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LIANG S Y MECH ENGR (404)894-7769

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Title: DYNAMIC DIELECTRIC MONITORING OF INSITU CONSOLIDATION OF THERMOPLASTIC ...

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
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OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 08/03/94

Project No. E-25-N03 Center No. 10/24-6-R7283-0A0

Project Director LIANG S Y School/Lab MECH ENGR

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. DDM-9110185 Contract Entity GTRC

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Title DYNAMIC DIELECTRIC MONITORING OF INSITU CONSOLIDATION OF THERMOPLASTIC ..

Effective Completion Date 940731 (Performance) 941031 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
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Other	N	

Comments
LETTER OF CREDIT APPLIES. PATENT INFO SUBMITTED IN 98A FORMAT.

Subproject Under Main Project No. ______

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Distribution Required:	
Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
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Filament Winding Process Monitoring via Dynamic Dielectric Analysis

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Abstract

Dynamic dielectric analysis as a sensing methodology for real-time process monitoring in thermoplastic filament winding has been presented in this paper. This scheme established an alternating electrical field across the filament contact point on the mandrel and identified the variation of resin dielectric properties in relation to the change in critical process parameters, namely the winding speed and compression pressure, as well as the occurrence of unexpected impurity in the material that have direct bearing on the degree of resin consolidation at the contact point. The methodology presented in this paper involved the establishment of the analytical basis for the normalization of dielectric quantities with respect to the time varying separation distance between roller and mandrel, the investigation on the frequency response of the resin-fiber system, as well as experimental implementation of the proposed scheme on an actual thermoplastic filament winder.

1. Introduction

Current filament winding techniques frequently use thermosetting resins which require post curing procedures in an autoclave or oven. The advent of high strength thermoplastic resins has allowed the process to be "completed" at the time of winding, in that temperature and pressure can be applied simultaneously during the winding process. At the prepreg laydown point, the resin material is heated above its melting temperature and compressed via a compression roller into intimate contact with the other plies. This process is referred to as the "in-situ" consolidation of the resin and fiber.

Void content (the percentage of air remaining in the finished part) is directly related to the degree of consolidation at the filament laydown point. The degree of consolidation is, however, prone to fluctuation during the winding process due to the unpredictable arrival of material or thermal disturbances and changes in process parameters of winding speed, winding pressure and heat [Carpenter, 1992]. Therefore, an on-line measurement tool is needed to measure changes in process parameters and feed this information to a control algorithm which could control the temperature and/or pressure applied to the laydown point. This process control could be used to lower void content and make the overall process more applicable to widespread manufacturing use.

Current void content measurements for filament wound parts are completed off-line by ultrasonic attenuation C-scan [Jones et al., 1976], X-radiography [Bolylas, 1976], Fokker bond-testing [Schliekelmann, 1978], optical holographic stress wave interferometry [Querido, 1976] and thermography [Pye et al., 1979]. None of these measurement methods is currently applied in real-time nor would they be suitable for application to a control process. This lack of suitability comes either from difficulties in implementation into current winding equipment, the speed at which measurements are made, or possible structural damage to the part itself.

The current lack of an effective monitoring methodology commonly causes excessive amounts of pressure and heat to be applied during the filament winding process. Although the objective of the heat and pressure is to reduce void content, too much of either parameter causes problems in the finished product. Over pressurizing causes an undesirable high fiber volume fraction by squeezing too much resin away from the fibers. Too much heat can degrade the thermoplastic matrix and adversely affect the mechanical properties of the finished product.

In order to overcome these difficulties, this research sought to provide a means of real-time process monitoring of thermoplastic filament wound composites by the establishment of a dielectric monitoring methodology. The key concept involved is the sensitivity of the material dielectric properties to the degree of consolidation during winding. Resin consolidation at the lay down point proceeds as the thermoplastics is compressed above its melting temperature, the prepreg surfaces are brought into intimate contact, and the ply interfaces are eliminated by the molecular diffusion of resin [Anderson et al., 1989]. This is usually accompanied by the initiation and continuation of the polymer crystallization and an increase in the viscosity of the system [Bidstrup et al., 1989; Ciriscioli, et al., 1989; Kranbuehl et al., 1987]. These phenomena will affect the material dielectric properties through their influences on the ion mobility and dipole orientation energy. Therefore, any changes in the process condition to alter the degree of prepreg consolidation will show its effect on the rheological properties of the resin matrix.

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In this study, the monitoring system utilizes a sinusoidal input current passing through the prepreg tape laydown point on the filament winder. The rheological property changes of the polymer at the laydown point will dominate the magnitude and phase of the current passing through that point. Relating the current parameters back to dielectric quantities and then to process variables will allow real time monitoring of the process.

The dielectric monitoring methodology outlined here was implemented with a signal generator creating the input voltage, an actual thermoplastic filament winder creating the dielectric change to that signal, and a monitoring circuit to measure the differences between the input voltage and the output current. In acquiring real-time knowledge of the state of the part being wound via dielectric analysis, the real-time understanding regarding dielectric quantities such as permittivity and loss factor has to be available. Prior to this research effort, there were no analytical forms to these quantities which take into account the dynamic factors associated with filament winding, such as time varying roller/mandrel separation. This lack of analytical relationships for the dielectric quantities is one challenge in proving dielectric analysis as a viable sensor methodology. In this paper, a systematic procedure to normalize the dielectric quantities of permittivity and loss factor has been developed in a format applicable to real-time implementation. It is followed by the discussion on the electrical characteristics of the winding apparatus and the derivation of an electric circuit element model for the winder. This model was then used in the design, simulation, and analysis of the frequency response of the dielectric sensing circuit. A series of experiments based on the static and dynamic winding cases were performed. Results on the dielectric sensitivity to the change of process condition in terms of roller pressure, winding speed, and unexpected impurity in the material are presented and discussed to verify the applicability of the proposed concept.

2. Normalization of Dielectric Quantities

As Figure 1 shows, the dielectric monitoring scheme as applied to filament winding consists of a sinusoidal excitation across the roller/mandrel electrodes. As the input voltage is applied, an electrical field is created, which includes a point of specific interest: the prepreg lay down point. Responding to the electrical field, the polymer resin in the laydown area will become polarized and conduct a charge. A displacement current [Ramo et al., 1984] across the capacitor which emerges from the other side of the laydown point is used as the output signal. Comparison of the input and output signals, in terms of the amplitude ratio and phase difference, provides the information required to derive the dielectric quantities of the resin at the lay down point.

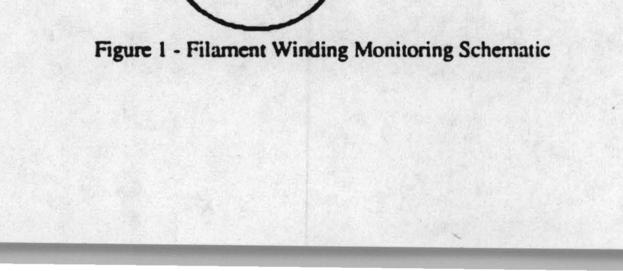

Figure 1 - Filament Winding Monitoring Schematic

Both input voltage and output current have the same frequency (ω), but the output exhibit a phase difference (ϕ) with the input. This phase difference is input frequency dependent and is defined as:

$$\phi(\omega) = \frac{2\pi\tau(\omega)}{T} \tag{1}$$

where τ is the time difference between the input and output peaks and T is the period of the input sinusoid. For the resin of interest, the dielectric quantities are permittivity (ε') and loss factor (ε''). Designating the input as v(t) and the output i(t), we have

$$v(t) = V_0 \sin(\omega t) \tag{2}$$

$$i(t) = I_0(\omega) \sin(\omega t + \phi(\omega)) \tag{3}$$

where V_0 is the input voltage magnitude, I_0 is the output current magnitude, and "t" represents time. The complex admittance of the material is defined as the ratio:

$$\Psi(\omega) = \frac{I_0(\omega)}{V_0}\cos\phi(\omega) + j\frac{I_0(\omega)}{V_0}\sin\phi(\omega) \tag{4}$$

