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# Tools for Integration of Analysis and Testing

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## ABSTRACT

The automotive vehicle design process has relied for many years on both analytical studies and physical testing. Testing remains to be required due to the inherent complexities of structures and systems and the simplifications made in analytical studies. Simulation test methods, i.e. tests that load components with forces derived from actual operating conditions, have become the accepted standard. Advanced simulation tools like iterative deconvolution methods have been developed to address this need. Analytical techniques, such as multi body simulation have advanced to the degree that it is practical to investigate the dynamic behavior of components and even full vehicles under the influence of operational loads. However, the approach of testing and analysis are quite unique and no seamless bridge between the two exists.

This paper demonstrates an integrated approach to combine testing and analysis together in the form of virtual testing. Multi body simulation software [1] was used for multi body simulation of both the component under investigation as well as the test equipment used for physical testing. Road load simulation software [2] was used to reproduce field observed data on both the physical and virtual test rigs. There are two main advantages to this approach. The integrated application of physical and virtual tools allows the user to conduct virtual tests prior to having physical prototypes available. This accelerates the design process and can reduce cost. Secondly, by using a common framework for all physical and virtual investigations, the results remain comparable and trouble shooting of both domains is facilitated. This paper presents the results of a study of a vehicle mounted refrigeration unit. Observed failures in both physical and virtual tests corresponded very closely with respect to location and time to failure.

## INTRODUCTION

Good vehicle design requires extensive analysis and adequate testing. In the past, the analysis and testing were separate entities. The approaches of test engineers and analysts to study vehicle behavior are quite different. In the lab, accelerated testing methods have been developed and proven to provide accurate durability and performance information. These methods usually involve special test equipment and simulation software [3], [4], [5]. On the other hand, analysts usually only simulate the vehicle on the road rather than in the lab. As a result, physical and virtual results do not agree due to:

- Load paths are not the same
- Boundary Conditions are not the same
- Test procedures differ
- Test setup and transducer locations differ
- File formats are different
- Result processing and display differ
- Inaccuracy in modeling in non-linear systems.

The desire, therefore, is to integrate the testing and analysis by conducting virtual tests. Virtual testing in this context is defined as the simulation of physical tests by using a variety of analysis tools. The following are advantages of the virtual test method:

- Virtual tests can be conducted at a very early design stage.
- The design can be evaluated before an expensive prototype is built.
- A test can be simulated before the test equipment is available.
- The simulation can provide information regarding the type of test equipment needed.
- Load and boundary conditions can be investigated.
- Virtual tests can be conducted faster, easier, and at lower cost than physical tests.
- Additional information can be obtained from a virtual model that is not readily available from a physical test. For example, “requests” can be made for displacement, velocity, acceleration and load at any point in the structure.
- A number of design alternatives can be rapidly evaluated in “what if” studies. This allows optimized design with respect to cost, weight, durability, etc.

## PROBLEM DESCRIPTION

A refrigeration unit (often configured to provide heating and cooling) is used for different types of truck trailers. The refrigeration unit of Figure 1 is mounted in front of a trailer. During the 3 million kilometer projected lifetime of a refrigeration unit, the trailer will travel on different types of road surfaces that will induce specific loads.

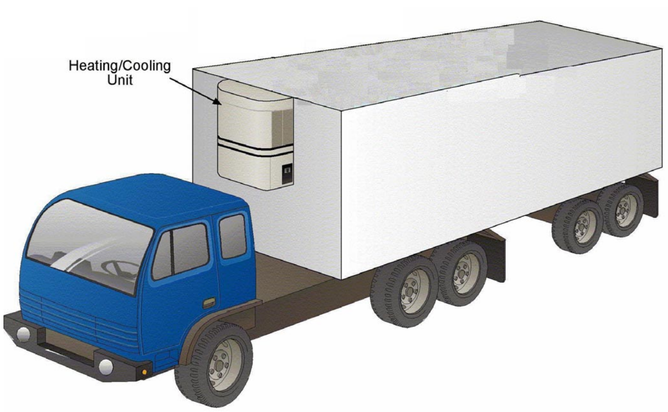


Figure 1. Truck, trailer and heating/cooling unit

Through the virtual test method, the frame design was evaluated with respect to fatigue life. The virtual test result was then validated by a physical test.

