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THE DESIGN, FABRICATION AND TESTING ISSUES OF
AN ELECTORRHEOLOGICAL FLUID-FILLED COMPOSITE
HELICOPTER ROTOR BLADE

presented by

DAVID MARK MOOREHOUSE

has been accepted towards fulfillment
of the requirements for

MASTERS degree in MECHANICAL ENGINEERING

C. V. Gandhi
Major professor

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**THE DESIGN, FABRICATION AND TESTING ISSUES OF
AN ELECTORHEOLOGICAL FLUID-FILLED COMPOSITE
HELICOPTER ROTOR BLADE**

By

David Mark Moorehouse

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

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Department of Mechanical Engineering

1993

ABSTRACT

THE DESIGN, FABRICATION AND TESTING ISSUES OF AN ELECTORRHEOLOGICAL FLUID-FILLED COMPOSITE HELICOPTER ROTOR BLADE

By

David Mark Moorehouse

Major Professor: Dr. Mukesh Gandhi

Helicopter manufacturers continually strive to achieve increased performance in the rotor blades. One area of focus has been control of vibration. One proposed method of achieving vibration control is through the use of electrorheological (ER) fluids. This thesis describes the design, fabrication and testing of an electrorheological fluid-filled composite helicopter rotor blade which successfully exhibited vibration damping via ER fluids. The blade contained two parallel sheet aluminum electrodes encapsulated in urethane rubber. The space between the electrodes was filled with an ER fluid and the assembly was wrapped in glass fiber/epoxy resin skins. The blade was tested in a non-rotating environment on an exciter. The test results showed the deflection of the tip to reduce by 14% and the velocity of the tip to reduce by 33% when applying voltage to the electrodes and comparing the results with the unpolarized case. Many design and manufacturing issues are discussed.

TABLE OF CONTENTS

LIST OF FIGURES	vi
INTRODUCTION	1
DESIGN ISSUES	4
Loading	4
Electrorheological (ER) Mechanism	5
Design-for-Manufacturing	8
Weight	9
Cost	9
GENERAL PHYSICAL ATTRIBUTES	10
Leading Edge	10
Skin Material	12
Filler Material	12
Spar	13
Airfoil	14
Root End	16
Blade Tip	17
Tip Weight	17
Aspect Ratio	18

DESIGN CONCEPTS	19
Continuous Skin Blade/Urethane Filler/Integral ER	
Cavity	20
Continuous Skin Blade/Polymethacrylimide	
Filler/Separable ER Cavity	21
Modular Blade With Composite Spar/Trailing Edge	
Skin/Separable ER Cavity	22
ELECTRORHEOLOGICAL ROTOR BLADE CONSTRUCTION	24
Electrorheological (ER) Cartridge	25
Silicon Carbide Leading Edge	27
Glass/Epoxy Skins Composite Skins	28
Urethane Rubber Filler	28
Airfoil	29
Aspect Ratio	29
ER CARTRIDGE FABRICATION AND TESTING	30
Multi-Layer ER Cartridge	31
Single Layer ER Cartridge	35
ROTOR BLADE TOOLING FABRICATION	40
Pattern	40
Molds	42
ROTOR BLADE FABRICATION	47
Cartridge Encapsulation	47
Skin Layup	50

Silicone Carbide Surface Coat Application	51
ROTOR BLADE TESTING	53
MANUFACTURING ISSUES	57
Manufacturing Processes	57
Tooling and Equipment	61
Quality Control	64
CONCLUSIONS	66
APPENDICIES	68
APPENDIX A: NACA 0012 AIRFOIL DATA	69
APPENDIX B: MULTI-LAYER ER CARTRIDGE	
RESPONSE	70
GENERAL REFERENCES	71

