Validation Study Of Silastic J Viscoelastic Model

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ABSTRACT

This research project is a validation exercise of a Silastic J viscoelastic material model that uses tools such as design of experiments (DOE), experimental testing, finite element analysis (FEA) modeling, feature extraction, and validation metrics. Because the Silastic J material is rate and temperature dependent, the material model is able to be developed from tests in the 0 to 10 Hertz range at varying temperatures. Analysts, however, are interested in using the Silastic J model in structural responses at far higher frequencies than the tested range. Material behavior is therefore extrapolated for these higher frequency ranges by using time-temperature superposition (TTS). Time domain acceleration data are collected from a concentric aluminum ring structure with a constrained layer of Silastic J. Acceleration histories are also extracted from nodes representing the physical accelerometer locations in a FEA model. Using these data sets and a rigorous validation process, the research project intends to prove whether or not the extrapolated TTS model holds true for the Silastic J compound for frequencies above 10 Hertz.

NOMENCLATURE

P_f = Signal Power

T = Time Period

$f(t)$ = Sinusoidal Function

1 Introduction

The purpose of this project is to validate a time-temperature superposition (TTS) model for Silastic J RTV silicone rubber. Silastic J was originally designed and manufactured by the Dow Corning Corporation and is a synthetic elastomer made from a cross-linked polymer reinforced with silica. The result of this unique composition is a very versatile material that can be used in a wide variety of demanding applications. The drawback, at least from the modeling standpoint, is that the Silastic J material also displays viscoelastic properties; meaning that the stress-strain characteristics of the material are dependent upon both loading rate and temperature. These viscoelastic properties make the material very difficult to model, especially when high-fidelity simulations are required; however, it is the viscoelastic properties of Silastic J that also allow the use of the TTS principle. Since the material will be stiffer at lower temperatures and higher strain rates, it can be tested at low temperatures (-60 ℃ to 0 ℃) and then the data can be shifted to an analogous higher strain rate. This temperature dependence allows the prediction of material behavior at higher frequencies. The supplied model came from tests of the Silastic J material in a dynamic mechanical analyzer equipped with a temperature control chamber. The material was physically tested over a variety of temperatures from 0-10 Hz and then a master curve for room temperature was extrapolated from the data. The intended purpose of this research is to validate whether or not the current TTS model provides a high-fidelity representation of the material when responding to frequencies higher than 10 Hertz.

Most of the background information on the project comes from various papers on verification and validation of simulations and models. Many times in modeling and experimentation, as long as the model fits the data, or if the viewgraph norm qualitatively looks good, the model is considered valid. However, researchers are now starting to more rigorously quantify the error and variance in the simulation results to justify and 'build a case' for whether the model actually predicts the system response [1]. Validation also relies heavily on various aspects of statistics to show a certain confidence level in the predictive capability of the model. Standard statistics such as mean, standard deviation, and variance are utilized along with a wide variety of other types of statistics and indicators, such as the t-test, in order to reinforce the argument for, or against, the accuracy of the model.

The motivation behind simulation and validation of models, overall, is to save time and money in research costs. For example, consider the automotive industry. It would be much more cost effective to develop simulations of cars crashing, and then only crash a few vehicles in order to validate the model, as opposed to crashing several dozen cars in all of the various accident configurations needed to ensure the safety of the vehicle for the general public. Projects like this one will validate models of a very small component, and then use that information, coupled with other small validated component models, to eventually model the complete system with a quantified uncertainty. This approach to modeling is known as the 'bottom up' approach to verification and validation [2]. In addition to cost savings, there are also instances, such as with large-scale civil infrastructure and nuclear weapons, in which full-scale testing is either not possible or prohibited for a variety of non-technical reasons. In these cases model validation is most important because the engineers must rely entirely on the models to predict how the systems will react when they are deployed for actual use.

