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Comparative Visualization for Noise Simulation Data

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Abstract

Noise, vibration, and harshness (NVH) simulation represents an important step in modern automotive design. This type of simulation produces large and complex data that is hard to analyze. The data resides in two domains, the spatial and the frequency domain. In this paper, we extend the current state of the art in the visual exploration of such data by supporting comparison tasks. We support the comparison of velocity values of a subset of surface elements for multiple frequency bands. We combine data aggregation on the 3D model with multiple bar charts in a coordinated multiple views system. This new approach allows for an intuitive comparison of multiple velocity values in the context of both domains. We demonstrate the deployment of this approach for an example from the automotive industry, but it can be used with any simulation that simultaneously relates to two domains.

Introduction

Modern engineering is simply unimaginable without simulation. There is a plethora of simulation approaches and techniques today. This paper deals with the noise, vibration, and harshness (NVH) simulation from the automotive industry. Increased awareness of noise pollution and, at the same time, increased expectations of customers regarding silent equipment make the NVH simulation increasingly important. Advances in computing and storage technology make it possible to simulate ever more complex scenarios. Complex simulations produce large and multivariate results that are not easy to comprehend. Interactive visualization has established itself as a valuable counterpart to automatic analysis, especially for exploratory analysis tasks [1]. In this paper, we build on our previous work [2] and describe an interactive visual analysis approach for the exploration of noise simulation data with focus on comparative analysis. In our previous work, we introduced an approach for the efficient exploration and analysis of data that simultaneously resides in two domains, the spatial and the frequency domain. In our particular case, this means that for each element of the outer surface of an engine, we have velocity levels computed for frequencies across the audible frequency range. The main challenge was how to allow simultaneous exploration at multiple levels of detail in each domain. Very positive feedback from engineers who deal with noise simulation motivated us to pursue our research further.

In this paper, we describe two newly identified comparative analysis tasks and provide a solution that supports these identified tasks. This comparative visualization solution enables us to show multiple results on each element in the spatial domain (an element on the surface of an engine, in our case) and, at the same time, to support the comparison of simulation results of individual elements across several frequency bands. We support direct comparison of computed velocity levels as well as comparisons of computed velocity levels in relation to their externally prescribed thresholds. We provide several ways of individual value comparison depending on different requirements defined together with engineers. The new solution is implemented as a coordinated multiple views system [3]. Each view can be configured according to the engineers' needs and supports linking and brushing.

The main contributions of the paper can be summarized as:
1. Identification of additional analysis tasks and corresponding requirements for visual analysis of noise simulation data.
2. An approach for comparative analysis of noise simulation data in the spatial and frequency domain.
3. An integrated tool that implements the new approach.

Related Work

We deal with comparative visualization of simulation data. A brief review gives an overview of relevant associated research work before we relate our approach to the visualization for simulation research.

Comparative Visualization

Comparative visualization is an active field of research. Gleicher et al. [4] introduced a taxonomy of the visualization for comparisons that consists of the three groups: juxtaposition, superposition, and explicit encoding. In the case of juxtaposition, images are placed next to each other, and the comparison is performed in the observer's mind. The concept of juxtaposition has been used in different contexts. Tufte [5] calls this approach small multiples. Munzner et al. [6] used the concept to compare large phylogenic trees by placing the information side-by-side, for example. The more objects are placed next to each other, the more complicated the comparison becomes. In our previous work [2], we used such an approach to compare simulation results shown on a 3D model for several frequency bands. However, as the number of bands to be compared increases, such an approach becomes inefficient. We used juxtaposition when comparing selected cells over a subset of frequency bands.

The idea of superposition is to place the objects in the same view and in the same coordinate space. There are different strategies to present several objects at once. Blending is a common method to place images in the same view. Konyha et al. [7] used it to depict many curves that result from a simulation ensemble in a single view. Color weaving [8] or attribute blocks [9] represent more advanced techniques for the superposition of images. A blending approach is not applicable in our case. We have to show several values per surface element. We considered an approach similar to the approach proposed by Malik et al. [10]. They subdivided the image space into hexagonal regions. Each region is then subdivided into smaller elements that depict data from different series. This works well for a limited number of hexagonal regions and a limited number of sub-regions. In our case, we have too many elements (even our simple engine has more than twelve thousand surface elements), and we would need to subdivide it in many sub-regions.

The juxtaposition and superposition leave the comparison task to the user. In the case of the explicit encoding, the differences are depicted directly. This is possible only if the differences can be computed by some metric. Wiebel et al. [11] used an explicit encoding approach to compare volume data sets. They computed the differences in a voxel-based way and explicitly encoded the differences by using surfaces. In the case of comparison of 3D surfaces, Masuda et al. [12], for example, used color. We deploy explicit encoding in the current solution for visualization on the 3D model. As color coding scales well for comparison of many elements, we also decided to use color and explicit encoding (using different metrics) to depict many velocity levels per surface element at once.