LIST OF FIGURES

Figure 1: Electrorheological Fluid Effect	2
Figure 2: Important Airfoil Geometric Quantities . . .	15
Figure 3: Aerodynamic Forces Developed by the Airfoil	16
Figure 4: Continuous Skin Blade/Urethane Filler/Integral ER Cavity	21
Figure 5: Continuous Skin Blade/Polymethacrylimide Filler/Separable ER Cavity	22
Figure 6: Modular Blade with Composite Spar, Trailing Edge Skin and Separable ER Cartridge.	23
Figure 7: ER Fluid-Filled Rotor Blade Cross-Section .	24
Figure 8: ER Cartridge Cross-Section	26
Figure 9: Multi-Layer ER Cartridge	31
Figure 10: Bottom Side View of Multi-Layer ER Cartridge Prior to Pouring	33
Figure 11: Multi-Layer Cartridge After Pouring	33
Figure 12: Multi-Layer Cartridge Assembly Showing Sheet Wax Spacers Prior to Pouring	34
Figure 13: Single Layer Cartridge Response - No Voltage	38
Figure 14: Single Layer Cartridge Response - 2000 Volts	39
Figure 15: Pattern Template	40

Figure 16:	Pattern Assembly	41
Figure 17:	Pattern Assembly After First Spline	42
Figure 18:	Pattern Box Prior to Surface Coat	43
Figure 19:	Pattern Box After Surface Coat	44
Figure 20:	Casting Sand/Resin in Pattern Box	45
Figure 21:	Both Mold Halves After Demolding	46
Figure 22:	Cartridge After Encapsulation into Airfoil	49
Figure 23:	Blade Droop and Flexibility After Demolding	50
Figure 24:	Plan View of Blade	51
Figure 25:	Root End View of Blade	52
Figure 26:	Tip View of Blade	52
Figure 27:	Blade Tip Velocity - No Volts, 3000 Volts .	54
Figure 28:	Blade Tip Velocity - No Volts, 2000 Volts .	55
Figure 29:	Blade Tip Deflection - No Volts, 3000 Volts	56

INTRODUCTION

Helicopter manufacturers are constantly seeking new design and manufacturing options that offer greater levels of performance in the main rotor blades. The inherent complexity of both designing and manufacturing rotor blades yields many factors to consider when attempting to improve performance. This multitude of factors makes improving performance a difficult task. Some of these factors are static loading, dynamic loading, vibration, fatigue, temperature, moisture, hub attachment, blade flexibility,... Of these issues, one area of focus has been control of vibration due to flapping. This attention is because rotor blade performance is limited by vibration.

The use of composite blades has improved the ability of a rotor blade to dampen vibrations simply due to the inherent structural damping nature of composite materials. Additional advantages of composite blades are decreased weight, greater resistance to crack propagation, lower vulnerability to corrosion, improved adaptability to complex geometries, improved aerodynamic performance, and reduced manufacturing costs. Although composites offer all of the above advantages and dampen vibrations better than metals,

rotor blade designers still desire to have improved damping of composite helicopter rotor blades.

One proposed method of achieving vibration control is through the use of electrorheological (ER) fluids. Electrorheological fluids are suspensions of fine particles in a non-conducting oil. A commonly used ER fluid is corn starch mixed with silicone oil. These fluids have the ability to change viscosity as a function of the electric field in which they exist. Upon application of an electric field, the polarized particles align and the fluid becomes a gel-like solid. Once the field is removed, the fluid reverts to its original viscosity. Figure 1 below shows this ER effect.

