Viscoelasticity of Composite Structures for Compulsators

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Viscoelasticity of Composite Structures for Compulsators

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Abstract—The University of Texas at Austin Center for Electromechanics (UT-CEM) is a research center which specializes in pulse power technology. DoD's mission for high performance power sources has lead UT-CEM to incorporate advanced composite materials into compulsator designs.

However, to achieve these high performance levels, improvements are needed in the thermal and structural properties for armature windings as well as for the surrounding composite structure. In particular, viscoelastic flow can limit compulsator performance life by loss of radial precompression. Composite structures with embedded electrical windings are particularly affected due to the localized, elevated operating temperatures.

Under ongoing programs, the viscoelasticity of these composite structures are being characterized by evaluating neat resin behavior. This paper will describe the thermal and structural properties of selected high performance neat resins as well as creep modulus characterization through Dynamic Mechanical Analyzer (DMA) tests. Also documented in this paper will be the results from specialized viscoelasticity tests performed on representative composite windings to determine preload loss versus time, temperature, and stress.

Also, in collaboration with the Army Research Laboratory, a nested cylinder code is being developed to predict viscoelasticity induced preload losses.

INTRODUCTION

The Center for Electromechanics (UT-CEM) is a research center at The University of Texas at Austin which specializes in pulse power technology through the design and development of high speed rotating electrical machines. DoD's mission for high performance, high specific power sources has lead UT-CEM to incorporate advanced composite materials into compulsator designs. Increased specific power generally results in higher operating temperatures in the electrical windings and the surrounding composite structure.

To achieve these high performance levels, improvements are needed in the composite's thermal and structural properties. These improvements will be derived from ongoing efforts to better understand critical characteristics of a compulsator's composite structure. Of particular importance is viscoelastic flow which can limit compulsator performance life by loss of radial precompression. Typical composite compulsator construction is a multi-ring design with an embedded electrical winding. At assembly, these rings are pressed together with an interference fit engineered to maintain an acceptable radial compressive stress level in the ring during all phases of operation. It is this radial compressive stress in an elevated thermal environment that aggravates viscoelastic flow of the resin. Excessive resin flow leads to radial dimensional changes, effectively reducing initial radial interference fits. The effect is loss of radial preload and degraded machine performance. Therefore, it is critical that viscoelastic characteristics be well understood in order to be able to design compulsators that meet their predicted performance requirements, and continue doing so for the life of the machine.

Under funding provided by IAT and in collaboration with the Army Research Laboratory, UT-CEM is developing an analytical technique to predict preload loss within a composite compulsator. This requires knowledge of the viscoelastic creep behavior of the structure over time at elevated temperatures. A typical approach for determining a structure's viscoelastic character is to build a scaled prototype and subject it to months or years of testing. In an attempt to provide a less time consuming and less expensive solution, UT-CEM is developing an approach based upon the neat resin's creep modulus properties derived from simple DMA tests. These creep moduli are used to formulate derated material properties for the neat resin as a function of time and temperature. To then formulate the final laminate material properties, the derated neat resin properties are combined with the material properties of the remaining structure (e.g., graphite fiber for a composite ring structure, litz wire with high voltage insulation for an electrical winding structure). These laminate material properties now reflect changes in the structure due to viscoelastic effects assuming all viscoelastic behavior is resin related. A finite element analysis can then provide preload loss information by comparing results using the nominal and derated material properties.
Preliminary activities focused on this effort and correlation of recent results with experimental data are discussed in this paper. Upon completion of these efforts, this technique will be used as a design tool for life cycle predictions of components specific to duty cycle and operational conditions.

In the next section the experimental approach is explained. In a subsequent section, we will discuss our computer model of the experiment, including our approach to modeling the viscoelasticity of the composites. Then the experimental data is presented along with a comparison between experimental and calculated data.

**Experimental Approach**

Fig. 1 shows a stress relaxation fixture that has been successfully used for measuring preload loss of composite rings due to viscoelastic flow. As shown in the figure, a composite ring is press fit onto a thick steel cylinder. The press fit geometry is tailored to develop a specific radial compression at assembly. The assembly is then placed in an oven at some elevated temperature for an extended period of time. Strain gauges on the bore of the steel are monitored and the elastic nature of the steel cylinder is used to infer changes in preload at the composite ring interface. The details of the experimental procedure for a single experiment follow. The procedure is identical for each experiment. The rings used in the experiments were primarily hoop wound IM7/8552 prepreg or IM7/977-2 prepreg and reinforced (10%) by off-axis fibers.

Fig. 2 is a cut-away schematic of experiment #3 with dimensions. The inner cylinder is made of steel, and the shorter, outer cylinder is the composite ring. The large groove in the steel cylinder, shown in the figure, helped to confine the deformations of the steel to the area directly beneath the composite.

On the inner surface of the steel cylinder we placed three evenly spaced strain gauges in a shallow groove located 1.6 in. from the large end of the cylinder. The groove assured accurate replacement of the strain gauges for future comparisons. The strain gauges were oriented to measure hoop strain.