Visualization for Simulation

Visualization and interactive visual analysis have been used to explore and analyze simulation data for a long time. In our work, we aim at depicting and comparing results from several frequency bands, thus it relates to ensemble visualization, particularly to ensembles computed by varying a single parameter. Previous research in ensemble visualization often uses feature- or location-based approaches to show simulation results [13]. Wang et al. [14] provide a recent survey on the visualization of ensemble simulations. Matković et al. [15] provide another overview.

Love at al. [16] use statistical summaries to visualize spreads in scalar-value ensembles. Such an approach is related to ours, as we also use summary data to show multiple values in the spatial domain. We also integrate elements probing where we get additional details for selected elements.

Noise Simulation and Data

NVH in the automotive industry deals with noise and vibration suppression as well as with suppression of squeaks, rattles, and 'tizzes' [17]. **Noise**, in the context of NVH, describes audible sound, with particular attention paid to the frequency range 30–4000 Hz. We differentiate between structure-borne noise, which is radiated by structural surfaces that are vibrating (due to internal or external sources), and airborne noise, which results from fluid pressure fluctuations transferred to a vehicle's structure (e.g., flow turbulence over an open roof window). **Vibration** describes tactile vibration in the frequency range of 30–200 Hz [18]. **Harshness** describes human perception related to the quality and transient nature of noise and vibration. It is a subjective measure, and, unlike noise and vibration, cannot be objectively measured.

In this paper, we deal with structure-borne noise analysis. The analysis starts with a time-domain multi-body model simulation of the initial design at a number of engine speeds, switching subsequently to the frequency domain to calculate the model's outer surface velocity levels that are responsible for noise.

The simulation itself computes vibration velocities for each surface element for a given engine speed. In our particular case, velocity values are computed for more than 12 000 surface elements for each of the more than 300 harmonics. The computed values in the frequency domain are then aggregated into 23 ⅓ octave bands. In addition, there are pre-defined velocity level thresholds that correspond to acceptable, medium, and non-acceptable noise levels. The thresholds are defined for the ⅓ octave bands. Figure 1 shows the 3D model of the engine with velocity levels at 500 Hz ⅓ octave band color coded for each surface element. The red elements vibrate more, and the blue ones have a lower vibration velocity.

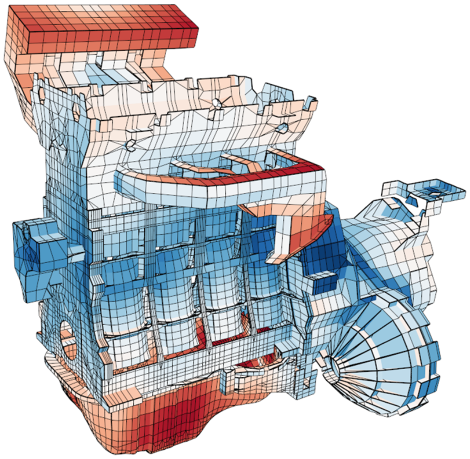


Figure 1. *Our data consists of vibration velocity values for each surface element (there are more than 12 000 elements in our case), and each harmonic. Harmonics are aggregated into ⅓ octave frequency bands (there are 23 bands in our case). Only one ⅓ octave frequency band is shown here.*

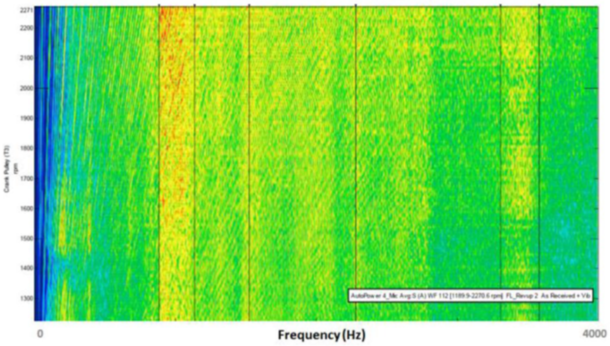
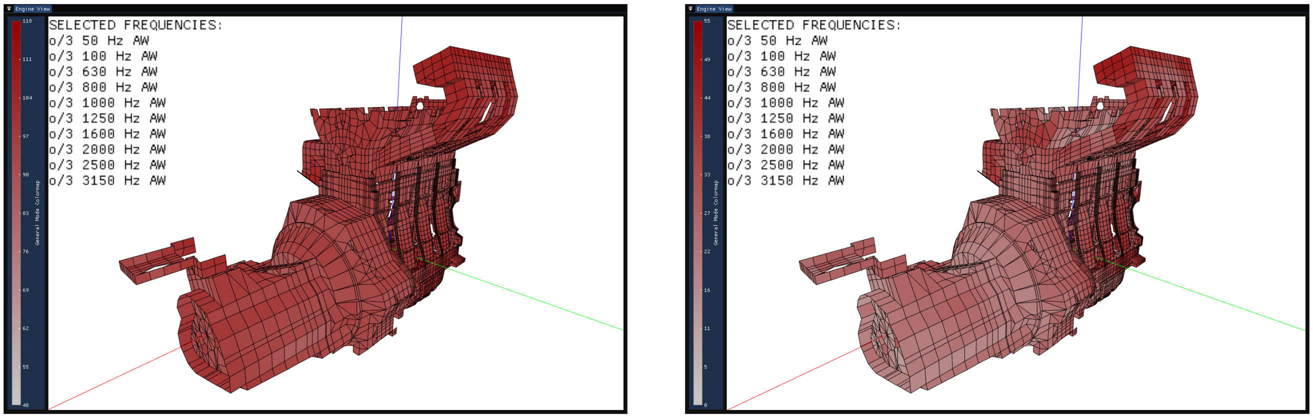


