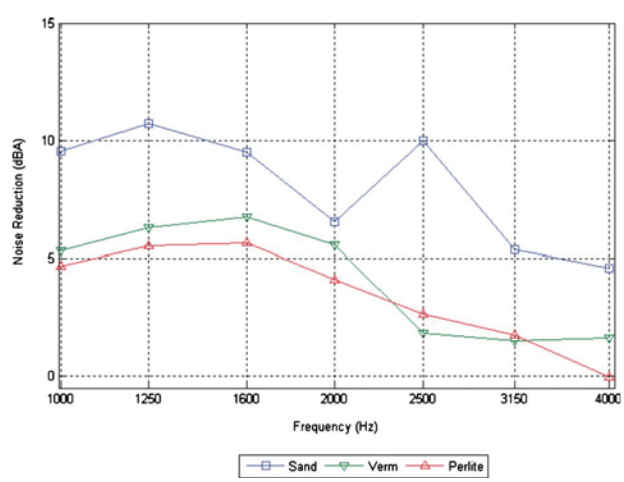



*Fig. 12—Noise reduction of various fill media between* 1000–4000 Hz.

*Table 3—Comparison of fill materials.*

| Material | Weight Increase (%) | Noise Reduction (dBA) | Heat Capacity (°F) | Potential Issues |
|---|---|---|---|---|
| Sand | 53.4 | Up to 10 | N/A | Heavy, difficult to handle |
| Vermiculite | 5 | Up to 6 | 2400 | Some dust |
| Perlite | 5 | Up to 5 | 2200 | Some dust |

much lower densities and only increase it by 5%. A significant increase in the weight might require increases in the structural support and thereby increase the overall cost considerably.

Perlite is known to change consistency when heated while vermiculite is more stable to high heat levels. This might affect the nature of the fill materials during assembly or maintenance including welding and the performance over time as the structure is heated from radiation exposure to the sun.

Considering the noise-reduction together with the weight and manufacturing characteristics the following conclusions can be made. Sand appears to be the most effective for sound reduction. Vermiculite and perlite provide good, though somewhat less noise reduction than sand. However, the significantly lower weight of vermiculite and perlite might justify their use instead of sand if the penalty (4 dB) of less noise reduction can be accepted. Finally, vermiculite may be a better choice than perlite due to its manufacturing and temperature characteristics.

## 5 CONCLUSION

This study presented field, theoretical and laboratory sound and vibration studies comparing the use of different fill materials to reduce the noise radiated from the rail structure of roller coasters. Field studies helped characterize the noise and vibration levels and frequencies of interest in different types of tracks. Finite element models illustrated the mode shapes that are characteristic in track sections and helped plan the lab study. A controlled lab comparison of different fill materials on a steel circular tube compared the effectiveness of sand, vermiculite and perlite. The results indicated that while sand is the most effective in noise reduction, vermiculite and perlite might be selected as alternatives especially due to their significant reduction in the overall weight of the structure and only slightly lower effectiveness in sound reduction than sand.


## 6 ACKNOWLEDGMENTS

The authors are indebted to the amusement park personnel and material vendors who offered their time, resources, and expertise to this research. In addition, the Sound Coaster Research Group advisors are acknowledged for their contributions in editing and revising this document. Special thanks to Adam Hudson and Benjamin Johnson for their assistance with additional finite element modeling results.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