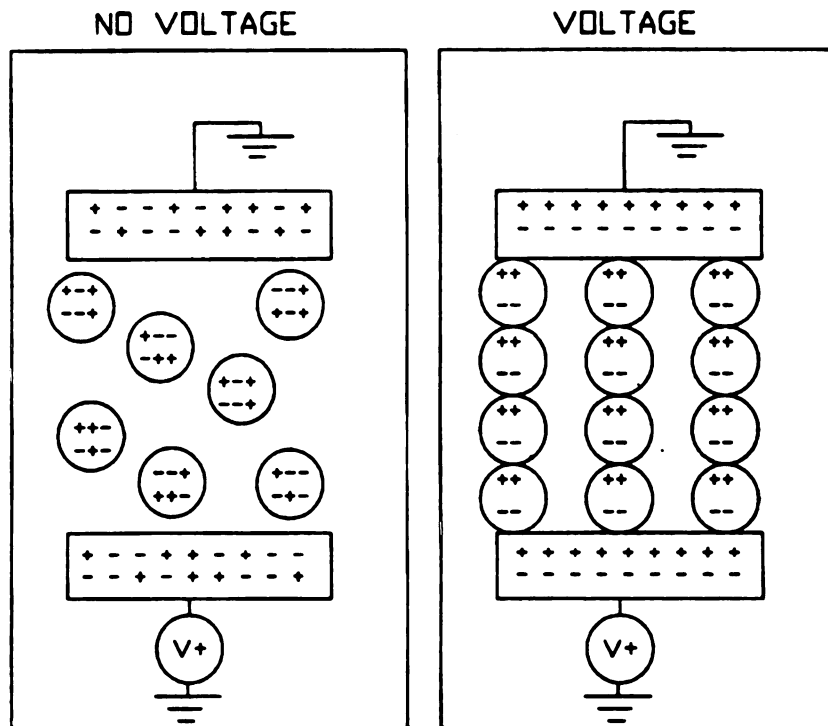


Figure 1: Electrorheological Fluid Effect

Using ER fluids inside a rotor blade would create a variable stiffness blade which would enable one to tailor the overall or local stiffness to respond optimally to varying operating environments.

Most work performed on ER fluids to date has been with small parallel electrodes on a laboratory scale. There has been little effort to advance these materials towards a production environment by fabricating larger test specimens and addressing some of the manufacturing issues.

This thesis describes a research effort which successfully utilized ER fluids in a scaled-down rotor blade to control vibration. Many of the design issues and physical attributes of ER blades are explained. Some broad design concepts are presented and a final design construction is generated based on the concepts. All aspects of tooling and actual blade fabrication are detailed. The testing procedure and results are discussed. Some of the manufacturing issues that surfaced through the research are highlighted. Finally, conclusions are made based on the research.

DESIGN ISSUES

Designing composite helicopter rotor blades is a very complex task. The requirement of vibration control via ER fluids adds an entirely new dimension to the design process. As a result the design process must consider many new issues. This section outlines the critical design issues of an ER fluid-filled composite blade. The issues fall into the categories of loading, ER mechanism, design-for-manufacturing, weight, or cost.

Loading

The loads induced on rotor blades may be structural, environmental, fatigue, or galvanic.

Structural. These types of loads include all static loads such as bending moments in the hub area due to the weight of the blade. Other types of loads induced include dynamic loading due to the centrifugal forces, vibration and aerodynamic loads.

Environmental. There are many types of issues resulting from the environment which may cause degradation of the blade. These types are as follows:

- | | |
|--------------------------|---------------------|
| 1) Thermal | 5) EMI Shielding |
| 2) Moisture | 6) Deicing |
| 3) Ultraviolet Radiation | 7) Lightning Strike |
| 4) Corrosion | |

Fatigue. Due to the cyclic loading imparted on a rotor blade, fatigue is a very important consideration. The mode of failure must also be considered (catastrophic versus non-catastrophic).

Galvanic. This type of loading or degradation would exist when two dissimilar materials such as aluminum and graphite come in contact in the presence of an electrolyte, such as salt water.

Electrorheological (ER) Mechanism

Fundamentally, the requirements for an electrorheological effect to occur are simply two isolated electrodes made of a highly conductive material separated by a constant gap of .020" - .040". The gap is filled with the ER fluid. Some of the new issues associated with an ER mechanism are described below.

Electrode Material/Spacing/Size/Insulation. Typically, sheet aluminum .015" - .030" has been used as the electrode material due to its high electrical conductivity, low cost and availability. Spacings of .020" - .040" have been used with good success. Gaps larger than .040" begin to show deterioration of the ER effect. The width of the electrodes must also be selected. Electrode widths from 1" to 12" square have been successfully used and it appears that the only limitation of electrode width is the assurance that the two electrodes do not come into contact and that the gap size remains constant. Finally, the electrodes must be insulated from each other as well as surrounding materials which may be damaged by the presence of an electric field. This is usually done with a silicone or urethane based rubber.