The loss factor (ε'') and permittivity (ε') are material dependent dielectric properties. They can be specified with respect to the admittance as follows:

$$\varepsilon' = \frac{1}{\omega} G\,\mathrm{Im}[\Psi(\omega)] \tag{5}$$

$$\varepsilon'' = \frac{1}{\omega} G\,\mathrm{Re}[\Psi(\omega)] \tag{6}$$

In these relationships, G is a function of electrode geometry only. In order to more clearly define this geometry factor, it can be noted that G contains one dynamic part (due to the increasing roller/mandrel separation that changes the electrode geometry) and other constant parts (degree of resin consolidation dependent). G" will be defined as the dynamic geometry factor and G' as the constant geometry factor. Therefore G can be defined as:

$$G = G'G''(\delta) \tag{7}$$

where δ is defined as the separation distance between the roller and the mandrel. Combining this geometry factor with the previous permittivity and loss factor equations yields:

$$\varepsilon' = \frac{I_0(\omega)}{V_0\omega}\sin\phi(\omega)G'G''(\delta) \tag{8}$$

$$\varepsilon'' = \frac{I_0(\omega)}{V_0\omega}\cos\phi(\omega)G'G''(\delta) \tag{9}$$

As it is desired to calculate the dielectric quantities in real-time, a way of obtaining the dynamic geometry factor $G''(\delta)$ must be derived that allows real-time application negating the effect of changing electrode geometry. Defining the geometry factor in terms of a parameter ξ:

$$G''(\delta) = \xi\varepsilon''\varepsilon_0 G' \tag{10}$$

where ξ can be determined experimentally as:

$$\xi = \frac{V_0 \omega}{I_0(\omega)\cos\phi} \qquad (11)$$

Note that all quantities appear to the right hand side of Equation (11) are measurable in real-time. For the approximation of dynamic geometry factor, a general, linear or non-linear, function for $G''(\delta)$ can assume the form of:

$$G''(\delta) = \gamma\delta^{\alpha} + \beta \qquad (12)$$

where γ is a proportionality constant, β is a boundary constant and α is the dynamic geometry exponent. Experimentally, several estimations of ξ can be made corresponding to different δ's:

$$\xi(\delta_1) = \xi_1 \qquad (13)$$

$$\xi(\delta_2) = \xi_2 \qquad (14)$$

$$\xi(\delta_0) = \xi_0 \approx 0 \qquad (15)$$

Substitution of γ and the boundary condition at the initial plate separation (δ_0) into Equation (12) gives:

$$G''_{\gamma}(\delta) = \delta^{\alpha} - \delta_0^{\alpha} \qquad (16)$$

Taking a ratio of different ξ values:

$$\frac{\xi_1}{\xi_2} = \frac{\delta_1^{\alpha} - \delta_0^{\alpha}}{\delta_2^{\alpha} - \delta_0^{\alpha}} \qquad (17)$$

Equation (17) can be solved numerically for α for different process configurations. The constant α can then be used throughout a particular process to calculate the dynamic geometry factor in real-time. This factor does not, however, take into account very small changes in the nip area which occur from temperature, winding speed or winding pressure changes. These effects are believed to be negligible compared to electrode distance effects.

The normalization of material dependent dielectric properties to negate the effect of changing electrode geometry then lead to:

$$\bar{\varepsilon}' = \frac{\varepsilon'}{G'\gamma} = \frac{I_0(\omega)}{V_0\omega\varepsilon_0}\sin\phi(\delta^{\alpha} - \delta_0^{\alpha}) \qquad (18)$$

$$\bar{\varepsilon}'' = \frac{\varepsilon''}{G'\gamma} = \frac{I_0(\omega)}{V_0\omega\varepsilon_0}\cos\phi(\delta^{\alpha} - \delta_0^{\alpha}) \qquad (19)$$

where the permittivity and loss factor, respectively, are divided by the static geometry factor and the nonlinear coefficient for the dynamic effects. The normalization allows the use of dielectric quantities for the monitoring of process condition related to the degree of resin consolidation, but not to the change of electrode separation as tape are continuously wound on to the mandrel. The values of these normalized quantities at the variation of electrode geometry is tested in actual winding situations, and the results are presented in section 4.2.1.

3. Sensing Circuit Design and Analysis

In this analysis the pressure roller and mandrel sandwiching a thermoplastic tape can be modeled as a capacitor in an electric circuit. Although the geometry involved is different than for a parallel plate capacitor, the capacitance rating of such a roller/thermoplastic combination remains proportional to the permittivity of the dielectric material and the surface area of the conductors while inversely proportional to the distance between the conductors.

As much previous research has shown [Sinchina, 1990], the permittivity of thermoplastics will vary during the temperature and pressure cycles of manufacturing processing. It is this point which presents the proper combination of a dielectric between two conductors. Therefore, from the point of view of the monitoring circuit, the pressure roller/thermoplastic tape/mandrel combination represents a varying capacitor as the tape undergoes the temperature and pressure cycles of processing on the filament winder.

The capacitor also took into account the loading effects of the signal measuring devices and operational amplifiers used to minimize the loading effects and amplify the output signal. These considerations are demonstrated by the sensing circuit schematic pictured in Figure 2. R_{in} and R1 are input buffer resistors for the operational amplifiers, R_f is a feedback resistor, R_w is the winder resistance, C_w is the winder capacitance and V_{in} is the input sinusoidal voltage.

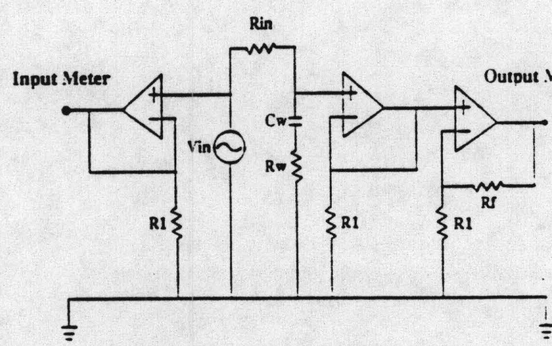

Figure 2 - Dielectric Monitoring Circuit

Initial capacitance measurements on the filament winder were taken and results revealed that the capacitance of the roller/mandrel apparatus was on the order of tens of picofarads. The sensing circuit would, therefore, need to be highly sensitive to changes in this already small capacitance. Thus, a method of increasing the circuit sensitivity was sought through increasing the area of the conductors of the roller/mandrel capacitor. This was accomplished by the creation of an additional conduction path from the input signal through the polymer tape to the mandrel. This additional signal path was a narrow copper strip between the pressure roller's mounting bracket and prepreg ring on the mandrel as seen in Figure 3. In practical applications, the use of a more compliant pressure roller or a series of rollers along the contour of the laid prepreg can serve the same prupose.

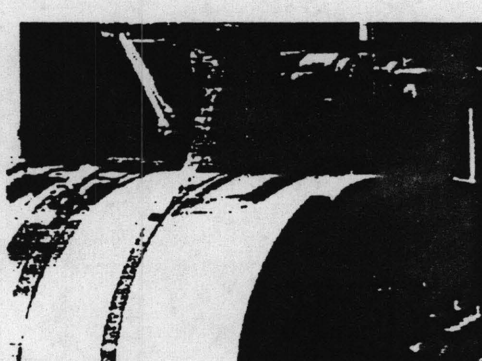

Figure 3 - Copper Capacitance Enhancement

The frequency response of the proposed monitoring circuit as outlined in Figure 2 was simulated for various capacitances. Simulation results, as shown in Figures 4 and 5 for the magnitude and phase lag, revealed that the circuit would have a low pass filter frequency characteristic with a drop off frequency of approximately 30 kHz.

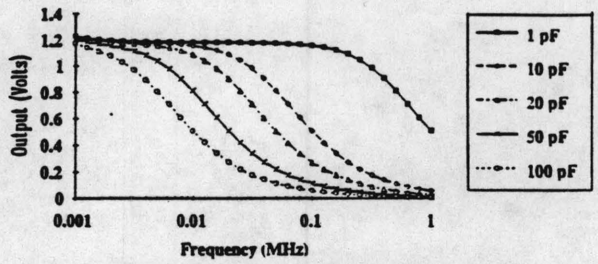

Figure 4 - Circuit Voltage Sensitivity to Capacitance

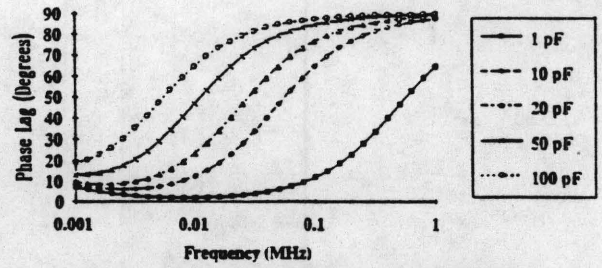

Figure 5 - Circuit Phase Sensitivity to Capacitance

4. Experimental Implementation

4.1. Hardware Components

The filament winding station used for these experiments is a two-axis winder retrofitted with a roller and heater mechanism for in-situ consolidation. More details on the winding machine is documented in [Carpenter, 1992]. The dielectric monitoring system itself was comprised of four primary components. Following the circuit from its origination, a 30 kHz sinusoidal input signal to be used by the circuit was generated by the function generator. The monitoring circuit was created on an electronic circuit prototype board. The circuit elements included carbon film resistors, one dual operational amplifier 8 pin DIP integrated circuit to buffer the oscilloscope channel, and one operational amplifier 8 pin DIP integrated circuit to amplify the dielectric sensor output signal.