## MODAL ANALYSIS

To understand the dynamic behavior of the refrigeration unit, modal analysis was conducted. Natural frequencies and corresponding mode shapes were found. The lowest natural frequency of the frame-bending mode was about 80 Hz. The frame design is considered sufficiently rigid. The result helped to understand the dynamic behavior of the refrigeration unit and provided guidance to select the fatigue analysis method. In an ideal situation, analytical results are correlated with modal test results to assure FEA accuracy, this step was not performed due to time constraints.

## SIMULATION TESTING [6]

With the advent of minicomputers and lower cost array processor technology in the mid-seventies, a technique was developed [7] that used an iterative technique to converge toward accurate recreation of measured service responses in the laboratory. This technique was based on the deconvolution of response errors with a linear frequency domain estimate of the system and the frequency response function (FRF). Due to the advantages of this compensation technique for accurate reproduction of both amplitude and phase in the response of non-linear, coupled, multiple-input systems several commercial versions of the algorithm were developed.

Initially the application of the iterative deconvolution method was the control of laboratory full vehicle automotive test systems, either tire or wheel spindle coupled. The control challenge is to simulate or reproduce service-loading conditions on these test systems (the desired specimen responses, accelerations, loads and displacements) by applying loads remote from the point of measurement. Service loads that can be measured and recorded on a vehicle component in service or on the proving ground are measured on the body or on the suspension components but the actual loading into the vehicle is through the tire contact patch with the road. At a minimum a non-linear tire spring is introduced into the control scheme. Additionally, the responses measured are frequently due to load inputs from more than one tire patch. By using an iterative deconvolution approach, both the non-linear spring effects and the cross-coupling can be compensated and accurate vehicle component responses can be simulated in the laboratory. Subsequently, the technique has found wide application in automotive sub-system and component testing where testing of the specimen involves recreation of specimen loading due to multiple inputs applied through a non-linear system. This technique can also be applied for the execution of virtual tests.

It is important to note that both the amplitude and phase of both the multi-axial input and output in the laboratory test have to be preserved to allow the multi-axial service loading effects on the specimen to be accurately reproduced. This limits the options available to the laboratory test engineer to “accelerate” the test beyond what would take place in service. The most common method is to examine the desired response loads and strains and use a time history editor to remove those sections of the service or proving ground load histories that provide low damage to the specimen. The software tools to perform this task, either manually or through some fatigue sensitive editing routine, are usually provided as part of the iterative deconvolution package. Depending on the mix of severity of the service or proving ground road surfaces test, “accelerations” in the order of five to ten times real time are possible. Insofar as the endurance life testing performed on such units in Europe, acceleration rates approach 275:1. This per the fatigue analysis provided by the test facility when comparing damage between “typical” road surfaces and the specified track regime.

The development of a typical iterative deconvolution compensation test takes place in six steps.

1. Record Service or Proving Ground Data - The specimen is instrumented with low frequency sensing accelerometers to measure its response to service loading, where the service loading is represented by running the vehicle at a proving ground. The specimen responses are simultaneously recorded as a time history on a tape recorder or equivalent

recording device. “Control” transducers are applied at the specimen mount interface for the purpose of recording the desired response motions. “Correlation” transducers are applied to obtain additional information to judge the quality of the simulation test and provide redundancy in case any of the control transducers fail [8].