Fluid Drain Plug/Fill Plug. Once the rotor blade is completely fabricated, there must be provisions for filling the ER cavity between the electrodes with fluid. It also may be necessary to drain the fluid on occasion hence there should be a drain plug.

Power Supply/Requirements. Voltages up to 3000 volts have been used to produce an ER effect. The voltage requirements must be evaluated so that appropriate hardware such as transformers, power supply, etc. can be determined.

Wire Harness. There must be wires from the transformer to the electrodes. The wires and connections should not be exposed to the environment yet should be accessible in the event of a repair. The connections shall also remain secure during all rotational speed and angles of the rotor blades.

Localized Control Via Separate ER Zones. It may be desired to only vary the stiffness of certain regions of the blade for optimal performance. This could be done with separate ER zones which would be insulated from adjacent zones. There would be separate wires and controls for each zone.

Packaging. Adding all of these additional components (electrodes, wires, etc.) to the blade may be a cumbersome task. It is desired to have the blade packaged in such a way that it attaches on to the hub similarly to existing blades with one wire connector which would also need to be connected. The more consolidated the wires, controls, etc. are, the more appealing this concept would be to helicopter manufacturers.

Control System. There would need to be additional controls on the instrument cluster to vary the voltage in the different ER zones. Also needed would be some sort of sensing mechanism to inform the pilot when and how much to vary the voltage. This sensing mechanism could utilize

optical fibers, however, addressing that issue would be a study in itself.

Design-for-Manufacturing

These new issues involved in designing an ER fluid-filled rotor blade also make manufacturing more difficult. The design process must include evaluation of design-for-manufacturing concepts such as processing and tooling. It should be determined beforehand whether a research effort of this nature will be either process or tooling prohibitive.

Processing. Typical composite blades are fabricated using cocured or precured and bonded techniques. The cocured process entails curing the composite skins and in the same cure cycle, bonding them to a filler such as honeycomb or foam. Precured techniques involve precuring the skins and bonding them to the core in a subsequent operation. Adding an ER mechanism will require a thorough process evaluation. This evaluation will entail determining whether the process will be cocured or precured and outlining the manufacturing sequence to determine feasibility.

Tooling. The evaluation of tooling required will be done concurrently with the process evaluation. When each manufacturing step is defined, a list of tooling for that

step should be generated so that a continual feasibility study can be performed.

Weight

Weight is an important factor in rotor blade design. The blade shall have enough weight to provide sufficient rotational inertia to lift the helicopter yet not be too heavy to decrease fuel consumption or performance.

Cost

The issue of cost must be thoroughly evaluated via a cost trade-off compared to existing composite blades. It should be approximately determined how much the increase in performance will cost on a production basis due to the increase in material cost and processing time.

GENERAL PHYSICAL ATTRIBUTES

There are many attributes which are common to all rotor blades and it is these attributes which the design will define based on the design issues covered in the previous section. This section discusses these attributes and some of the issues pertaining to the applicability of these attributes to an ER fluid-filled blade. The ER mechanism discussed earlier is also a physical attribute of the blade, however, it obviously is not common to all blades.

Leading Edge

Due to the operating environment of rotor blades, the leading edge must be extremely erosion resistant. This is primarily to protect wear caused by sand, rain or dust. There are several materials and methods that have been or can be used on the leading edge to provide erosion resistance. One important characteristic of a leading edge is that it should be repairable or replaceable. Eventually, any of the materials will wear necessitating restoration of the erosion resistant cap. Materials that can be used as an erosion resistant leading edge include metals (titanium or nickel), polyurethane tape, elastomeric sheet such as Viton,

kevlar/epoxy, thermoplastic film such as polyetheretherketone or polyetherimide or a silicon carbide/epoxy surface coat.

Although metallic leading edges are good erosion protectors, the tooling costs are high and the blade must be removed to replace the cap. Metallic leading edges require surface preparation, NDT and bonding processes which add cost and complexity as well.

The polyurethane tape typically is backed with an acrylic adhesive and it can be replaced while still on the aircraft.