Once the displacement current signal crossed the input resistor, R_{in}, it was carried to the winder capacitance by a connection cable mounted between the R_{in} resistor and the compression roller support arm on the winding machine. This support arm was isolated electrically from the rest of the machine by an acrylic mounting block. A digital storage oscilloscope was used to measure sensor circuit output. This oscilloscope's digital storage modes allowed for passive signal processing of the sensor output signal via a signal averaging function which averaged the signal with a 20 MHz frequency, or every five samples at the 100 MHz sampling rate.

The material used in this study was poly(etheretherketone) (PEEK)/glass unidirectional prepreg tape (ICI's APC-2-D-S2 Glass). The tape was 0.24 inches in width, nominally 0.009 inches thick. The manufacturer's suggested process temperature was 410°C. PEEK was chosen as the matrix because it is a polar polymer and should show dielectric effects better than most other matrices. Glass was chosen as a fiber because it is not conductive and, therefore, would not cause the current to leak away from the roller/mandrel interface area.

4.2. Experimental Results

4.2.1. Discontinuous Roller/Mandrel Separation Rate

Equations (18) and (19) are formulated to negate the effects of roller/mandrel separation distance. Experiments were conducted by cutting the incoming tape, after the winding process had reached steady state, to quickly bring the rate of change of roller separation to zero. It would be expected that this should produce no change in the normalized dielectric quantities resulting from the application of Equations (18) and (19). Figures 6 and 7 depict the normalized permittivity and loss factor measurements during this test.

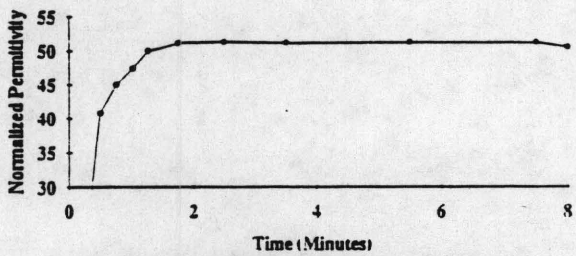

Figure 6 - Response of Normalized Permittivity to Tape Discontinuation

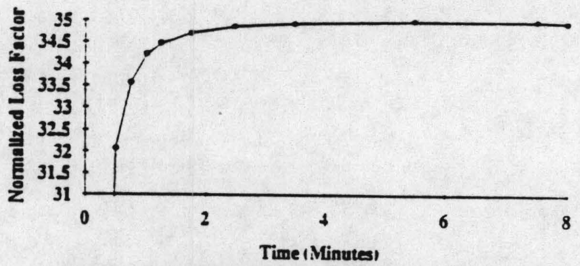

Figure 7 - Response of Normalized Loss Factor at Tape Discontinuation

In the beginning of the test, the normalized permittivity and loss factor see an increase at sharp slope as the material is brought up to temperature on the mandrel. The fact that the dielectric quantities do not start at their nominal values for winding is due to the fact that the first layer of the tape is not near melt temperature, because a section of prepreg tape must be taped to the mandrel in order to initiate the winding. After approximately 2 minutes, the permittivity and loss factor clearly show steady state values being reached. These steady state values exhibit no change during the part thickness build-up cycle (2 minute to 2.5 minute), the tape discontinuation point (2.5 minute), and the constant thickness cycle (2.5 minute to the end of test). It implies that the normalized dielectric quantities were able, as would be expected, to ignore the change in roller/mandrel separation rate.

4.2.2. Winding Speed Variation

A lower winding speed allows more voids to be removed thereby promoting the degree of consolidation during winding. This experiment demonstrates the sensitivity of resin permittivity and loss factor to the speed of winding. As shown in Figure 8, the lower winding speed curve exhibits a steady state normalized permittivity of approximately 62 while the same curve for the higher winding speed shows a steady state of approximately 48 for a change of 10% from the lower to higher speed. Similar conclusions can be made from the loss factor variation in Figure 9.

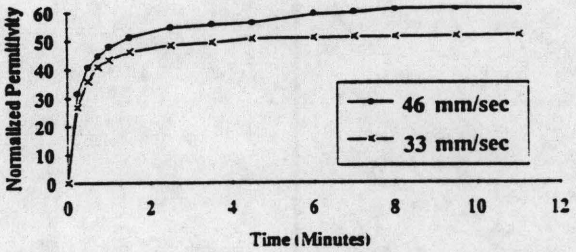

Figure 8 - Sensitivity of Normalized Permittivity to Winding Speed

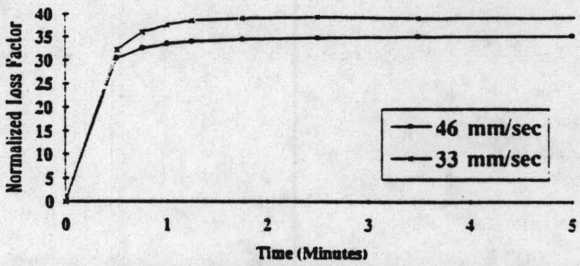

Figure 9 - Sensitivity of Normalized Loss Factor to Winding Speed

4.2.3. Roller Pressure Variation

This test saw two different rings wound at different pressures and their dielectric responses compared. It was expected that the higher pressure would induce an increase in the dielectric quantities, since it produced a higher degree of consolidation through the promotion of more intimate contact between layers. Representative permittivity data for this test appears in Figure 10, which indicated that the ring wound at the higher pressure clearly shows an increase in steady state permittivity.

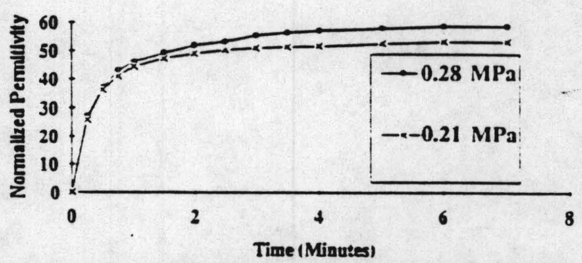

Figure 10 - Sensitivity of Normalized Permittivity to Roller Pressure

However, similar remarks could not be made for the loss factor data. As shown in figure 11 the normalized loss factor is essentially invariant to the change of compression pressure. This observation illustrates the non-redundancy between the measurements of permittivity and loss factor, therefore, as these quantities are monitored in parallel it is possible that different process condition changes can be differentiated.

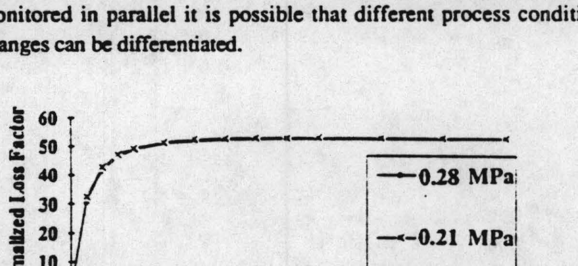

Figure 11 - Sensitivity of Normalized Loss Factor to Roller Pressure

4.2.4. Wound Material Impurity

The sensitivity of the dielectric measurement to the occurrence of an impurity in the wound material was tested by introducing a piece of a foreign object between two layers of the ring during winding. The object used was a 1 cm by 3 cm strip of aluminum foil.

During the very short time intervals that the aluminum foil was beneath the pressure roller or the copper strip, the output signal from the sensor circuit changed dramatically. The wave form during these quick reactions to the foil are presented in Figure 12. Analysis showed that the sensor output magnitude was attenuated by 36% and that the sensor voltage phase lag temporarily dropped by approximately 15%.