Figure 2. *The Campbell diagram provides an overview of velocity values across the computed frequency range* $(x-axis)$ *and engine speed* $(y-axis.$ *It uses strongly aggregated data and serves as an entry point into analysis.*

A standard way to visualize the results is the Campbell diagram [19], as shown in Figure 2. The Campbell diagram shows frequency values on the X axis and engine speeds on the Y axis. For each frequency and each speed, there is one point showing the noise level integrated over the whole engine surface, i.e., it is showing only highly aggregated results. We focus on one particular engine speed, i.e., a line in the Campbell plot, and provide an interactive visualization solution to support the comparison of detailed data.



```
SELECTED FREQUENCIES:
o/3 50 Hz AW
o/3 100 Hz AW
o/3 630 Hz AW
o/3 800 Hz AW
o/3 1000 Hz AW
o/3 1250 Hz AW
o/3 1600 Hz AW
o/3 2000 Hz AW
o/3 2500 Hz AW
o/3 3150 Hz AW
```

```
SELECTED FREQUENCIES:
o/3 50 Hz AW
o/3 100 Hz AW
o/3 630 Hz AW
o/3 800 Hz AW
o/3 1000 Hz AW
o/3 1250 Hz AW
o/3 1600 Hz AW
o/3 2000 Hz AW
o/3 2500 Hz AW
o/3 3150 Hz AW
```

Figure 3. *3D engine view with 10 frequency bands selected and aggregated with MAX (left) and SPREAD (right) function.*

Analysis Tasks and Requirements

In our previous work [2], we introduced tasks and requirements for a large part of the analysis workflow. We extend them here by focusing on the comparison tasks. Together with domain experts, we identify the following tasks:

- **T1:** Explore vibrations in the spatial context for a subset of the frequency bands in respect to the given limits, or to the simulated velocity values.
- **T2:** Compare velocities for selected surface elements for a subset of the frequency bands.

In order to support the identified tasks, we specify the following requirements:

- **R1:** Show several velocity values on each element at once.
- **R2:** Show if values of an element exceed prescribed threshold values.
- **R3:** Show differences between velocity values for selected elements using different comparative visualization strategies, such as juxtaposition or explicit encoding, e.g.

Visualization Design

In order to support the identified analysis tasks and to satisfy the requirements associated with them, we decided to deploy the well-known paradigm of coordinated multiple views since a single view could not fulfill all of the requirements. In the following, we describe the main views and interaction.

3D Model View

The task T1 and its related requirements R1 and R2 need to show the data in a spatial context. Since we have data that relates to a 3D surface, we use a 3D view. For each surface element, velocity values for 23 1/3 octave frequency bands were computed. The main challenge now is how to show these values at once for each surface element. Due to the element size, it is not feasible to divide each one into 23 parts and show the individual frequency bands. Adding additional elements to the view, like billboards, for example, is also not possible due to the large number of elements.

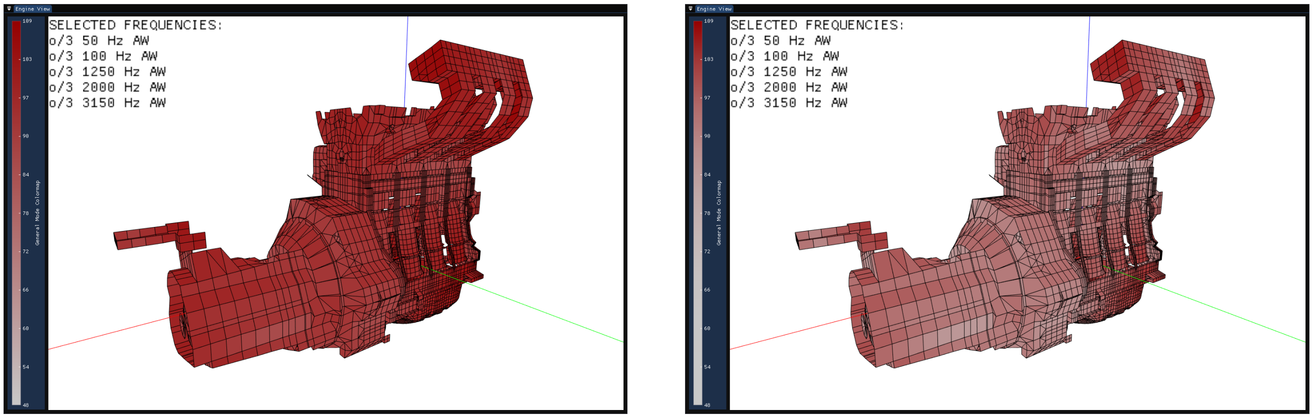
To satisfy requirement R1, we propose to provide different modes of aggregation, and compute a single value based on multiple, user-selected velocity values. Depending on the analysis tasks, the engineer can choose between the following aggregation strategies:

- MIN - show the lowest velocity,
- MAX - show the highest velocity,
- AVERAGE - show the average velocity,
- MEDIAN - show the median of velocities,
- SPREAD - show the difference between the lowest and highest velocity.

Figure 3 shows the 3D model view depicting the maximum of ten frequency bands selected on the left and the spread for the same data on the right. The analyst can see the elements with high velocities that can potentially cause noise and also the elements that have a high variation of velocities across the selected frequency bands, which can help to answer some specific design questions.

The proposed solution satisfies the requirement R1 in many cases really well when just using the default linear color mapping. But it was observed that for data that is clustered around extremes of the mapping range, the visualization results are not very clear since the default color mapping expects linearly distributed data. Hence, we implemented an additional cubic color mapping [20] that helps in differentiating vibration strengths at the extremes of the mapping range. Figure 4 displays obvious positive effects of such a color mapping as, for the given case, the additional precision provided by cubic color mapping makes it easier to differentiate elements whose vibration strength positions them at the higher end of the mapping range.

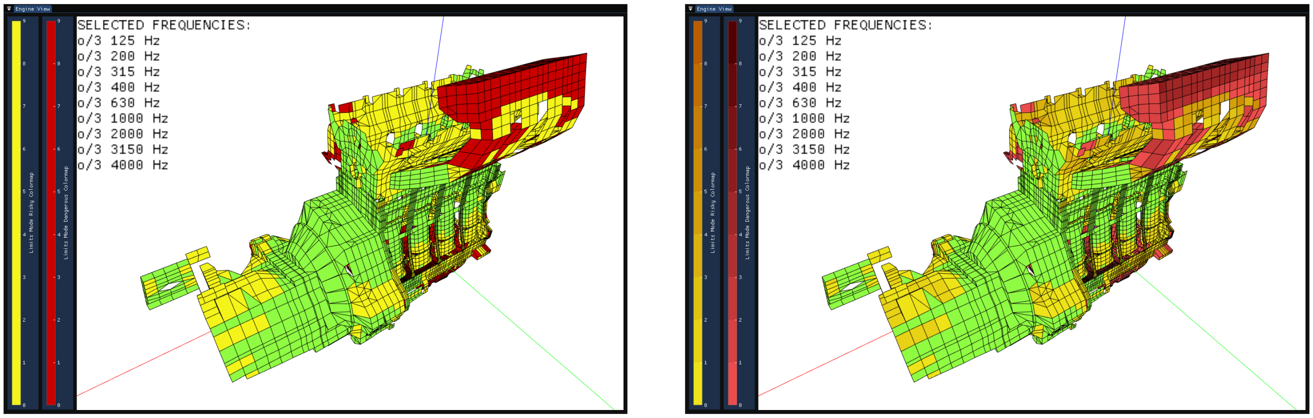
In addition to showing the computed velocity values, requirement R2 deals with externally specified thresholds. These thresholds are defined per frequency and specify if a velocity value is acceptable, borderline, or unacceptable. The thresholds are frequency-dependent, since the human sense of hearing reacts differently to different frequencies. We chose the commonly used traffic light metaphor, i.e., we use shades of green, yellow, and red, to depict the three acceptance values/zones in our visualization. Again, we have to show multiple values per element. This is accomplished by employing the following two strategies. First, if an element is in the red zone for at least one frequency band, we depict it as red; else if it is in the yellow zone for at least one frequency, we depict it as yellow; otherwise, we show it as green. In order to intuitively differ elements that belong in the same zone but for different number of frequency bands, we introduce a gradi-



SELECTED FREQUENCIES:
o/3 50 Hz AW
o/3 100 Hz AW
o/3 1250 Hz AW
o/3 2000 Hz AW
o/3 3150 Hz AW

SELECTED FREQUENCIES:
o/3 50 Hz AW
o/3 100 Hz AW
o/3 1250 Hz AW
o/3 2000 Hz AW
o/3 3150 Hz AW

Figure 4. *3D model view when using linear (left) and cubic (right) color mapping*