2. Digitize and Analyze Data - The recorded time history is transferred to the computer-based analysis system. This may involve digitizing an analog time history recording. Using the analysis tools provided in the iterative deconvolution software package, the data is checked for accuracy and possibly reduced in length using the editing tools described earlier. The output of this step is a set of multi-channel digitized time history records or files containing the "desired response" of the laboratory test system.
3. Measure the System Frequency Response Function (FRF) - The test specimen is connected to a laboratory or virtual test system. A set of drive signals is developed to excite the specimen in the test system and the specimen response is measured through the same instrumentation used to measure the service load data. Typically the drive signal developed is a set of uncorrelated shaped random multi-channel time histories although a single channel may be subsequently excited. In this application, multi-channel excitation was used. Using FFT based spectral analysis methods a linear estimate of the frequency domain response function of the complete test system plus specimen is computed. These linear Multiple-Input Multiple-Output (MIMO) models of the system contain the amplitude and phase of the input-output characteristic of the system between all inputs and outputs over the frequency control band of interest. This system model is then mathematically inverted to become an output-input model in preparation for the next step in the process. In some cases a system model where the number of outputs exceeds the number of inputs may be useful. In these cases the system is over-determined and the general approach is to compute a “pseudo-inverse” where residual errors are minimized in a “least squares” sense. This takes the response of more locations into account and averages their respective influence.
4. Apply Drive Estimate to the System - Each of the desired response time histories is convolved with the inverted system model, which is deconvolved with the forward system model to provide an estimate of the system drive signal required to produce the response. Note that this estimate is based on a linear model and therefore may be substantially in error. From safety considerations (in case of a lab test, not required for virtual tests) this drive estimate is scaled, typically by half, and applied to the test system. The resulting response of the specimen is measured.
5. Calculate Error and Iterate - The desired specimen response is subtracted from the response achieved on the test system due to the drive signal and a calculated response error signal. The response error signal is convolved with the inverse system model and a linear estimate of the drive error signal results. A scaled proportion of this drive error is added to the previous drive signal to produce a better estimate of the drive signal required to produce the desired response, scaling being employed to reduce the possibility of overshoot and instability in the iterative process. The modified drive signal is then used to run the test system and the new response is recorded. A new response error is calculated as described above and the process repeated (“iterated”) until the response error is reduced to an acceptable value, that is, when the achieved response on the test system has converged onto the desired service load response. This process is repeated for all separate service load recordings made. The final sets of drive files for each response signal are combined into a durability test schedule.
6. Execute Durability Schedules - The final step is to run the durability test schedule into the test system and monitor the performance of the test specimen over the laboratory simulated service life. For a virtual test fatigue analysis can be performed to estimate the fatigue life for a given durability schedule of loads.

Attributes of iterative deconvolution control:

- Can over-program, i.e. during the iteration process loads higher than field measured loads may be applied
- Requires use of a computer (typically a PC) and an analog-to-digital, digital-to-analog conversion device to drive the test system and measure the responses.
- Pre-training required through measurements of the system transfer function using multi-channel orthogonal white noise or input-by-input excitation.
- Works with non-linear systems that exhibit cross coupling between inputs and outputs.
- Matches achieved system amplitude and phase to the desired responses.
- Number of iterations required for a given accuracy of reproduction can be reduced through modification of system frequency response function at each iteration step.
- Applicable to both physical and virtual tests.

## DATA ACQUISITION AND ANALYSIS

In this application, the refrigeration unit was mounted to the trailer frame through seven mounting locations. Four tri-axial accelerometers were positioned at four corners of the refrigeration unit. Two vertical, three longitudinal, and one lateral acceleration channel were used as control channels for a total of 6 degrees of freedom. Additional acceleration channels were acquired as correlation channels. Data was collected directly in digital format using a sample and hold circuit prior to the analog-to-digital (A/D) converter. The data acquisition sample rate was 512 points per second. Because the highest frequency to be reproduced was less than 50 Hz, the sampling rate was considered high enough to provide good peak resolution. The truck trailer was towed over five selected proving ground surfaces to measure the response-time histories that were representative for a variety of operating conditions. Low-pass analog filters, designed to roll off before the Nyquist frequency, were applied to the data prior to digitizing to prevent aliasing on each recorded channel. The data collected from the proving ground was analyzed to determine the most significant and required inputs for the specimen under consideration. Non damaging portions were removed and remaining sections of the files were then smoothed on either side of the deletion region to remove any discontinuity prior to joining them to a new history.

The edited time history was then band pass filtered. The pass band for the acceleration signals is from 1 Hz to 50 Hz. The reason for this selection is that the testing system is an inertially reacted system for which it is difficult to achieve low frequency control without large actuator displacements. The upper frequency is chosen based on the experience that little road-induced damage is induced for frequencies above 50 Hz.

