

# BOBCAT REDUCES OPERATOR VIBRATIONS WITH WHOLE-VEHICLE ANALYSIS

Vehicles that run on tracks present unique vibration challenges. To minimize the effect on the operator, the partners Brüel & Kjær and Sound Answers equipped and trained Bobcat to characterize the entire, finished vehicles in all their complexity. Correlating these results with their finite element models helps improve their designs.



## CHALLENGE

Reducing human vibration from tracked vehicles, by understanding the complex modal behaviour of the complete structure

## SOLUTION

A complete system for structural analysis, with installation, support and training by expert consultants Sound Answers in partnership with Brüel & Kjær

## RESULTS

Improved understanding of structural behaviour, leading to new investigations and design directions, based on improved FE models

## BACKGROUND

Bobcat, established in 1947, has been a division of Doosan Infracore of South Korea since 2007. Bobcat Company is a leading global provider of compact equipment for construction, landscaping, agriculture, grounds maintenance, government, industrial and mining. They are North Dakota's largest manufacturer, with a distribution network comprising approximately 1000 independent dealers in more than 100 countries. In 2014, Bobcat reached the historic milestone of manufacturing their millionth loader.

The Bobcat family includes skid-steer loaders, compact track loaders, all-wheel steer loaders, compact excavators, utility work machines, utility vehicles and job matched attachments. In recent years, the compact track loader has become increasingly popular, and is an important part of Bobcat's product family.

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*Patrick Stahl, Bobcat engineer*

## CHALLENGE

The compact track loader creates unique comfort challenges due to vibration from the metal tracks. The resulting human vibration is increasingly becoming a differentiating factor, which can mark a vehicle out from the competition. This low-frequency vibration can also affect the machine's durability.

To improve the operator's comfort, Bobcat's engineers sought to improve their understand-

ing of vibration by assessing its causes and transmission. They wanted to use the knowledge gained to improve their computer-based finite element (FE) models, in order to help designers mitigate the problematic vibration.

### Large, heavy structures

For many years, Bobcat's engineers have regularly performed modal evaluations of components, using an impact hammer to excite the structure. But on large machines, they

### Vibrations in structures

Noise and vibration problems are often directly related to resonances in the structure, when operational forces excite one or more of the structural and/or acoustic modes. Modes are naturally occurring frequencies at which a small amount of input force creates a large amount of response.

All structures and systems have modes. In fact, any dynamic response of a structure can be described as a discrete set of modes. Each mode is described in terms of frequency, damping and mode shapes (bending, torsional, etc.).

With this information, engineers formulate a dynamic model of the structure. This can be used to understand and communicate how structures behave under dynamic loads, and help predict future behaviour if certain changes are made.



*The hard tracks on a compact track loader present a unique vibration challenge*

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had found that the energy input is insufficient to perform a broader, vehicle-level, modal evaluation, or to evaluate larger components. To get sufficient vibration energy into large and complex structures, there is a tendency to

‘overdrive’ the excitation when only a single input is used, which may result in non-linear behaviour at some locations, giving inaccurate measurements for linear processing approaches.

Even if an impact hammer was sufficient to excite the structure, it was a time-consuming method, requiring many small measurements using a limited number of measurement channels.



## SOLUTION

Sound Answers, a strategic consulting partner of Brüel & Kjær, helped to provide a solution for Bobcat. This comprised a 40-channel data acquisition and analysis system, accelerometers, and PULSE™ Reflex post-processing software. The team trained Bobcat's engineers while demonstrating the system in use on a test vehicle in a project to characterise a T630 compact track loader.

### Complete vehicle characterization

With their new system, Bobcat can test tracked vehicles in a completely assembled condition, with the loader in a single orientation. To make space for the shakers underneath the vehicle, the loader is set on level, wooden blocks. Input force is supplied by two 400 N shakers mounted underneath, and a 40-channel acquisition system collects and records the data.

For the initial testing, the response at approximately 190 points was measured all over the structure, using 12 roving triaxial accelerometers. The measurements were made with a bandwidth of 200 Hz, which was sufficient to define typical vibration durability and tactile vibration issues.

### Multiple input, multiple output

To characterize the complete structure of a T630 tracked vehicle, the team decided on a multiple-input, multiple-output (MIMO) approach to modal analysis. This means the input-force energy is distributed over more

### Complex component interactions

In order to use test results for correlation with FE (finite element) design models, it is important to evaluate components as part of the larger system, where the dynamic interaction of the whole structure influences the results. Bobcat had found that it was usually easy to get a good correlation between FE models and experimental results when evaluating simple weldments. However, as more components were added and complexity increased, it became difficult to know how to simplify the system into a reasonable FE model.

Minimizing the complexity was one solution, but in the final, complete vehicle, bolted joints and other components such as the cooling system, and hydraulic hoses increase the amount of structural damping. So it was difficult to know how many components could be removed while still giving a faithful picture of the structural performance. Consequently, Bobcat's FE models often over-predicted the number of important modes, leading to un-

necessary design limitations. As one engineer at Bobcat, Patrick Stahl, says, "Over-predicting the important modes meant that the model was unrealistic, which led to us trying to design for things that were not actually a problem."

Added to this were difficulties in properly accounting for the machine's interaction with ground when making modal assessments.

"THIS PROJECT GAVE US THE BEGINNING THAT WE NEEDED, PROVIDING THE SPARK THAT BEGAN THE INVESTIGATIONS WE ARE NOW CONTINUING ON OUR OWN."