SELECTED FREQUENCIES:
o/3 125 Hz
o/3 200 Hz
o/3 315 Hz
o/3 400 Hz
o/3 630 Hz
o/3 1000 Hz
o/3 2000 Hz
o/3 3150 Hz
o/3 4000 Hz

SELECTED FREQUENCIES:
o/3 125 Hz
o/3 200 Hz
o/3 315 Hz
o/3 400 Hz
o/3 630 Hz
o/3 1000 Hz
o/3 2000 Hz
o/3 3150 Hz
o/3 4000 Hz

Figure 5. *3D model view displaying vibrations with regard to threshold values for a selected number of frequency bands. It is easier to notice which surface elements belong to the unacceptable or borderline zone. On the left, the surface elements are colored solely based on the "worst" zone that they belong to. On the right, the number of frequency bands that belong to the "worst" zone is taken into account when the zone's gradient is sampled.*

ent coloring scheme. We use shades of red and yellow to indicate if many frequency bands contribute to red or yellow (dark color) or just a few (light color). Figure 5 shows the two modes.

Detail Comparison View

The 3D model view provides a good overview, but once critical places are identified, a detailed analysis is needed. The detail comparison view uses bar charts to compare velocity values for selected surface elements for a selected subset of frequency bands. We use bar charts as they excel at comparing quantitative values [21]. We have also considered line charts, but we have rejected this option after discussing all advantages and disadvantages with the domain experts. Since the user can select multiple frequency bands and multiple surface elements, there are several ways to organize the charts.

We always use the $X-axis$ to depict frequency bands. Maintaining consistency in the layout of the charts lowers the mental load on the analysts, and they can focus on the analysis task without thinking what is shown on which axis. Figures 6-8 display three different options of graph comparison, which were added in order to satisfy T3. Aforementioned figures show that these options can display different aspects of the same selected dataset. Figure 6 showcases the option to display multiple bars per bar chart where each bar corresponds to a selected surface element. This makes it possible to compare the surface elements for each frequency band, and also to comprehend the overall trend across all selected bands.

Figure 7 shows that if we are more interested in comparing values for single surface elements across frequency bands, we show several bar charts, one for each surface element.

Finally, if we want to see how a particular surface element compares to the others, we explicitly depict differences to the selected surface elements. Figure 8 shows such a case. Positive and negative values are possible now. Note that in all the cases, surface elements are uniquely color-coded. When a surface element is selected, a unique color is assigned to this element.

Interaction

The two main views, the 3D model view and the detail comparison view, are integrated into a coordinated multiple views system. Interaction plays an important role in our approach. Due to data complexity and size, it is clear that not everything can be shown all the time. We access details by means of interaction.

Figure 9 shows a possible configuration of the system. Besides the two main views, there are several configuration views, where the user can select frequency bands, color scales, compari-

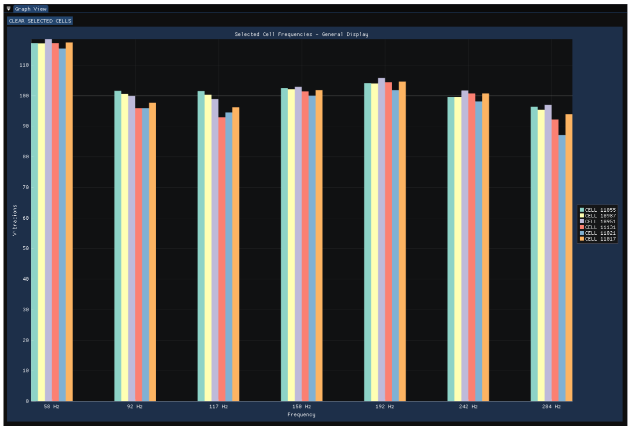


Figure 6. *The detail comparison view showing one bar for each selected element for all of the selected frequency bands.*

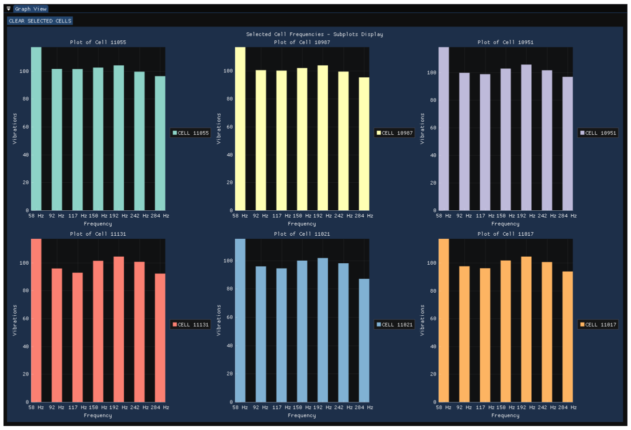


Figure 7. *The detail comparison view showing one bar chart for each selected surface element. Now it is easier to compare values for different frequency bands for each element.*