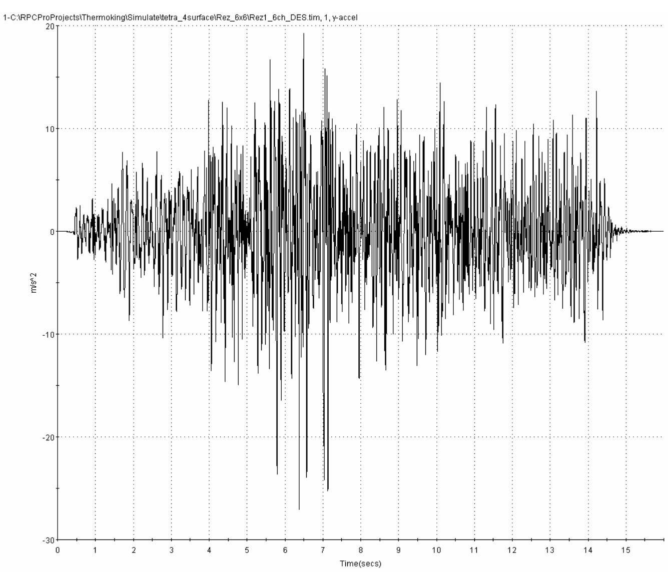


Figure 3. Representative Edited and Filtered Acceleration Time History

## PHYSICAL TEST RIG

One commonly used test system for components that experience loads due to their inertia, such as the refrigeration unit, is a multi-axial simulation table, shown in Figure 4. This type of system allows the excitation of each of the six degrees of freedom (namely translation in x, y, z and rotation around these axes). Typically, the simulation range is up to 50 Hz.

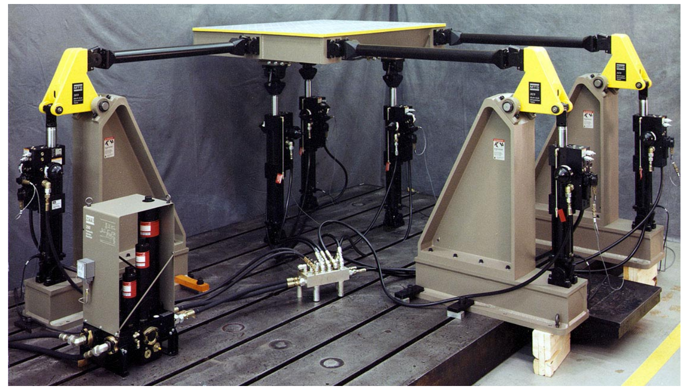

Figure 4. Multi-axial simulation table

## VIRTUAL TEST RIG MODEL

Functional Virtual Prototypes are based on three-dimensional component solid models and modal representations of component finite element models to accurately predict the operating performance of the product. Depending on the level of detail desired individual components will be modeled with a varying degree of complexity and resulting accuracy [9].

The multi body dynamics model of the test system originated from the CAD model. Care was taken to replicate key features such as geometry, mass properties, and global stiffness properties. All of the appropriate communicators were set up so that the test rig model would couple directly to a multi body dynamics model of the specimen.

For this initial study, the test stand model was kept as simple as possible. All of the test stand components were assumed to be rigid bodies. While this is a simplification of the existing physical test rig it was believed that all relevant static and dynamic properties required for a comparison of responses from analytical and physical prototypes were retained. In most test cases, this can be assumed, in that the Eigen-frequencies of the fixture are typically above 50 Hz. Model development always involves trade-offs between model accuracy and computational efficiency. The development of a validated model is elusive at best. A model is only valid over a specific range of applications.

A multi body simulation model of the test rig, fixture and the refrigeration unit was built (Figure 5). The fixture and part of the refrigeration unit was modeled by beam elements to consider the flexibility of the system. The refrigeration unit was connected to the fixture through seven fixed joints at the actual frame mounting locations. Requests were set up to output the acceleration information at the accelerometer mounting locations. The power train assembly was modeled as a rigid body. The three engine mounts were modeled by bushing elements. The three snubbers, which restrict engine travel, were modeled by force elements.