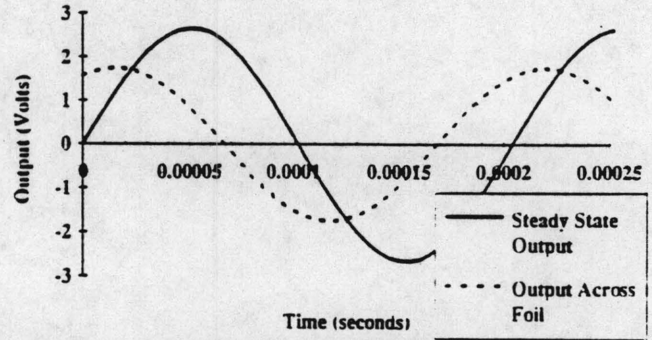

Figure 12 - Output Attenuation at the Passage of Foil

The foil represents a negative void effect. A void, if it did exist, would be represented as an area of very low permittivity to the dielectric sensor. The foil presents the exact opposite picture. Therefore, if the sensor shows the foil passage as a sharp, transient dip in the output response, it is expected to show a large void as a positive spike in the sensor output.

5. Conclusions

The objective of this research is to establish the feasibility of a dielectric sensing methodology as applied to monitoring process variable changes in thermoplastic filament winding. This methodology utilizes the pressure roller and winding mandrel as electrodes and observes the normalized permittivity and loss factor of the prepreg at the prepreg laid down point to infer the state of resin consolidation and the condition of the winding process. Advantages of this application include the simplicity in the circuit construction, the ease of connection to an existing filament winder, the negligible noise in the sensor output, and the real-time implementation capability for the purpose of in-process monitoring.

The effectiveness of the dielectric quantities normalization procedure as derived in this research was verified experimentally by the insensitivity of these quantities to the variation of roller separation distance.

With a 33% increase in winding speed, the sensor showed a 16% change in steady state permittivity and a 15% change in steady state loss factor. With a 33% increase in winding pressure, the sensor showed a 10% increase in steady state permittivity and no change in loss factor. The monitoring circuit's sensitivity to local disturbances was shown by a 36% output attenuation and 15% phase shift at the passage of a small piece of aluminum foil beneath the sensing electrodes. These results revealed the potential of using dielectric properties as a process monitor or as a feedback measurement for the control and regulation of thermoplastic filament winding processes.

Acknowledgement

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Dynamic Dielectric Monitoring of In-Situ Consolidation of Thermoplastic Filament Winding

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George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology

for the period of August 15, 1992 to August 14, 1993

ABSTRACT

A dynamic dielectric sensor, embedded in the compression roller, as utilized for the real-time monitoring of thermoplastic filament winding has been presented in this report. The unit establishes an alternating electrical field across the filament contact point on the mandrel and identifies the variation of resin dielectric properties in relation to the change in critical process parameters, namely the winding speed and compression pressure, as well as the occurrence of unexpected impurity in the material that have direct bearing on the degree of resin consolidation at the contact point. The methodology presented in this report involves the establishment of the analytical basis for the normalization of dielectric quantities with respect to the time varying separation distance between roller and mandrel, the investigation on the frequency response of the resin-fiber system, as well as experimental implementation of the proposed scheme on an actual thermoplastic filament winder.

INTRODUCTION

Filament winding techniques frequently use thermosetting resins which require post curing procedures in an autoclave or oven. The advent of high strength thermoplastic resins has allowed the process to be completed at the time of winding, in that temperature and pressure can be applied simultaneously during the winding process. At the prepreg laydown point, the resin material is heated above its melting temperature and compressed via a compression roller into intimate contact with the other plies. This process is commonly referred to as the "in-situ" consolidation of the resin and fiber, and it can be accomplished without the need of post-process autoclaving.

The mechanical property of a thermoplastic filament wound part is greatly affected by the amount of remaining air in the finished part. The air amount, or the void content, is in turn dictated by the achievable degree of consolidation at the filament laydown point. The degree of consolidation is, however, prone to fluctuation during the winding process due to the unpredictable arrival of material or thermal disturbances and changes in process parameters of winding speed, winding pressure and heat [Carpenter, 1992]. Therefore, an on-line measurement tool is needed to measure changes in process parameters and feed this information to a control algorithm which could control the temperature and/or pressure applied to the laydown point. This process control could be used to lower void content and make the overall process more applicable to widespread manufacturing use.

Current void content measurements for filament wound parts are completed off-line by ultrasonic attenuation C-scan [Jones *et al.*, 1976], X-radiography [Bolylas, 1976], Fokker bond-testing [Schliekelmann, 1978], optical holographic stress wave interferometry [Querido, 1976] and thermography [Pye *et al.*, 1979]. None of these measurement methods is currently applied in real-time nor would they be suitable for application to a control process. This lack of suitability comes either from difficulties in implementation into current winding equipment, the speed at which measurements are made, or possible structural damage to the part itself.

The current lack of an effective monitoring methodology commonly causes excessive amounts of pressure and heat to be applied during the filament winding process. Although the objective of the heat and pressure is to reduce void content, too much of either parameter causes problems in the finished product. Over pressurizing causes an undesirable high fiber volume fraction by squeezing too much resin away from the fibers. Too much heat can degrade the thermoplastic matrix and adversely affect the mechanical properties of the finished product.

In order to overcome these difficulties, this research sought to provide a means of real-time process monitoring of thermoplastic filament wound composites by the establishment of a dielectric monitoring methodology. The key concept involved is the sensitivity of the material dielectric properties to the degree of consolidation during winding. Resin consolidation at the lay down point proceeds as the thermoplastics is compressed above its melting temperature, the prepreg surfaces are brought into intimate contact, and the ply interfaces are eliminated by the molecular diffusion of resin [Anderson *et al.*, 1989]. This is usually accompanied by the initiation and continuation of the polymer crystallization and an increase in the viscosity of the system [Bidstrup et al., 1989; Ciriscioli, et al., 1989; Kranbuehl *et al.*, 1987]. These phenomena will affect the material dielectric properties through their influences on the ion mobility and dipole orientation energy. Therefore, any change in the process condition to alter the degree of prepreg consolidation will show its effect on the rheological properties of the resin matrix.

In this study, the monitoring system utilizes a sinusoidal input current passing through the prepreg tape laydown point on the filament winder. The rheological property changes of the polymer at the laydown point will dominate the magnitude and phase of the current passing through that point. Relating the current parameters back to dielectric quantities and then to process variables will allow real time monitoring of the process.

The dielectric monitoring methodology outlined here was implemented with a signal generator creating the input voltage, an actual thermoplastic filament winder creating the dielectric change to that signal, and a monitoring circuit to measure the differences between the input voltage and the output current. In acquiring real-time knowledge of the state of the part being wound via dielectric analysis, the real-time understanding regarding dielectric quantities such as permitivity and loss factor has to be available. Prior to this research effort, there were no analytical forms to these quantities which take into account the dynamic factors associated with filament winding, such as time varying roller/mandrel separation. This lack of analytical relationships for the dielectric quantities is one challenge in proving dielectric analysis as a viable sensor methodology. In this report, a systematic procedure to normalize the dielectric quantities of permitivity and loss factor has been developed in a format applicable to real-time implementation. It is followed by the discussion on the electrical characteristics of the winding apparatus and the derivation of an electric circuit element model for the winder. This model was then used in the design, simulation, and analysis of the frequency response of the dielectric sensing circuit. A series of experiments based on the static and dynamic winding cases were performed. Results on the dielectric sensitivity to the change of process condition in terms of roller pressure, winding speed, and unexpected impurity in the material are presented and discussed to verify the applicability of the proposed concept.

NORMALIZED DIELECTRIC QUANTITIES

As Figure 1 shows, the dielectric monitoring scheme as applied to filament winding consists of a sinusoidal excitation across the roller/mandrel electrodes. As the input voltage is applied, an electrical field is created, which includes a point of specific interest: the prepreg lay down point. Responding to the electrical field, the polymer resin

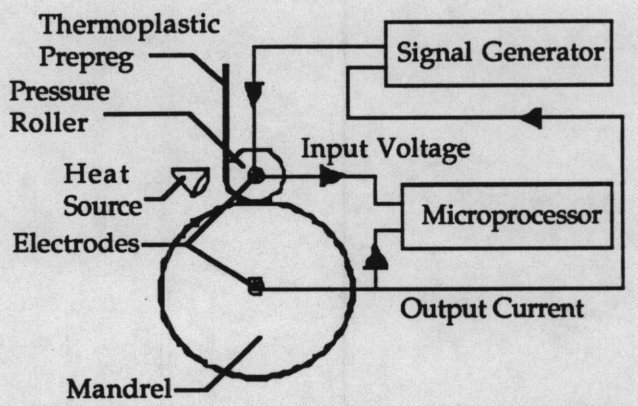

Figure 1. Filament Winding Monitoring Schematic

in the laydown area will become polarized and conduct a charge. A displacement current [Ramo *et al.*, 1984] across the capacitor which emerges from the other side of the laydown point is used as the output signal. Comparison of the input and output signals, in terms of the amplitude ratio and phase difference, provides the information required to derive the dielectric quantities of the resin at the lay down point.