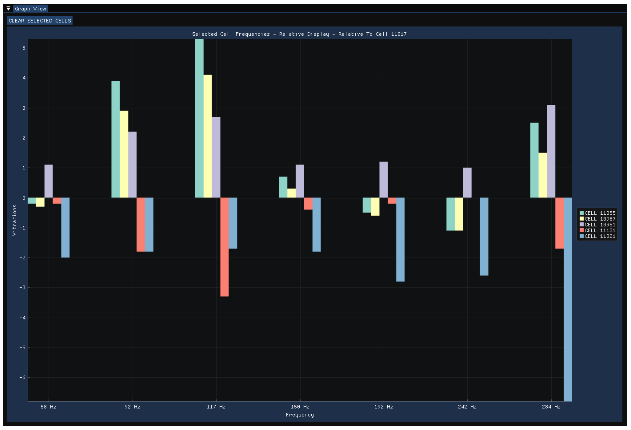


Figure 8. *The detail comparison view explicitly encodes differences of all elements to a selected element across frequency bands.*

son modes, etc. Figure 10 shows the color mapping configuration view for the 3D model view.

The 3D model view supports standard navigation (rotate, pan, and zoom) so that areas of interest can be seen. In addition, the surface element under the cursor is highlighted on mouse hovering. If the user wants to get details for the highlighted surface element, a simple click adds it to the elements of interest. All these elements are then shown in the detail comparison view. Similarly, hovering the mouse over the bars in the detail comparison view highlights the corresponding surface elements in the 3D model view.

Implementation

In order to evaluate the new approach, we have implemented a stand-alone Windows desktop application using Visual C++. We use OpenGL 3.3 for graphics and Dear ImGui and Dear ImPlot for GUI and graph elements. In the case of the model with 12 000 surface elements we achieve interactive frame rates. The frame rate was capped to 60 frames per second due to V-Sync being enabled on a monitor with 60 Hz refresh rate. The hardware configuration on which the application was tested consists of Intel® Core™ i5-6300HQ processor that runs at 3.20 GHz, Nvidia GeForce GTX 950M with 4 GB DDR3, and 16 GB DDR4 RAM main memory. We estimate that the system would run at interactive rates for more than 70 000 surface elements using the hardware configuration as described above.

Use Case

The new approach will be evaluated in depth with engineers from the simulation domain. Here, we briefly describe a preliminary use case employing our NVH data set. The goal of such an analysis is to help engineers identify critical parts of the engine. In order to reduce noise, they have to reduce velocities, i.e., vibration of the identified parts. This can be achieved by stiffening the structure, either by using stronger materials or by introducing additional stiffening elements, such as ribs, for example. The experience of engineers plays a crucial role in the selection of stiffening measures.

The analysis starts by checking which surface elements do not adhere to the externally defined threshold levels for selected frequency bands. We select four potentially critical frequency bands, the 800 Hz, 1250 Hz, 200 Hz, and 3150 Hz 1/3 octave bands. Figure 11 shows the threshold values for each surface element. There are some red values, and the oil-pan in the bottom part of the engine is one of the red parts. We zoom in to this part and switch the color mapping to the aggregated velocity values using the aggregation mode ”maximum” and a linear color scale, as shown in Figure 12. We hover with the mouse over the area of interest and observe the velocity values for each surface element in detail. We select some representative surface elements by mouse click. Figure 13 shows the seven elements we selected and the velocity values for these elements for each frequency band that is selected. Each element gets assigned its own color, which is also shown in the 3D model view. We see different distributions of the velocity values for different elements. In all cases but one, the maximum velocity values can be observed in the second frequency band (1250 Hz). The patterns for the other frequency bands differ more. The first frequency band is sometimes very similar to the second, and sometimes it is lower. The third and fourth frequency bands also follow different patterns. In order to examine distributions across elements for each frequency band, we switch to the comparison mode, which shows how values of individual elements vary for each frequency band (Figure 14). We