In this study the virtual test process is predicated on data gathered from an existing production unit with similar structural and mass characteristics.

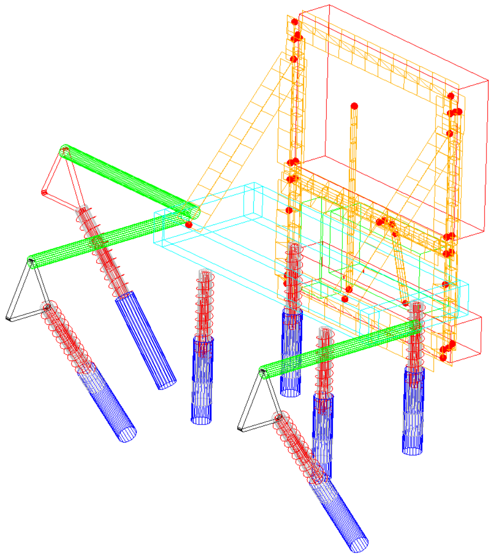

Figure 5. Multi Body Simulation Model of the Test Rig and Specimen

VIRTUAL TEST SERVER

For a complicated multi body simulation model, it usually takes a long time to obtain a simulation result. In this case, it took about 60 minutes for a 1 GHz, 1 GB RAM PC computer to obtain the solution for a sixteen second event. Therefore, the iteration process with a virtual system could be quite lengthy especially when the system is quite nonlinear and many iterations are needed to minimize the error.

Software has been developed that allows for seamless communication between the road load test rig simulation software and the multi-body simulation software. This allows for the exchange of files and multiple iterations to be conducted automatically. This facilitates batch type execution of the iteration process without requiring user interaction and thereby saving time.

## DURABILITY TEST

PHYSICAL TEST

The drive files are nested together in a sequence/block that reproduces a lap around the proving ground. The block is repeated until a target goal has been met. In this test, a block sequence was defined that contained five different road surfaces. The physical durability test then repeated this block sequence. At 10,070 repeats a failure was observed at a snubber mounting location (Figure 6). In addition a bracket and bolt failure were observed. It is assumed that these failures were independent of each other.

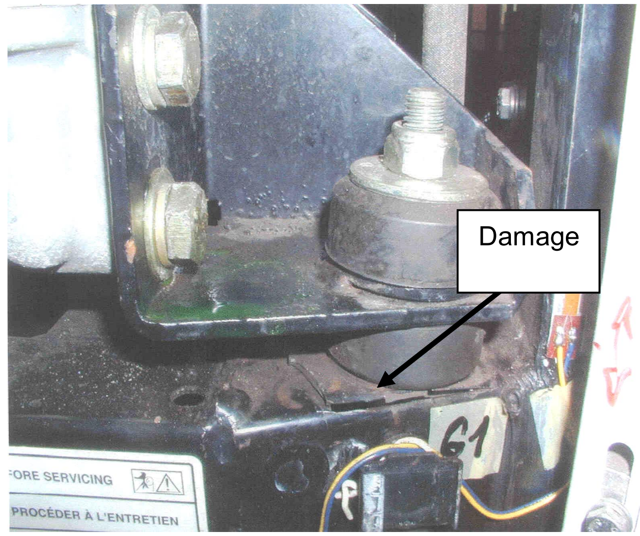


Figure 6. Frame damage at the snubber mounting location

VIRTUAL TEST

Unlike the physical system, the virtual system is perfectly repeatable and therefore a single repetition and average building was sufficient to estimate the frequency response function (Figure7).