To summarize, this project will perform a validation study for the Silastic J material model. This validation study will be accomplished using design of experiments (DOE), modeling and experimentation, feature extraction, and the application of statistical validation metrics. In the end, the question that will be answered is whether or not the current material model of Silastic J, developed from the TTS principle, provides accurate predictions of the actual material's dynamic behavior. While conducting this validation study, it is anticipated that advances will be made in the validation of numerical models that can be applied to other validation studies in the future.

2 Procedure

The experimental structure that is used in the experiments is a layered aluminum and J Rubber ring assembly. The ring consists of three concentric layers and has a total outside diameter of 30.48 cm. The outer ring is 6061 aluminum with a thickness of 2.7 mm. The middle ring portion consists of a 1mm thick layer of the Silastic J material, and the inner ring is another 2 mm thick layer of 6061 aluminum.

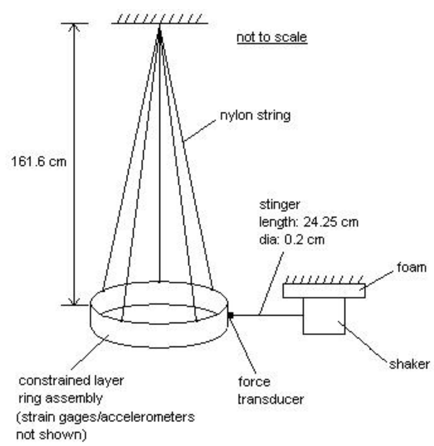

Figure 1: Experimental setup showing the ring suspended from nylon string and forced by a shaker through a thin stinger.

As shown above in Figure 1 the ring is suspended from a height of 161.6 cm by monofilament line which is super-glued to the outer edge of the ring. The ring is setup in this manner to simulate free-free boundary conditions and lower pendulum rigid body modes. The shaker is mounted with foam between the shaker and mounting structure and also between the mounting structure and the ground in order to reduce any environmental influences on the experiments.

Sine-dwell testing is performed on the constrained layer ring assembly to collect data on the energy transmission qualities of the Silastic J rubber. Sine-dwell testing of the ring involves exciting the structure with a sinusoidal input of various frequencies and magnitudes. The experimental setup and data collection strategy was revised multiple times and organized in order to collect as much information as possible. To do this, a National Instruments PXI data acquisition system is used, running LabVIEW software, with 21 channels of input. These channels are used to accommodate 19 accelerometers, 1 strain gauge, and 1 force transducer. The 19 accelerometers are mounted at the vertical midpoint of the ring and at 10 equally spaced positions around the inner and outer circumference with wax. An accelerometer is placed on the inner ring opposite of the force transducer but not on the outside, hence why there are 19 accelerometers instead of 20. The ring setup with accelerometers can be seen in Figure 2 below.

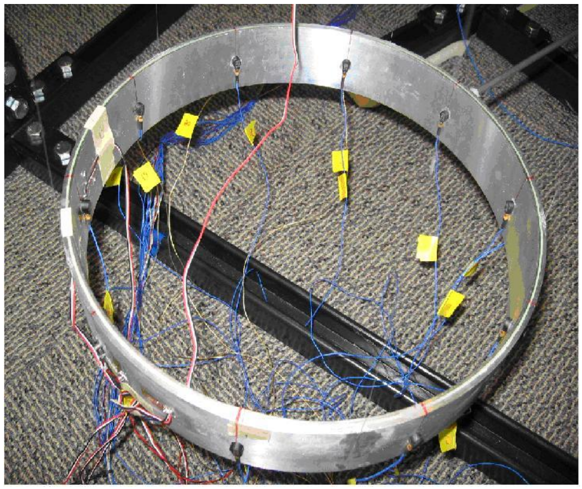

Figure 2: Suspended ring assembly with symmetrical accelerometer arrangement.