Both input voltage and output current have the same frequency (ω), but the output exhibit a phase difference (ϕ) with the input. This phase difference is input frequency dependent and is defined as:

$$\phi(\omega) = \frac{2\pi\tau(\omega)}{T} \qquad (1)$$

where t is the time difference between the input and output peaks and T is the period of the input sinusoid. For the resin of interest, the dielectric quantities are permitivity (ε') and loss factor (ε'') Designating the input as $v(t)$ and the output $i(t)$, we have

$$v(t) = V_0 \sin(\omega t) \qquad (2)$$

$$i(t) = I_0(\omega) \sin(\omega t + \phi(\omega)) \qquad (3)$$

where V_0 is the input voltage magnitude, I_0 is the output current magnitude, and "t" represents time. The complex admittance of the material is defined as the ratio:

$$\Psi(\omega) = \frac{I_0(\omega)}{V_0} \cos\phi(\omega) + j\frac{I_0(\omega)}{V_0} \sin\phi(\omega) \qquad (4)$$

The permitivity (ε') and loss factor (ε'') are material dependent dielectric properties. They can be specified with respect to the admittance as follows:

$$\varepsilon' = \frac{1}{\omega} G\, Im[\Psi(\omega)] \qquad (5)$$

$$\varepsilon'' = \frac{1}{\omega} G\, Re[\Psi(\omega)] \qquad (6)$$

In these relationships, G is a function of electrode geometry only. In order to more clearly define this geometry factor, it can be noted that G contains one dynamic part (due to the increasing roller/mandrel separation that changes the electrode geometry) and other constant parts (degree of resin consolidation dependent). G'' will be defined as the dynamic geometry factor and G' as the constant geometry factor. Therefore G can be defined as:

$$G = G'G''(\delta) \qquad (7)$$

where δ is defined as the separation distance between the roller and the mandrel. Combining this geometry factor with the previous permitivity and loss factor equations yields:

$$\varepsilon' = \frac{I_0(\omega)}{V_0\omega} \sin\phi(\omega) G'G''(\delta) \qquad (8)$$

$$\varepsilon'' = \frac{I_0(\omega)}{V_0\omega} \cos\phi(\omega) G'G''(\delta) \qquad (9)$$

As it is desired to calculate the dielectric quantities in real-time, a way of obtaining the dynamic geometry factor $G''(\delta)$ must be derived that allows real-time application negating the effect of changing electrode geometry. Defining the geometry factor in terms of a parameter ξ:

$$G''(\delta) = \xi\varepsilon''\varepsilon_0 G' \qquad (10)$$

where ξ can be determined experimentally as:

$$\xi = \frac{V_0\omega}{I_0(\omega)\cos\phi} \qquad (11)$$

Note that all quantities appear to the right hand side of Equation (11) are measurable in real-time. For the approximation of dynamic geometry factor, a general, linear or non-linear, function for $G''(\delta)$ can assume the form of:

$$G''(\delta) = \gamma\delta^{\alpha} + \beta \tag{12}$$

where γ is a proportionality constant, β is a boundary constant and a is the dynamic geometry exponent. Experimentally, several estimations of ξ can be made corresponding to different δ∋s:

$$\xi(\delta_1) = \xi_1 \tag{13}$$

$$\xi(\delta_2) = \xi_2 \tag{14}$$

$$\xi(\delta_0) = \xi_0 \approx 0 \tag{15}$$

Substitution of γ and the boundary condition at the initial plate separation (δ_0) into Equation (12) gives:

$$G'_{\gamma}(\delta) = \delta^{\alpha} - \delta_0^{\alpha} \tag{16}$$

Taking a ratio of different ξ values:

$$\frac{\xi_1}{\xi_2} = \frac{\delta_1^{\alpha} - \delta_0^{\alpha}}{\delta_2^{\alpha} - \delta_0^{\alpha}} \tag{17}$$

Equation (17) can be solved numerically for a for different process configurations. The constant a can then be used throughout a particular process to calculate the dynamic geometry factor in real-time. This factor does not, however, take into account very small changes in the nip area which occur from temperature, winding speed or winding pressure changes. These effects are believed to be negligible compared to electrode distance effects.

The normalization of material dependent dielectric properties to negate the effect of changing electrode geometry then lead to:

$$\bar{\varepsilon}' = \frac{\varepsilon'}{G'\gamma} = \frac{I_0(\omega)}{V_0\omega\varepsilon_0} \sin\phi(\delta^{\alpha} - \delta_0^{\alpha}) \tag{18}$$

$$\bar{\varepsilon}'' = \frac{\varepsilon''}{G'\gamma} = \frac{I_0(\omega)}{V_0\omega\varepsilon_0} \cos\phi(\delta^{\alpha} - \delta_0^{\alpha}) \tag{19}$$

where the permitivity and loss factor, respectively, are divided by the static geometry factor and the nonlinear coefficient for the dynamic effects. The normalization allows the use of dielectric quantities for the monitoring of process condition related to the degree of resin consolidation, but not to the change of electrode separation as tape are continuously wound on to the mandrel. The values of these normalized quantities at the variation of electrode geometry is tested in actual winding situations, and the results are presented in section 4.2.1.

SENSING CIRCUIT REALIZATION

In this analysis the pressure roller and mandrel sandwiching a thermoplastic tape can be modeled as a capacitor in an electric circuit. Although the geometry involved is different than for a parallel plate capacitor, the capacitance rating of such a roller/thermoplastic combination remains proportional to the permitivity of the dielectric material and the surface area of the conductors while inversely proportional to the distance between the conductors.

As much previous research has shown [Sinchina, 1990], the permitivity of thermoplastics will vary during the temperature and pressure cycles of manufacturing processing. It is this point which presents the proper combination of a dielectric between two conductors. Therefore, from the point of view of the monitoring circuit, the pressure roller/thermoplastic tape/mandrel combination represents a varying capacitor as the tape undergoes the temperature and pressure cycles of processing on the filament winder.

The capacitor also took into account the loading effects of the signal measuring devices and operational amplifiers used to minimize the loading effects and amplify the output signal. These considerations are demonstrated by the sensing circuit schematic pictured in Figure 2. *Rin* and *R1* are input buffer resistors for the operational amplifiers, *Rf* is a feedback resistor, *Rw* is the winder resistance, *Cw* is the winder capacitance and *Vin* is the input sinusoidal voltage.

Initial capacitance measurements on the filament winder were taken and results revealed that the capacitance of the roller/mandrel apparatus was on the order of tens of picofarads. The sensing circuit would, therefore, need to be highly sensitive to changes in this already small capacitance. Thus, a method of increasing the circuit sensitivity was sought by increasing the area of the conductors of the roller/mandrel capacitor. This was accomplished by

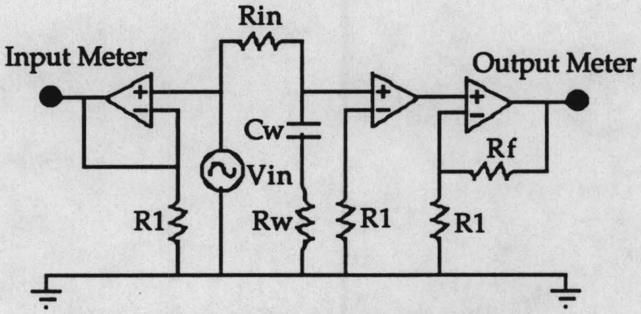

Figure 2. Dielectric Monitoring Circuit

the creation of an additional conduction path from the input signal through the polymer tape to the mandrel. This additional signal path was a narrow copper strip between the pressure roller's mounting bracket and prepreg ring on the mandrel. In practical applications, the use of a more compliant pressure roller or a series of rollers along the contour of the laid prepreg can serve the same purpose.