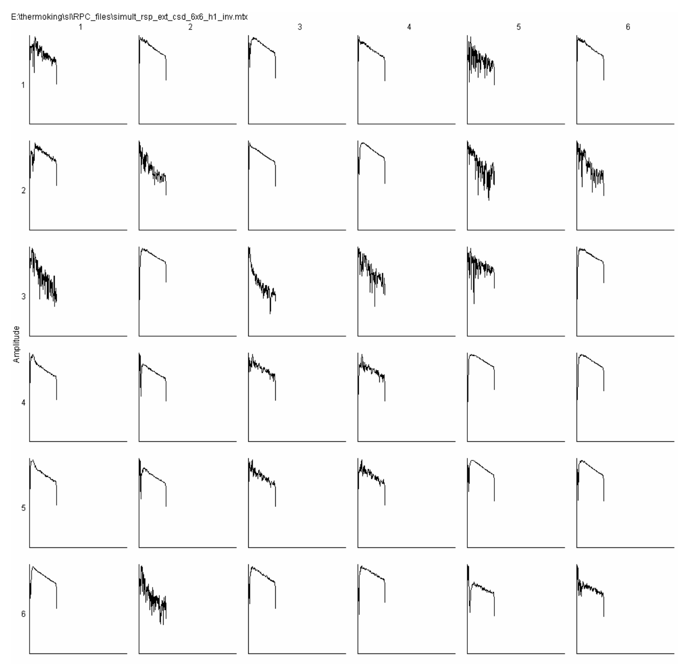


Figure 7. FRF of the Virtual Test System

Like for the physical system, iterative improvements to the drive signals were performed to reproduce the desired response signals. In this application, two iterations were conducted for each road surface. After two iterations, the

RMS errors for the six acceleration channels were all below 15% for all events.

Figure 8 shows the desired vs. achieved time history of one such event. This demonstrates that a virtual test system in conjunction with iterative road load simulation can reproduce the road measured acceleration signals accurately.

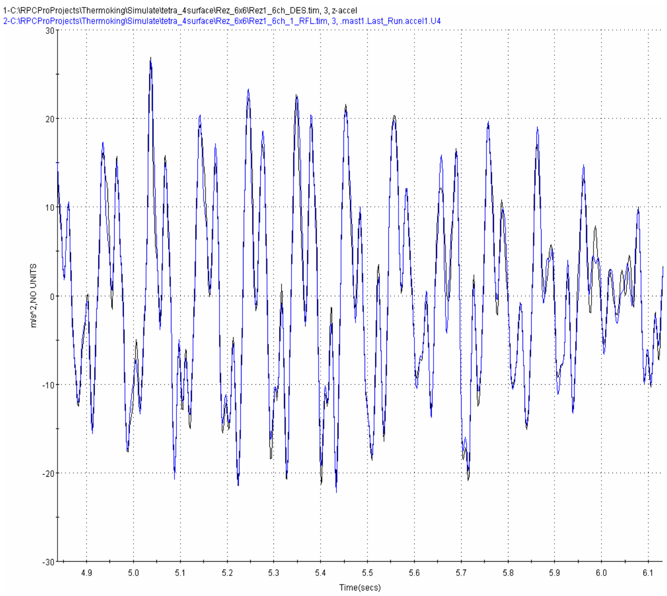


Figure 8. Desired and Achieved Time History after Iterations

LOAD OUTPUT

After the drive files that could reproduce the measured acceleration signals were developed, they were played out through the virtual model. The loads transferred through each frame mounting location, each engine mount location, and each snubber location were recorded in the for the subsequent fatigue analysis. At each frame mounting location and each engine mount location, six load channels of data were exported (three forces and three moments). At each snubber mounting location, there is one force output channel. Therefore, a total of sixty-three channels of loads were exported from the virtual prototype model for each road event. The load time history files can also be used as input for a dynamic stress analysis.

STRESS ANALYSIS

To calculate the stress distribution, an Finite Element Analysis (FEA) model was built. A total of sixty-three load cases were considered. These consisted of seven mounting locations, three engine mount locations, and three engine snubber locations with a total of sixty-three load components. For each case a unit load was applied. Inertial relief calculations were conducted for each load case to obtain the stress distribution. In the inertial relief calculation, the FEA software finds an acceleration field to balance the applied load and then finds a static solution to obtain the stress distribution due to the applied load and the balancing acceleration field. An inertial relief calculation was chosen because it does not require any boundary conditions to be applied.

After solving the sixty-three load cases, the result was exported for fatigue analysis.