Another testing method considered for the validation study is shock response testing. This shock method could be implemented by performing drop tests on the ring assembly. It was later decided that there would be too many inconsistencies involved with the shock tests and these inconsistencies would inhibit useful comparisons of extracted features. Some simple testing is done on the ring assembly for initial verification. Modal impact tests are performed as a simple verification exercise of the data collected on the same ring assembly in 2004 by Harvey Mudd College. The data collected from the modal tests shows resonant frequencies that match those found in the Harvey Mudd study.

Using National Instruments LabVIEW, various sinusoidal functions are generated and input to the system. After waiting 30 seconds for the system to reach steady-state response, data is collected from the force transducer and the accelerometers. Data from one of the permanently attached strain gages is also collected. Features of the force transducer and accelerometer time histories are compared to see what effects the layer of Silastic J rubber has on energy transmission from the outside of the ring assembly to the inside. Specifically, the normalized signal power of the force and acceleration time histories are compared to the prediction from a finite element model in ABAQUS. The data are normalized with respect to a specific time period. Also, the time histories are squared to eliminate the cancellation effect of a periodic function. Equation 1 defines the general concept of signal power [3].

$$P_f = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} (|f(t)|)^2 dt \tag{1}$$

Design of experiments (DOE) methodology is used to control the input variables of the experiments. The input variables identified include the sinusoidal forcing frequency, magnitude of voltage applied to the shaker, ambient temperature, shaker size, stinger size, stinger position, and user. Three principles of DOE are employed to control the uncertainty associated with each of these variables [4]. First, the variables that are of less concern are *blocked*, or held constant. These blocked variables are the shaker, stinger, and stinger position. Based on expert opinion of staff members at Los Alamos National Laboratory, one shaker size, one stinger size, and one stinger position are used throughout the experiments. Next, there are variables in the experiment that cannot practically be controlled, so they are *randomized* in order to balance the effects they have. The randomization of the variables reduces the chance of biases being injected into the collected data. The ambient temperature and the user are the variables that are randomized. The two remaining variables, frequency and magnitude, are the most important for the material model validation. The experiments are performed with three levels of input magnitude (V) and ten levels of input frequency (Hz) for the sinusoidal function. Every combination of these two variables is tested; this is known as a full-factorial DOE [4]. To further reduce uncertainty, a third principle, *replication* is applied. For each combination of frequency and magnitude, ten replicates (trials) are performed. In order to randomize the effects of temperature and the user, we used JMP computer statistics software to generate a random schedule for the desired full-factorial DOE. This full-factorial DOE is illustrated in Table 1.

Table 1: Full-factorial DOE for magnitude and frequency factors with ten replicates.

Factor	Description	Number of Levels
1	Magnitude (V)	3
2	Frequency (Hz)	10
3	Replicates	10

For the simulations, expert opinion is utilized to select elastic moduli within a given distribution. We were given an experimental Young's modulus of the material and the coefficients of a Prony series used to predict the J rubber's dynamic behavior. In the simulations, there are no random variations that occur as with experimentation. Therefore, uncertainties associated with the material model are introduced to the model from the probability distributions of the values of the elastic modulus properties of the Silastic J viscoelastic material. Instead of running simulations with every possible material property within a certain confidence interval, the simulation is run with five different values for the elastic modulus. The simulation is run with the material property set at a level of 90, 95, 100, 105, or 110 percent of the nominal modulus that was originally supplied to us. These data on the material properties come from the previous testing done with a dynamic mechanical analyzer on the Silastic J rubber that employed the TTS principle.

After all of the data are collected following the DOE and techniques described above, analysis of variance (ANOVA) is used to determine what input parameters have the greatest effect on the variance of the extracted feature [5]. Again, the extracted feature is the signal power of the force and acceleration time histories taken at steady-state. From the experiments, it is determined whether the variation of frequency or magnitude has the greatest effect on the response features. From the simulations, the effects of frequency and magnitude variation are also extracted for comparison to the effects these variables have on the experimental data. Once the ANOVA is complete, the response features from the simulations and experiments are compared using test-analysis correlation to see if the numerical model accurately represents the behavior of the ring assembly for this particular design space. The design space is the range of frequencies and magnitudes over which testing will occur. The variance information provided by the ANOVA allows more detailed comparison of the results from the experiments and simulations and shows where there is an accurate representation of the physical structure.