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locations, to fully excite all the modes of interest and provide a more uniform vibration response over the structure. Excitation in multiple locations also better represents the real-world excitation forces that the structure will face.

A basic modal hammer pre-test survey helped to assess the best excitation locations for the two shakers. Two vertical direction locations were selected at opposing corners on the main chassis. However, some shaker correlation difficulties were encountered due to the combined high stiffness of the structure and relatively close proximity of the shakers. Consequently, the shakers could not run simultaneously without poor FRF (frequency response function) quality, but were instead run separately, which ultimately combined two SIMO data sets per accelerometer rove.

### Sound Answers

Sound Answers is an engineering services company that specializes in noise and vibration (NV). It offers unique consulting expertise in sound and vibration quality target development, in cascading NV targets from system to component levels, in root-causing NV issues, and in developing cost-effective processes to streamline the noise and vibration aspects of product development.

The co-founders of Sound Answers, Dr Gabriella Cerrato and DJ Pickering, have worked together since the late 1990s, initially for the test software and consulting division of Structural Dynamics Research Corporation (SDRC), which was later acquired by MTS Systems Corporation. In 2005, when MTS discontinued their noise and vibration division, Cerrato and Pickering started Sound Answers Inc. Sound Answers staff has since grown by an additional 11 engineers, with experience in all areas of product noise and vibration.

A further modal hammer test was also performed on the loader arms, to confirm that the vertical shaker locations on the chassis were sufficient to excite the modes of the loader arms.

### RESULTS

The project conducted under the guidance of Brüel & Kjær and Sound Answers achieved a good understanding of the structure. "Being able to test an entire machine has been help-



ful in determining the critical components,” says Patrick. “Just reviewing the mode shapes was useful.”

Brüel & Kjær’s PULSE™ Reflex Modal software was used to process the data, and provided Bobcat with a list of natural frequencies and damping ratios. It provided static plots of mode shapes, modal animations, and sensitivity transfer functions between sources such

as the engine, the hydraulic pump, the tracks, and the cab where the vibration is received.

“The project has been useful for improving our FE models,” says Patrick. “We are already better able to represent the machine-to-ground interaction and include the appropriate damping.” Bobcat also updated their FE models for their hydraulic cylinders as a result of the project.

### **Knowledge transfer gave Bobcat expertise**

Bobcat’s engineers worked alongside Brüel & Kjær and Sound Answers to learn about the test methods. “We followed Sound Answers’ and Brüel & Kjær’s expertise when it came to setting up the project,” says Patrick. “Their help was very valuable, giving a good idea of the frequencies we were looking for, and where to place accelerometers to give a good spatial resolution so as not to miss any modes.”

Bobcat’s engineers learnt how to perform a hammer modal test on the powertrain, in order to identify the rigid body modes. They also learnt about including additional, high-mass components in the test. They learnt about reducing the number of measurement points, and the option of using skewed shaker inputs was also discussed, as a potential to aid the overall body excitation and modal curve-fitting. In addition, modal correlation methods were discussed, using Brüel & Kjær’s PULSE™ Reflex Modal Correlation software.

### **Insights led to new design approaches**

The engineers found that there wasn’t as much activity in the lift arm as they had expected from the modelling, which had over-predicted the modes. Perhaps the most

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important finding, however, was in the cab where the operator sits. Here, they discovered much more activity than expected, especially in the operator’s door.

As a result, they then took on a new project to analyze the cab in minute detail – down to the level of the window seals. This follow-on investigation is seeking to improve the whole cab structure and mounting in future iterations, all to better isolate the operator.

“This project gave us the beginning that we needed, providing the spark that began the investigations we are now continuing on our own,” says Patrick.

As their expertise has bloomed, Bobcat’s testing has also become more sophisticated. With more complex set-ups they can measure at more points, and develop a better understanding. “As we’ve learnt more about our product, we’ve refined the measurement process in

many ways,” says Patrick. “We used to look only at FFT spectrums and 3rd-octave analysis, but now we are looking at time histories and using sound quality metrics. “We’ve also become able to locate our transducers better, with the result that we can predict the operator experience more effectively. An example is that we’ve begun placing microphones at the operator’s head position and in the engine compartment, so that we can understand the sound transmission loss.”



## CONCLUSION

The project revealed valuable insight into the structural performance of Bobcat's compact track loaders. "Not everything on the machine was as important as we thought," says Patrick. "The results have led us in a different design direction as we look for ways to improve operator comfort."

It also gave Bobcat the start they needed, leading to refined investigations that help them understand their product, and, in turn, help them innovate to improve the operator's experience. As Patrick says, "Working with Brüel & Kjær and Sound Answers has been beneficial as we gained a lot of knowledge about the modal analysis process. They have been a valuable contact for us." Bobcat will continue to perform this testing in-house in the future, thanks to the partnership team's help.

DJ Pickering, Vice President of Sound Answers Inc. says, "With our combined experience and access to Brüel & Kjær's world-class equipment, we were confident that we could help Bobcat come up with a modal testing solution ultimately for their operator comfort and durability issues."

MIMO testing is useful for large and complex structures with heavy damping, and Bobcat is now equipped to perform it. However, SIMO testing was better for this initial project. And with a complete data acquisition and analysis system, Bobcat is equipped for many structural testing scenarios, allowing them to continually improve their FE models, and thus their design approaches.



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