Initially, the strain gauges were zeroed and the composite ring pressed on to the cylinder. A Teflon-based lubricant facilitated the assembly. Readings from the strain gauges were taken at regular intervals to monitor settling of the fit between the composite and the steel. Settling occurs as lubricant leaks from the interface and residual temperatures from assembly dissipate.

The strain gauges were disconnected after settling and the assembly was placed in an oven. The oven maintained constant, elevated temperature to within 5°F.

Periodically the assembly was removed from the oven. After cooling, the strain gauges were reconnected and zeroed. The composite was pushed off of the steel cylinder and the reading from the strain gauges allowed to settle. Due to the elastic nature of steel, any difference in hoop strain from assembly to disassembly can be attributed to relaxation of the composite. The experiment was reassembled and returned to the oven.

This procedure was followed for all cases except for the room temperature experiment performed in experiment 4. Measurements were taken continuously from the bore dial gauge attached before assembly. Again, due to the elastic nature of steel, any loss of bore diameter was attributed to relaxation of the composite ring.

**Computer Model for Predicting Viscoelastic Behavior**

A finite element model was developed for viscoelastic simulations. The model was constructed and evaluated in ABAQUS™ using axi-symmetric 8 node elements.

The material properties used in the models were calculated by LAMPAT. LAMPAT is a software tool licensed from the...
Army Research Laboratory for analyzing and designing thick laminated composite structures. The input to LAMPAT is tow properties, tape properties, and composite lay-up. The output from LAMPAT is a table of the anisotropic material properties for the composite laminate.

Creep properties of the composite were modeled using data from a constant strain creep test and DMA analysis performed on the neat resin matrix by Thermal Options in Escondido, CA. For an isotropic, linear viscoelastic material such as the neat resins used in these experiments, stress relaxation, $E(t)$, is defined as:

$$E(t) = \frac{\sigma(t)}{\varepsilon}$$  \hspace{1cm} (1)

where

- $\sigma(t)$ = stress as a function of time
- $\varepsilon$ = constant strain

In addition to time dependency, viscoelastic materials exhibit history dependency. However, Schapery [1] found, for quasi-elastic problems over long periods of time, that the history dependent stress relaxation is approximately equal to the time dependent elastic response. So, we used the stress relaxation from the constant strain creep test and DMA analysis directly in our computer models.

To find the time dependent stress relaxation, the stress relaxation master curve for each material was found experimentally from several tests of the neat resin at varying temperature. For a selected temperature and an elapsed time at that temperature, a change in modulus can be found. In the experiment, the strains were measured at room temperature, so we calculated the change in modulus at elevated temperature, and subtracted this from the initial room temperature modulus to obtain the derated room temperature modulus.

$$E_1 = E_0 - \Delta E_T$$  \hspace{1cm} (2)

where

- $E_0$ = initial elastic modulus of the neat resin at room temperature
- $E_1$ = derated modulus
- $\Delta E_T$ = change in modulus at the selected temperature over the time period of interest.

The derated elastic modulus of the neat resin was used in the Halpin-Tsai equations [2],[3], and [4] to modify tow and tape properties. The fibers were assumed to be perfectly elastic. These new properties were input into LAMPAT to calculate the derated composite material properties. The material properties were then input into the computer model to simulate losses due to creep over time at elevated temperature. The Halpin-Tsai equation is shown below and used to separately calculate longitudinal and transverse properties. For longitudinal properties, the constant $\xi = \infty$. For transverse properties, $\xi = 2$ and is matched to experimental data.

$$P = P_m \left(\frac{1 + \chi \nu_f}{1 - \chi \nu_f}\right)^{\frac{1}{\nu_f}}$$  \hspace{1cm} (3)

where

- $P$ = property of the composite
- $P_m$ = associated property of the matrix
- $P_f$ = associated property of the matrix
- $\nu_f$ = volume fraction of the fiber

**EXPERIMENTAL DATA AND RESULTS**

Table 1 is a summary of the experiments performed to date. Experiment #3 and experiment #5 are still ongoing. The preload loss presented in the table was determined from the measured hoop strain by the following relation:

$$\% \text{ loss} = \left(\frac{\varepsilon_o - \varepsilon}{\varepsilon_o}\right) \times 100$$  \hspace{1cm} (5)

The first two experiments at high temperature exhibited significant creep after only two weeks. In experiments #4 and #6, it was observed, as is expected, that at lower temperatures the creep behavior improved.

<table>
<thead>
<tr>
<th>Exp #</th>
<th>Material</th>
<th>Post-Cured</th>
<th>Temp (°F)</th>
<th>Pre-Load Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IM7/977-2</td>
<td>No</td>
<td>250</td>
<td>17.09 after 14 days</td>
</tr>
<tr>
<td>2</td>
<td>IM7/977-2</td>
<td>No</td>
<td>250</td>
<td>16.32 after 17 days</td>
</tr>
<tr>
<td>3</td>
<td>IM7/8552</td>
<td>Yes</td>
<td>250</td>
<td>3.76 after 19 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.46 after 92 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.65 after 292 days</td>
</tr>
</tbody>
</table>