3 Modeling and Experimentation

Our initial finite element models of the ring were produced with ABAQUS CAE. With this package it was difficult to properly constrain and tie the different ring layers together. It also eventually became very difficult to properly align the different nodes in order to accurately pick nodes where the accelerometers were located on the actual test structure. After consulting several lab staff members we switched over to Cubit software package in order to define our structure, elements and nodes. With cubit we were able to place nodes exactly where we had placed accelerometers, making it easier later to pull given accelerations off the ABAQUS finite element model. We ran the FEA models and exported acceleration time histories of where the accelerometers were located around the ring. After the model was constructed we generated a set of ABAQUS input decks to be run; however, with the model, computing time is significant for the length of dynamic response tested and the amount of tests performed (150). The first finite element model of an impact test took approximately 60 hours to run initially; however, after we made a revised model in Cubit with fewer, but more properly selected elements, the simulations ran significantly faster. Even with the revised model, we were still faced with large amounts of computing time in order to complete all of the runs we wanted. In order to get these done we split up the input decks to run on over a dozen different single-processor machines and then exported the acceleration time histories. Once completed, the results from the simulations and experiments are compared to see if the numerical model accurately represents the behavior of the ring assembly for this particular design space. The design space is for frequencies between 8 and 3000Hz in combination with input magnitudes of 300, 500, and 800mV to the shaker. Figure 3 illustrates the concept of design space. As shown in Figure 3, the expected results allow prediction of behavior, but the expected results are only valid in the region where experimental and simulated results are available.

The experimental setup provides acceleration time history data along with data from the force transducer and the single strain gauge. The force histories collected are being input into ABAQUS and the simulation outputs are then compared to the acceleration time histories obtained experimentally. This analysis allows statistical comparison and validation of the material properties of the Silastic-J rubber material model.

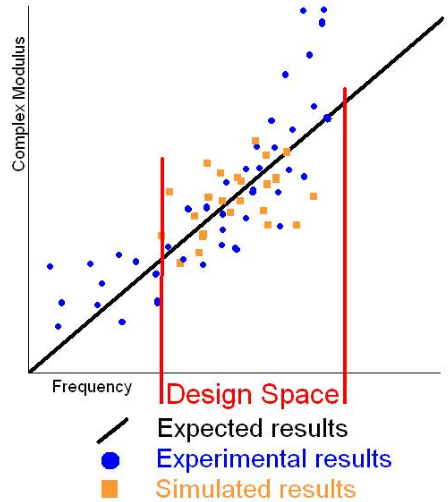

Figure 3: Design space and results for experimental and simulated material properties.

4 Analysis

Because of computing power limitations, only 120 simulations are run in ABAQUS. The two lower frequencies of 8 and 12 Hz are ignored because they are of less interest than the higher frequencies where the TTS model is utilized. Despite the amount of simulations performed, enough acceleration time-history data is obtained to compare with the experimentally generated data. MATLAB scripts are used to import the raw acceleration-time history data from LabVIEW and ABAQUS and produce the signal powers for the experimental and simulation data in a format that enables them to be easily analyzed. It is the signal powers that are analyzed using analysis of variance (ANOVA) and the statistical t-test.

Once the ANOVA was performed, it was determined that the input frequency has the greatest influence on the variance of the experimental results, while the input magnitude has the greatest influence on the simulation results. The graph in Figures 4 and 5 illustrates these results for one-half of the ring assembly. Note that the "variance contribution" is just a relative value with no specific meaning. The accelerometers are referred to by their analogous position on the face of a clock. Starting with the accelerometer behind the force transducer as 12:00 and then making the way around clockwise when looking at the ring from above. In addition there is an 'i' or an 'o' after the clock position indicating whether the accelerometer is on the inside or outside circumference of the ring.