FATIGUE ANALYSIS

The sixty-three load cases of stress information from the FEA model and the sixty-three load time histories from the virtual prototype model were imported into the fatigue analysis software [10]. Based upon the schedule of the accelerated test, a static strain life calculation was conducted to estimate the life of the structure. The static fatigue analysis was chosen because the modal analysis shows that the lowest frame natural frequency is above the frequency range interested. Smith-Watson-Topper mean stress correction and Neuber elastic-plastic correction was used.

After fatigue calculation, the result file was output in FEA model, where the life of the refrigeration unit was plotted. In this way, the life estimation of the refrigeration frame can be observed at all locations.

A physical durability test takes at least several weeks even for the accelerated test. However, the virtual durability test is only a fatigue analysis, which may only take several hours. The time saving fatigue analysis is a big advantage of the virtual test.

## VIRTUAL VS. PHYSICAL TEST RESULT COMPARISON

Virtual testing predicts that the snubber mounting locations would fail first which matches the lab test observation. Figure 9 shows the virtual life prediction plot that corresponds to the failure location in Figure 6.

From the fatigue life plot, one can see the fatigue life of the virtual test = $10^{4.243}$ = 17,500 repeats. In the lab test, failures were observed at 10,070 repeats. The ratio between virtual and physical fatigue life is 1.7, which can be considered a close match.

The bracket and the bolt failures that occurred in the lab test were not predicted, as these parts were not modeled due to their complexity. These failures may have been caused by the snubber failure. This reinforces the continuing need for physical testing as not every aspect can be efficiently modeled with current technologies.

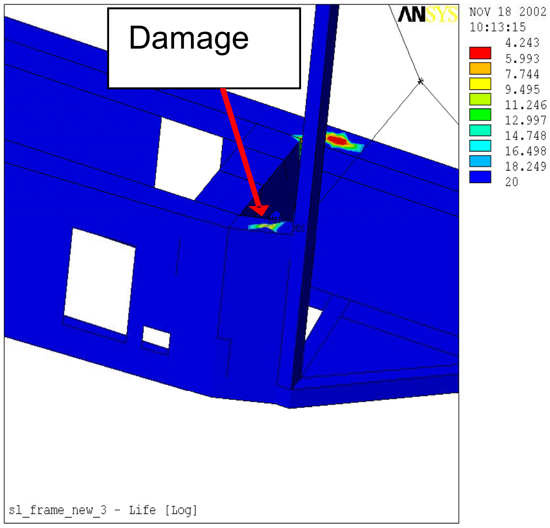


Figure 9. Fatigue life prediction at the snubber mounting location, same location as failure in Figure 5

## SOUND QUALITY ANALYSIS OUTLOOK

A range of additional predictive analysis can be performed within the virtual prototype environment once the level of correlation to a physical prototype is shown. One such study that the authors are contemplating is the prediction, and comparison to measured results, of sound power emitted from the structure. The pre-requisite of predicting structural response accurately with respect to phase and amplitude has been met as can be seen from the close fatigue life prediction and waveform agreement as shown in Figure 8. The validated finite element model can provide input information for an acoustic analysis model. Sound power emission of the evaporator unit can then be predicted by the acoustic analysis. From the actual sound power a host of subsequent analysis can be performed with respect to measured and perceived sound characteristics. After the acoustic model is validated, what if type of analysis can be conducted to evaluate options to insulate the system.

## CONCLUSION

By conducting a virtual and physical test of a truck trailer refrigeration unit, we have demonstrated an integrated approach to evaluate a vehicle component design. This approach involves both physical testing and virtual testing. Simulation of road load data using iterative road load simulation software was used for both the physical and virtual tests. The virtual test can help to evaluate the design at the very early design stage.

Due to the inherent complexities (especially when flexible bodies are considered) and the fact that not all dynamic effects and details of the design will be modeled accurately, uncertainties arise. Therefore, it is highly recommended to validate the models before signing off on a design for production. The optimal method for validating an analytical prediction is to perform a physical and virtual test that correspond to one another and reflect realistic operating conditions. Virtual testing as presented in this paper is intended as a design development tool and not as a substitution for final acceptance testing of a design.

The virtual test can provide information to design the test setup and conduct better tests. The virtual and physical integrated approach can accelerate the vehicle design process significantly.

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