A study of several other candidate neat resin matrices was performed. Additional cross-linking of the matrix induced by post curing was found to have a significant affect on creep properties. In addition, rings made from IM7/8552 were found to have better creep performance than the original IM7/977-2 rings. Consequently, experiments #3 and #5 were performed using the new material with post curing. In these experiments, the observed losses were modest over long time periods and high temperatures.
We also included in table 1, wherever possible, a ten year prediction of preload loss. This prediction is the extrapolation of a power law fit to the experimental data as per the following formula:

\[
\% \text{ loss} = C_1 \times t^n
\]  

(6)

\( C_1 \) and \( n \) are constants determined from the experimental data. A power law fit was chosen because a large number of materials have been shown to exhibit power law degradation of creep compliance \( D(t) \) [5][6], and it is easy to see from the definition of creep compliance,

\[
\varepsilon(t) = D(t) \times \sigma
\]  

(7)

that

\[
\frac{\varepsilon_o - \varepsilon_f}{\varepsilon_o} = \frac{D_o - D_f}{D_o}
\]  

(8)

for constant stress (quasi-elastic). The left hand side of equation (8) was defined in equation (5) to be preload loss. Also, the creep compliance for the materials studied fit approximately a power law curve for the range of time and temperature found in the experiment.

Figs. 3, 4, and 5, show graphically for select cases, the experimental data, the power law constants, and the curve fit extrapolated to the ten year prediction. The experimental data shown in Fig. 4 was taken from a continually monitored bore dial gauge. The figures show a good fit of the experimental data to a power law.

**Comparison of Experimental Results to Computer Models**

Experiment 3, conducted at 250°F, was chosen to compare with a computer model. It was chosen because it had the most experimental data available from any experiment conducted at elevated temperature. For the comparison, the hoop strain on the inside bore of the steel cylinder at 1.6 in. from the large end of the taper was calculated. This calculation should be identical to the experimental reading obtained from strain gauges fixed to the steel cylinder.

Table 2 compares model versus measured data hoop strain values at assembly (beginning of the experiment) against values at the end of the experiment (292 days). Also calculated and included in the table were the radial interface pressure 1.6 in. from the large end of the taper, the maximum interface pressure over the entire interface, and the percentage of preload loss. Only the preload loss calculated from the longest time period was included because it would exhibit the greatest divergence of experimental data from modeled data.
Table 2. Comparison of experiment and computer model

<table>
<thead>
<tr>
<th></th>
<th>At Assembly</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Alpiin-Tsai</td>
<td>Inteface Max. Pre-Load Pressure (psi)</td>
<td>Inteface Loss Pressure (psi)</td>
</tr>
<tr>
<td>Experiment</td>
<td>2.00 x 10^-3</td>
<td>18,856</td>
<td>21,711</td>
<td></td>
</tr>
<tr>
<td>ABAQUSTM</td>
<td>2.19 x 10^-3</td>
<td>18,525</td>
<td>21,439</td>
<td>1.1</td>
</tr>
<tr>
<td>After 292 Days</td>
<td>1.87 x 10^-3</td>
<td>17,635</td>
<td>20,929</td>
<td>6.95</td>
</tr>
</tbody>
</table>

The DMA analysis suggested a loss in the matrix elastic modulus of 32.5% for the temperature and elapsed time of experiment #3. Using this derated modulus in the Halpin-Tsai equation to modify the elastic moduli of the tow properties, the calculated preload loss of the composite ring was only 1.18% after 292 days. As demonstrated earlier in tables 1 and 2, the experimentally measured preload loss was 6.65%. This discrepancy is, as of yet, unexplained. As a check on the upper bound of the creep calculated by our viscoelastic model, the percentage loss in the elastic modulus of the matrix was assumed to be equal to the percentage loss of the transverse elastic properties of the composite ring. The longitudinal modulus was assumed to be perfectly elastic. This procedure effectively ignores the effects of fibers for the transverse direction, and so assumes a 100% dependence of the creep of the composite upon the properties of the matrix.

The upper bound case was calculated to have a preload loss of 5.76% after 292 days. This calculated loss was less than, but approaching the loss determined from experiment. These results suggest that creep is highly dependent upon the matrix properties. They also suggest that the assumption of perfect elasticity in the longitudinal direction may be invalid. Further analysis has shown that a small degradation in the longitudinal (fiber) direction can account for large preload losses.

Conclusions
As was observed from experiment, the choice of neat resin can affect the creep properties of the composite flywheel greatly. In the experiments, it was also shown that composite flywheels and compulsators may have the capability to operate at elevated temperatures for up to ten years before preload losses relax the interference fit past safe operating levels.

The computer model agreed well with experimental data at assembly. The ABAQUSTM model calculated the initial conditions to within 10% of those experimentally observed. However, our viscoelastic model could not sufficiently account for preload losses observed in the experiment. Only by assuming near zero participation of the fibers to creep in the transverse directions were we able to almost duplicate losses found from the experiment. This indicates that the creep properties of the composite are highly dependent upon the creep properties of the matrix, or there exist other factors affecting the observed losses. Further experimentation and analysis is required. Ongoing effort will focus on viscoelastic behavior in the longitudinal direction of the composite laminate.

Acknowledgments
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References