The frequency response of the proposed monitoring circuit as outlined in Figure 2 was simulated for various capacitances. Simulation results, as shown in Figures 3 and 4 for the magnitude and phase lag, revealed that the circuit would have a low pass filter frequency characteristic with a drop off frequency of approximately 30 KHz.

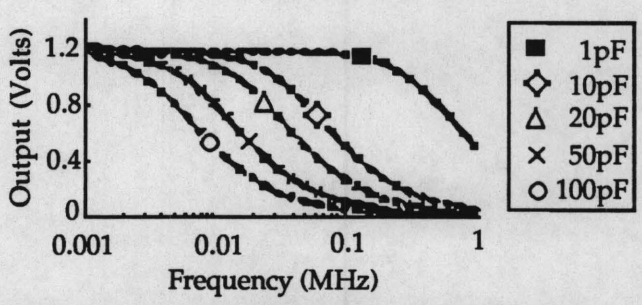

Figure 3. Circuit Voltage Sensitivity to Capacitance

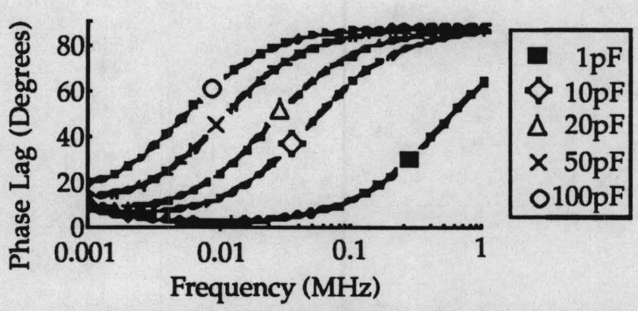

Figure 4. Circuit Phase Sensitivity to Capacitance

EXPERIMENTAL IMPLEMENTATION

Hardware Components

The filament winding station used for these experiments is a two-axis winder retrofitted with a roller and heater mechanism for in-situ consolidation. More details on the winding machine is documented in [Carpenter, 1992]. The dielectric monitoring system itself was comprised of four primary components. Following the circuit from its origination, a 30 KHz sinusoidal input signal to be used by the circuit was generated by the function generator. The monitoring circuit was created on an electronic circuit prototype board. The circuit elements included carbon film resistors, one dual operational amplifier 8 pin DIP integrated circuit to buffer the oscilloscope channel, and one operational amplifier 8 pin DIP integrated circuit to amplify the dielectric sensor output signal.

Once the displacement current signal crossed the input resistor, *Rin*, it was carried to the winder capacitance by a connection cable mounted between the *Rin* resistor and the compression roller support arm on the winding machine. This support arm was isolated electrically from the rest of the machine by an acrylic mounting block. A digital storage oscilloscope was used to measure sensor circuit output. This oscilloscope's digital storage modes allowed for passive signal processing of the sensor output signal via a signal averaging function which averaged the signal with a 20 MHz frequency, or every five samples at the 100 MHz sampling rate.

The material used in this study was poly(etheretherketone) (PEEK)/glass unidirectional prepreg tape (ICI's APC-2-D-S2 Glass). The tape was 0.24 inches in width, nominally 0.009 inches thick. The manufacturer's suggested process temperature was 410^0C. PEEK was chosen as the matrix because it is a polar polymer and should show dielectric effects better than most other matrices. Glass was chosen as a fiber because it is not conductive and, therefore, would not cause the current to leak away from the roller/mandrel interface area.

Results

Discontinuous Roller/Mandrel Separation Rate. Equations (18) and (19) are formulated to negate the effects of roller/mandrel separation distance. Experiments were conducted by cutting the incoming tape, after the winding process had reached steady state, to quickly bring the rate of change of roller

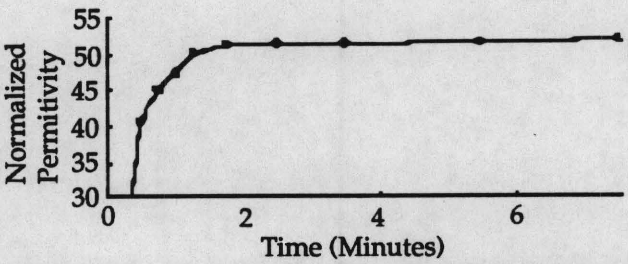

Figure 5. Sensitivity of Normalized Permitivity to Tape Discontinuation

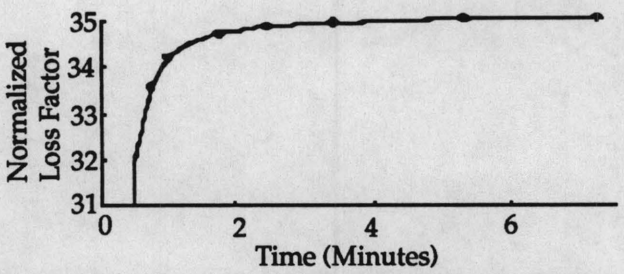

Figure 6. Response of Normalized Loss Factor at Tape Discontinuation

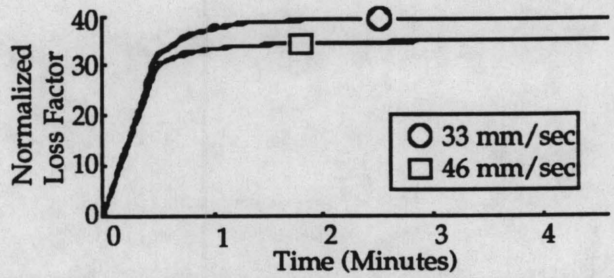

Figure 7. Normalized Loss Factors in Different Winding Speeds

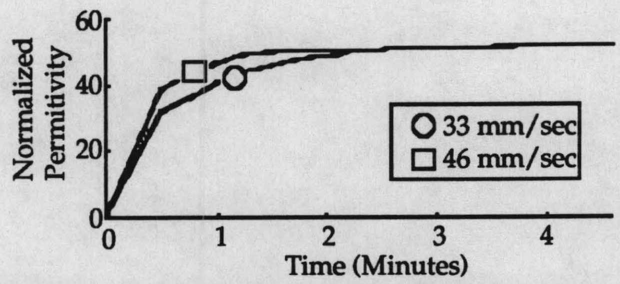

Figure 8. Normalized Permitivity in Different Winding Speeds

separation to zero. It would be expected that this should produce no change in the normalized dielectric quantities resulting from the application of Equations (18) and (19). Figures 5 and 6 depict the normalized permitivity and loss factor measurements during this test.

In the beginning of the test, the normalized permitivity and loss factor see an increase at sharp slope as the material is brought up to temperature on the mandrel. The fact that the dielectric quantities do not start at their nominal values for winding is due to the fact that the first layer of the tape is not near melt temperature, because a section of prepreg tape must be taped to the mandrel in order to initiate the winding. After approximately 2 minutes, the permitivity and loss factor clearly show steady state values being reached. These steady state values exhibit no change during the part thickness build-up cycle (2 minute to 2.5 minute), the tape discontinuation point (2.5 minute), and the constant thickness cycle (2.5 minute to the end of test). It implies that the normalized dielectric quantities were able, as would be expected, to ignore the change in roller/mandrel separation rate.

<u>**Winding Speed Variation.**</u> This experiment demonstrates the sensitivity of resin permitivity and loss factor to the speed of winding. As shown in Figure 7, the lower winding speed curve exhibits a steady state normalized loss factor of approximately 37 while the same curve for the higher winding speed shows a steady state of approximately 33 for a change of 12% from the lower to higher speed. However, the similar behavior can not be observed for the normalized permitivity in response to the winding speed difference as shown in Figure 8. A lower winding speed may allow more voids to be removed due to the prolonged air escape time thereby promoting the degree of consolidation during winding. On the other hand, previous work [Carpenter, 1992] has shown that PEEK is a shear thinning polymer which responds to a higher strain rate by reducing viscosity and allowing more void removal. These competing factors complicates the relationship between the winding speed and the dielectric quantities.