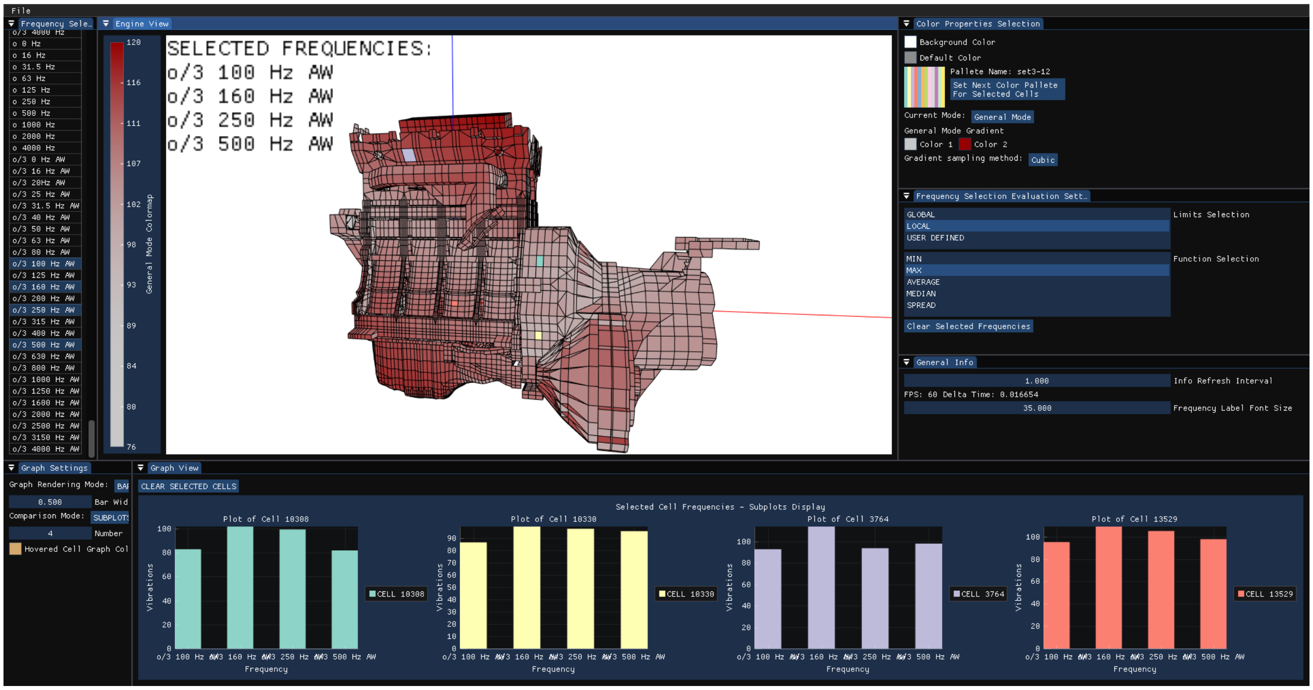
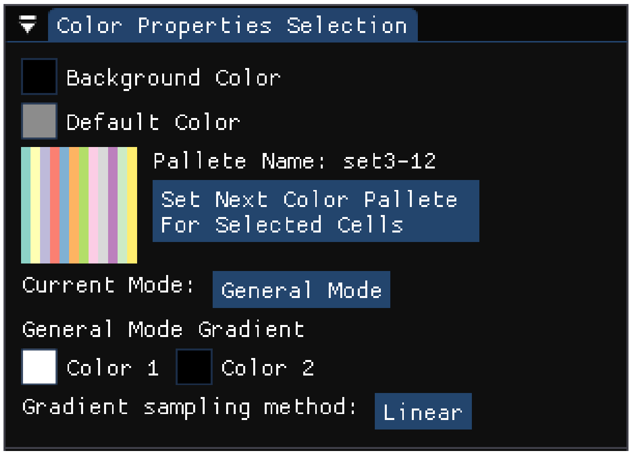


Figure 9. *A possible configuration of the views that make up the proposed solution: 3D model view, detail comparison view, settings for color, graph and frequency evaluation, frequency selection and general information.*



Color Properties Selection

Background Color

Default Color

Pallete Name: set3-12

Set Next Color Pallete For Selected Cells

Current Mode: General Mode

General Mode Gradient

Color 1 Color 2

Gradient sampling method: Linear

Figure 10. *Color settings view for the 3D model view.*

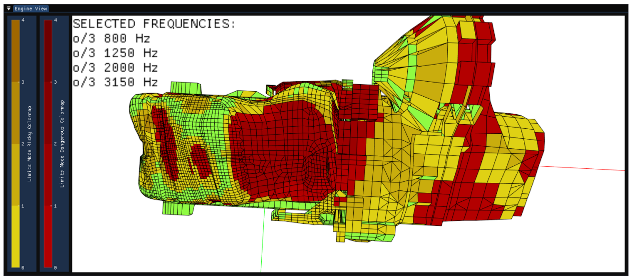


Figure 11. *A typical workflow for comparative analysis of NVH simulation data, step 1: Visualization of adherence to the external thresholds serves as the entry point into the analysis.*

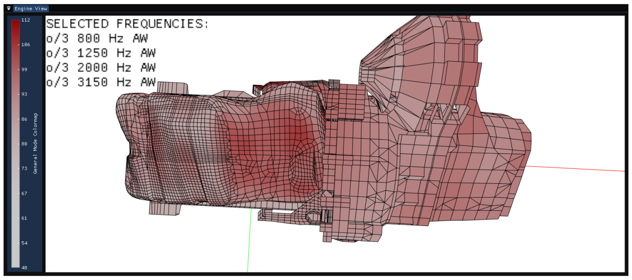


Figure 12. *A typical workflow for comparative analysis of NVH simulation data, step 2: The aggregated values for four selected frequency bands are shown using the aggregation mode "maximum". Velocities are visualized in more detail compared to Figure 11 since the engineers can see the value of maximum velocity that an element vibrates at, for given frequency bands, by looking at the element's colors and referencing the colormap on the left.*

see that the first two bands have higher values, and we can also see which elements contribute more. Finally, we are interested in how the elements compare to the blue element, which is the leftmost selected element in the 3D view. Figure 15 shows the differences to the blue surface element. There are always some values that are larger and smaller than the selected element. However, for the last frequency band, only one element has a smaller value (and the difference itself is small), and for the third frequency band, most of the values of other elements are larger. The first two frequency bands show mixed patterns.