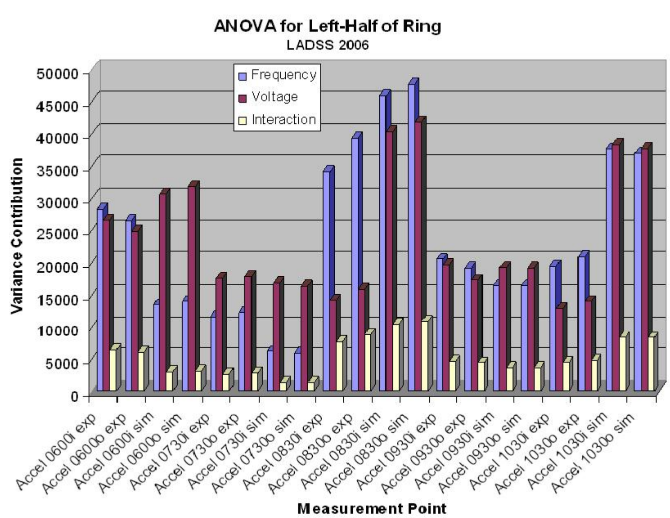

Figure 4: ANOVA results for left half of ring assembly.

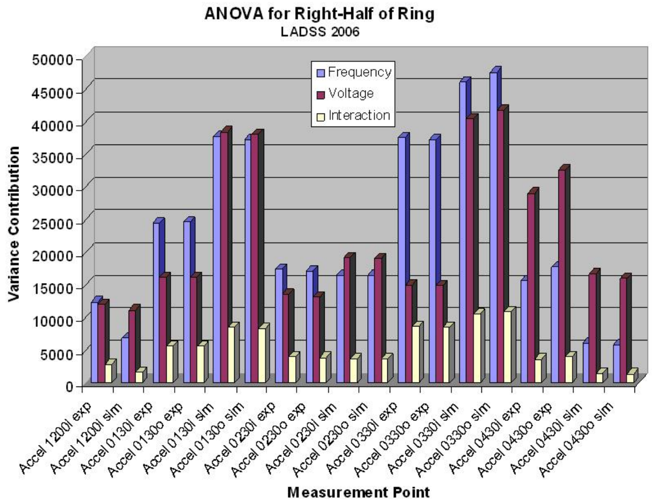

Figure 5: ANOVA results for right half of ring assembly.

It is possible that the accelerometer locations that were affected more by voltage changes than frequency changes could correspond with the anti-nodes of various mode shapes for the ring assembly. The ANOVA results for the ABAQUS signal powers look rather suspicious. A similar pattern is recognized between the experimental and simulation ANOVAs, but the simulation results show voltage to have the highest variance contribution at many of the accelerometer locations. This could be the result of the input parameters for the Silastic J material, ABAQUS not modeling the ring assembly correctly, or variations not accounted for in the experiments. A statistical t-test comparison is also made on the signal powers from the experiments and numerical model. A t-test compares the means of two samples to determine if they are the same within a certain confidence interval. The t-test is performed with a 99% confidence interval and the results of this test for each accelerometer are given below in Table 2.

Table 2: T-test pass rate of accelerometers around the ring.

Accelerometer	12:00i	1:30i	2:30i	3:30i	4:30i	6:00i	7:30i	8:30i	9:30i	10:30i
Pass Rate	0 %	0 %	4 %	4 %	8 %	8 %	4 %	4 %	0 %	0 %
Accelerometer		1:30o	2:30o	3:30o	4:30o	6:00o	7:30o	8:30o	9:30o	10:30o
Pass Rate		0 %	0 %	4 %	8 %	8 %	0 %	4 %	0 %	0 %

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