<u>**Roller Pressure Variation.**</u> It was expected that the higher pressure would induce an increase in the dielectric quantities, since it produced a higher degree of consolidation through the promotion of more intimate contact between layers. In this study an abrupt roller pressure change from 0.21 MPa to

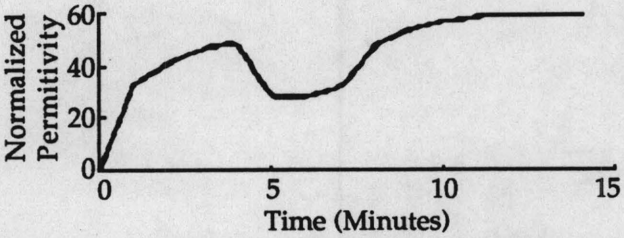

Figure 9. Normalized Permitivity in Response to a Pressure Increase at 4 Minutes

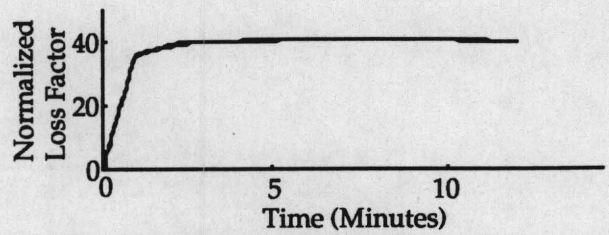

Figure 11. Normalized Loss Factor in Response to a Pressure Increase at 4 Minutes

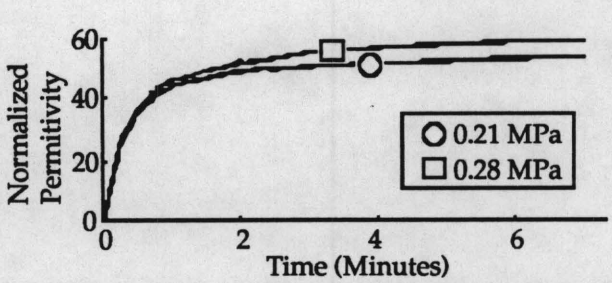

Figure 10. Steady State Normalized Permitivity in Different Pressures

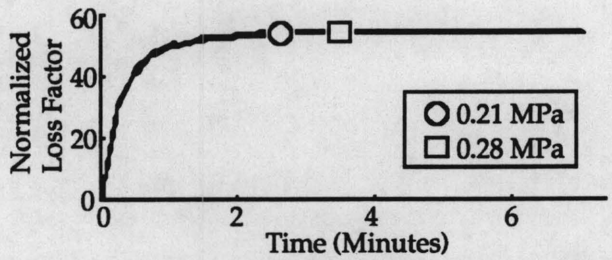

Figure 12. Steady State Normalized Loss Factor in Different Pressures

0.28 MPa is introduced to a steady state winding situation and the responding permitivity is seen in Figure 9. The permitivity is characterized by a sudden drop and then a return to a higher steady state value than before. The transient behavior is expected from the squeezing of resin away from both sides of the longitudinal axis of the tape and perpendicular to the tape rotation direction. The higher pressure makes the newly wound layers slightly thinner and wider than previous layers. Measurements of the finished part support this speculation as the inner layers had a width of approximately 6.73 mm while layers on the outer diameter of the ring (those laid down after the pressure change), had a width of approximately 7.06 mm. One possible mechanism on the cause of this transient effect is that during this movement of resin, the conducting surface area between the tape and the roller is being subject to nonuniformities of contact and perhaps viscoelastic effects as well. Once the movement of resin is complete, there is a return to normal consolidation.

In addition, a set of rings were sound at different pressures and their steady state dielectric responses compared in Figure 10. It is clearly indicated that the ring wound at the higher pressure exhibits a higher steady state permitivity.

However, similar remarks could not be made for the loss factor data. As shown in figure 11 and 12 the normalized loss factor is essentially invariant to the change of compression pressure in the context of both the transient and the steady state values. This observation, along with the study of winding speed effect, illustrates the non-redundancy between the measurements of permitivity and loss factor. Therefore, as these quantities are monitored in parallel it is possible that different process condition changes can be differentiated.

Wound Material Impurity. The sensitivity of the dielectric measurement to the occurrence of an impurity in the wound material was tested by introducing a piece of a foreign object between two layers of the ring during winding. The object used was a 1 cm by 3 cm strip of aluminum foil.

During the very short time intervals that the aluminum foil was beneath the pressure roller or the copper strip, the output signal from the sensor circuit changed dramatically. The wave form during these quick reactions to the foil are presented in Figure 13. Analysis showed that the sensor output magnitude was attenuated by 36% and that the sensor voltage

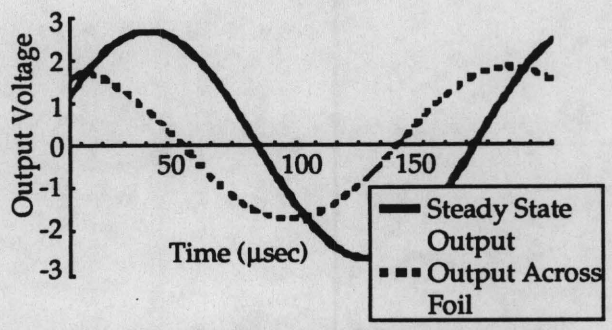

Figure 13. Output Attenuation at Passage of Foil

phase lag temporarily dropped by approximately 15%.

The foil represents a negative void effect. A void, if it did exist, would be represented as an area of very low permitivity to the dielectric sensor. The foil presents the exact opposite picture. Therefore, if the sensor shows the foil passage as a sharp, transient dip in the output response, it is expected to show a large void as a positive spike in the sensor output.

CONCLUSIONS

The objective of this research is to establish the feasibility of a dielectric sensing methodology as applied to monitoring process variable changes in thermoplastic filament winding. This methodology utilizes the pressure roller and winding mandrel as electrodes and observes the normalized permitivity and loss factor of the prepreg at the prepreg laid down point to infer the state of resin consolidation and the condition of the winding process. Advantages of this approach include the simplicity in its circuit construction, the ease of connection to an existing filament winder, the negligible noise in the sensor output, and the real-time implementation capability for the purpose of in-process monitoring.

The effectiveness of the dielectric quantities normalization procedure as derived in this research was verified experimentally by the insensitivity of these quantities to the variation of roller separation distance.

With a 33% increase in the winding speed, the sensor showed a 12% change in steady state loss factor and no change in permitivity. With a 33% increase in the compression pressure, the sensor showed a decreasing transient response in permitivity due to the resin movement, and a 10% increase in steady state permitivity, but no change in loss factor. The monitoring circuit's sensitivity to local disturbances was shown by a 36% output attenuation and 15% phase shift at the passage of a small piece of aluminum foil beneath the sensing electrodes. These results revealed the potential of using dielectric properties as a process monitor or as a feedback measurement for the control and regulation of thermoplastic filament winding processes.

ACKNOWLEDGE

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ABSTRACT

The concept of dynamic dielectric sensing for the monitoring of thermoplastic filament winding process is studied. The sensing system establishes an alternating electrical field across the filament contact point on the mandrel and identifies the variation of resin dielectric properties. The sensitivity of the dielectric property variation in relation to the change in critical process parameters, namely the winding speed and compression pressure, as well as the occurrence of unexpected impurity in the material that have direct bearing on the degree of resin consolidation at the contact point has been experimentally tested. The requency response of the resin-fiber system and the decomposition of the roll separation effect and the consolidation effect on dielectric properties has been evaluated.

TECHNICAL SUMMARY

The advent of high strength thermoplastic resins has allowed the filament winding process to be completed without post-proceess autoclaving, in that temperature and pressure can be applied simultaneously during the winding process to accomplish resin consolidation in an "in-situ" manner. This research sought to provide a methodology to monitor the thermoplastic filament winding process by identifying the state of resin consolidation in reference to its instantaneous dielectric property. Resin consolidation at the lay down point proceeds as the thermoplastics is compressed above its melting temperature, the prepreg surfaces are brought into intimate contact, and the ply interfaces are eliminated by the molecular diffusion of resin. This is usually accompanied by the initiation and continuation of the polymer crystallization and an increase in the viscosity of the system [Bidstrup et al., 1989; Ciriscioli, et al., 1989; Kranbuehl *et al.*, 1987]. These phenomena will affect the material dielectric properties through their influences on the ion mobility and dipole orientation energy. Therefore, any change in the process condition to alter the degree of prepreg consolidation will show its effect on the rheological properties of the resin matrix.