Our approach makes the tedious comparison process much more efficient. As initial feedback is very positive, we expect that the engineers will soon incorporate the new approach into their daily workflow.

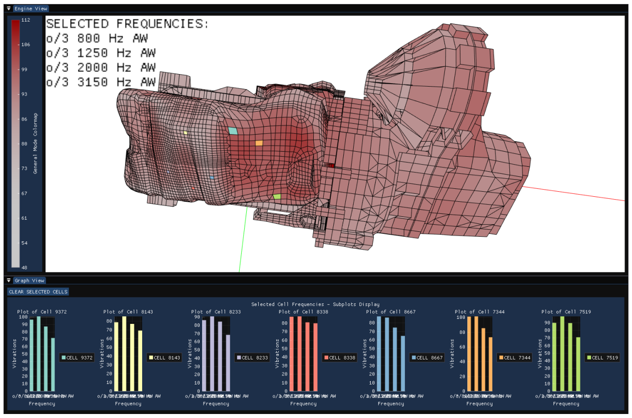


Figure 13. *A typical workflow for comparative analysis of NVH simulation data, step 3: Representative elements are selected and details for each of them are shown by using the bar charts. The bar charts show velocity values for each frequency band for all of the selected elements.*

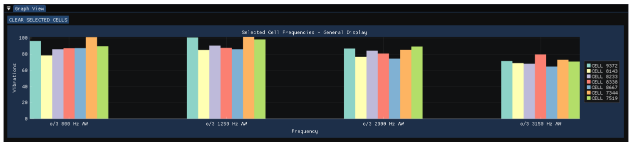


Figure 14. *A typical workflow for comparative analysis of NVH simulation data, step 4: The bar charts show all elements together for each frequency band. Here, the distribution of values for each band is in focus.*

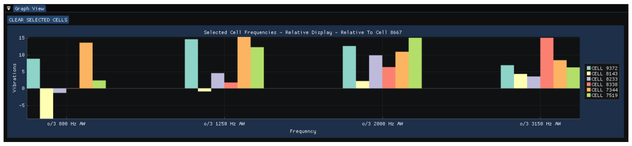


Figure 15. *A typical workflow for comparative analysis of NVH simulation data, step 5: The blue element is selected and differences between the blue and each other element are shown for each frequency band.*

Conclusion

In this paper, we describe an approach to comparative analysis for NVH data. Depending on the task, we deploy various comparison strategies, such as aggregation, juxtaposition, or explicit difference encoding. The newly proposed tool supports several methods of aggregating velocity data for every cell, which makes the tool more flexible to use for visualization tasks where aggregation seems to be the fitting approach. The proposed tool also supports displaying vibrations with regards to externally defined threshold values for selected frequency bands. When mentioned threshold values are taken into account, all cells are split into three categories based on the level of noise they produce and gradients are used to indicate for how many frequency bands do cells belong in their respective categories. In addition, various color mappings also support different comparison tasks and ease the comparison if the data is not uniformly distributed. All of the previously mentioned approaches provide spatial context when displaying data on cell velocities for given frequency bands, but our approach also allows the user to see velocity data in more detail but without spatial context by using bar graphs in which only cells selected in 3D model view are shown. In our case, we compare the value for different frequency bands. As we have 23 1/3 octave bands, we can have up to 23 bar charts. For a modern high resolution screen, this amount is just on the limit. The engineers rarely compare all the bands at once since the problems mostly occur in just some of the bands. The same is true for the surface elements. Although we do have many of them, only a limited subset is usually selected for detailed analysis. If the overview would show too many critical places, some radical changes to design would be needed anyhow.

The highly interactive nature of the newly proposed approach also contributed to a very positive feedback that we gained from the engineers. They can rapidly compare velocity values for large models now, and, by doing so, speed up the analysis process.

We plan to further continue our research on interactive visual analysis for NVH simulation data. An extension to support ensemble simulations, so that multiple lines from the Campbell plot are considered, is probably our next step. Additional research into topology-based methods might be interesting in order to see if this approach facilitates the overall structure comparison. Finally, we want to underline that the applicability of the proposed approach presented in this paper is not limited to the automotive NVH analysis. Obviously, it can be easily applied to NVH simulation data from other domains (such as any development of machinery). More importantly, it can be applied to the exploratory analysis of complex data that resides in two domains at the same time. We hope to find collaborators from different domains with complex data of similar structure.

Acknowledgments

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