In this study, the monitoring system utilizes a sinusoidal input current passing through the prepreg tape laydown point on the filament winder. The rheological property changes of the polymer at the laydown point will dominate the magnitude and phase of the current passing through that point. Relating the current parameters back to dielectric quantities and then to process variables will allow the monitoring of the process to be performed in real-time.

The dielectric monitoring methodology established here was implemented with a signal generator providing the input voltage, an actual thermoplastic filament winder creating the dielectric change to that signal, and a monitoring circuit measuring the differences between the input voltage and the output current. Figure 1 shows the schematics of the sensing system.

In this study, a systematic procedure to normalize the dielectric quantities of permitivity and loss factor based on the decomposition of effects due to consolidation and electrode shape factor has been developed. An electric circuit element model for the winding process was formulated for the design, simulation, and analysis of the frequency response of the dielectric sensing circuit.

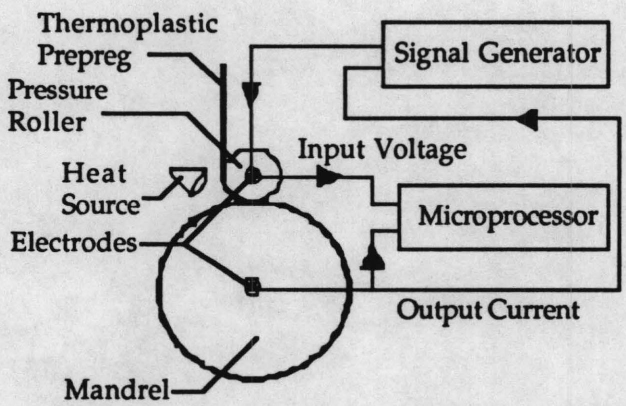

Figure 1. Filament Winding Monitoring Schematic

The filament winding station used for these experiments is a two-axis winder retrofitted with a roller and heater mechanism for in-situ consolidation. The dielectric monitoring system itself was comprised of four primary components. Following the circuit from its origination, a 30 KHz sinusoidal input signal to be used by the circuit was generated by the function generator. The monitoring circuit was created on an electronic circuit prototype board. The circuit elements included carbon film resistors, one dual operational amplifier 8 pin DIP integrated circuit to buffer the oscilloscope channel, and one operational amplifier 8 pin DIP integrated circuit to amplify the dielectric sensor output signal.

Once the displacement current signal crossed the input resistor, *Rin*, it was carried to the winder capacitance by a connection cable mounted between the *Rin* resistor and the compression roller support arm on the winding machine. This support arm was isolated electrically from the rest of the machine by an acrylic mounting block. A digital storage oscilloscope was used to measure sensor circuit output. This oscilloscope's digital storage modes allowed for passive signal processing of the sensor output signal via a signal averaging function which averaged the signal with a 20 MHz frequency, or every five samples at the 100 MHz sampling rate.

The material used in this study was poly(etheretherketone) (PEEK)/glass unidirectional prepreg tape (ICI's APC-2-D-S2 Glass). The tape was 0.24 inches in width, nominally 0.009 inches thick. The manufacturer's suggested process temperature was 410^{0}C. PEEK was chosen as the matrix because it is a polar polymer and should show dielectric effects better than most other matrices. Glass was chosen as a fiber because it is not conductive and, therefore, would not cause the current to leak away from the roller/mandrel interface area.

A series of experiments based on the static and dynamic winding cases were performed to evaluate the sensitivity of the system with respect to the change of discontinuous roller/mandrel separation rate, winding speed variation, roller pressure variation, and wound material impurity. Results showed that the normalized dielectric quantities were not affected by the change of roller/mandrel separation rate as seen in a simulated tape-break case. It implied that the growth of the wound part diameter, thus the change of electrode shape factor, does not play an important role in the effectiveness of the monitoring system. Additionally, with a 33% increase in the winding speed, the sensor showed a 12% change in steady state loss factor and no change in permitivity. With a 33% increase in the compression pressure, the sensor showed a decreasing transient response in permitivity due to the resin movement, and a 10% increase in steady state permitivity, but no change in loss factor. The monitoring circuit's sensitivity to local disturbances was shown by a 36% output attenuation and 15% phase shift at the passage of a small piece of aluminum foil beneath the sensing electrodes. These results revealed the potential of using dielectric properties as a process monitor or as a feedback measurement for the control and regulation of thermoplastic filament winding processes.

References: 1. Joseph A. Urquhart-Foster, *Dynamic Dielectric Analysis in Thermoplastic Filament Winding Process Monitoring*, M.S. thesis, Georgia Institute of Technology, May 1992. 2. Steven Y. Liang and Joseph A. Urquhart-Foster, "Electromagnetic Dielectric Sensor for Process Monitoring of Thermoplastic Filament Winding," *Proceedings of the Symposium on for Mechatronics*, ASME Winter Annual Meeting, November 1993, pp. 261-269.

HUMAN RESOURCE DEVELOPMENT

This project has involved the interdisciplinary participation of the following faculty members in the format of weekly technical meetings:

1. Steven Y. Liang, Assistant Professor of Mechanical Engineering,
2. Jonathan S. Colton, Associate Professes of Mechanical Engineering, and
3. John D. Muzzy, Professor of Chemical Engineering.

The project has supported the research program of the following students:

1. Y. S. Chiou, Ph.D. candidate, research in progress, degree completion expected 1994. advisor: S. Y. Liang

2. Joseph A. Urquhart-Foster, 1992 M.S. graduate, advisor: S. Y. Liang

3. Anthony Stevens, M.S. candidate, research in progress, degree completion expected 1993, advisor: S. Y. Liang. (The candidate is from a group of underrepresented minorities).

4. Stephanie Jaeger, Undergraduate Research Program in Composite Materials, advisor: J. S. Colton. (The student is from a group of women engineers).

RESULTING PUBLICATIONS

1. Steven Y. Liang, "Dynamic Dielectric Monitoring of In-situ Consolidation of Thermoplastic Filament Winding," *Proceedings of the NSF Design and Manufacturing Systems Conference*, 1992, Atlanta, GA, January, 1992, pp. 1063-1067.

2. Joseph A. Urquhart-Foster, *Dynamic Dielectric Analysis in Thermoplastic Filament Winding Process Monitoring*, M.S. thesis, Georgia Institute of Technology, May 1992.

3. Steven Y. Liang and Joseph A. Urquhart-Foster, "Filament Winding Process Monitoring via Dynamic Dielectric Analysis," *Proceedings of the NSF Design and Manufacturing Systems Conference*, Charlotte, NC, January 1993, pp. 217-222.

4. Steven Y. Liang and Joseph A. Urquhart-Foster, "Electromagnetic Dielectric Sensor for Process Monitoring of Thermoplastic Filament Winding," *Proceedings of the Symposium on for Mechatronics*, ASME Winter Annual Meeting, November 1993, pp. 261-269.

5. Steven Y. Liang and Joseph A. Urquhart-Foster, "A Dynamic Dielectric Sensor for Process Monitoring of Filament Winding," to appear in *Proceedings of the NSF Design and Manufacturing Systems Conference*, Boston, MA, January 1994.

RESULTING PATENT APPLICATION AND INVENTION DISCLOSURE

1. Patent application: "Dielectric Sensor for Thermoplastic Winding," US Patent Application Serial No. 08/001, 499, Filed January 7, 1993.

2. Invention disclosure: "Dielectric Sensor for the Process Monitoring of Thermoplastic Filament Winding" NSF Invention Disclosure No. 93-45.

OMB Number 3145-0058

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NATIONAL SCIENCE FOUNDATION
FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. Design and Manufacturing Systems Engr Div.

2. Program Name Manufacturing Processes and Equipment Program

3. Award Dates (MM/YY) **From:** 08/15/1991 **To:** 07/31/1994

4. Institution and Address

Georgia Tech Research Corp - GIT
Administration Building
Atlanta, GA 30332

5. Award Number 9110185

6. Project Title

Research Initiation: Dynamic Dielectric Monitoring of In-situ COnsolidation of Thermoplastic Filament Winding

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens					2			1		
B. Total, Permanent Residents	1									
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian	1									
Black, Not of Hispanic Origin.........					1					
Hispanic										
Pacific Islander										
White, Not of Hispanic Origin					1			1		
C. Total, Other Non-U.S. Citizens										
Specify Country 1.										
2.										
3.										
D. Total, All participants (A + B + C)										
Disabled[3]										

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[2] Use the category that best describes the ethnic/racial status fo all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3] A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

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