Elastomeric sheets have been successful in this application. They may either be cocured with the composite skins or bonded on in a subsequent operation.

Kevlar/epoxy requires a separate mold in which the leading edge can be premolded. It is then bonded and/or fastened to the blade in a subsequent operation.

Thermoplastic films make excellent erosion barriers but are a poor bonding substrate. This disadvantage has made them unsuitable for most applications.

The silicon carbide/epoxy surface coat is applied to the female airfoil shape mold prior to laminating. During the cure, the silicon carbide flows partially into the first few plies and becomes an integral part of the laminate. An alternative application technique is to abrade and solvent clean the outside of the composite skins after the cure and spray the coating on. This coating is also easily

repairable as it can be splined on the leading edge and will cure at room temperature.

Skin Material

Rotor blade skins have been made out of kevlar, graphite, glass and boron. The fiber orientations are typically ± 0 or ± 45 degrees with 0 degrees being spanwise. In many cases unidirectional graphite will be put in localized areas requiring higher stiffness in the spanwise direction. The most suitable fiber and orientation depends on the structural, weight, and cost requirements. Epoxy is generally the matrix system used. To properly select the fiber type and orientation for an ER fluid-filled blade, the stiffness of the ER mechanism with and without voltage applied across will have to be characterized.

Filler Material

The filler material is the material used to fill the empty space between the skins, spar and trailing edge. It should be lightweight, have a high compressive strength, and shall have processing requirements conducive to the overall processing of the blade. Materials used by blade manufacturers have typically been either honeycomb or foam. Honeycomb must be machined prior to bonding. The honeycomb can either be a fiber reinforced polymer such as Nomex or it

can be aluminum. An important consideration when selecting the most suitable honeycomb is the potential for galvanic corrosion. If it is aluminum honeycomb, it has to be coated with a corrosion resistant primer prior to bonding. The foam is usually an epoxy based, microballoon filled compound. A unique foam sometimes used for this application is Rohacell foam made by Rohm Tech, Inc. It is a polymethacrylimide lightweight foam capable of exerting pressure on the skin laminae while being cocured to them. A scrim-supported film adhesive is placed between the foam core mandrel and the skin plies.

The ER blade will be significantly different than traditional blades from a filler standpoint because the ER mechanism will occupy most of the space between the skins. The material will have to be compatible with both the skins and the insulation material on the outside of the electrodes. A third possible filler material is the same rubber used as insulation for the electrodes. Using rubber rather than honeycomb or foam reduces the stiffness which would further enhance the contribution of the ER mechanism to the overall stiffness.

Spar

The spar is the spanwise structural portion of the blade whose purpose is to counteract centrifugal forces as well as bending and twisting moments. Spar materials have

typically been epoxy resins reinforced with glass, graphite and kevlar fibers. Due to the purpose of the spar, the fiber orientation is always 0 degrees (spanwise). The configurations of the spars are C spar, D spar, and multi-tubular spar. These spars are usually premolded separately and post-bonded in the blade assembly. The necessity of a spar in an ER fluid-filled blade needs evaluation. The stiffness of the ER mechanism may be sufficient to eliminate the need for a separate spar.

Airfoil

There are several different sources for airfoil shapes. One popular source is the National Advisory Committee for Aeronautics. They publish a vary complete catalog including X-Y coordinates for numerous airfoils. Much of the data generated by the helicopter manufacturers is proprietary and more difficult to access. Figure 2 contains a diagram of an airfoil showing the important geometric quantities. These are the chord, chord line, camber line, and maximum thickness. The chord line is the line connecting the most extreme points at the leading and trailing edges. It is considered to be the reference line of the airfoil. The camber line is the line equidistant from the upper and lower flow lines and is indicative of the amount of curvature in the airfoil shape. Highly cambered airfoils generally produce more lift than slightly cambered ones. If an

airfoil is symmetric about the chord line, it has no camber. Maximum thickness is the greatest thickness in the airfoil measured perpendicular to the chord line. This term is expressed in terms of percent chord.

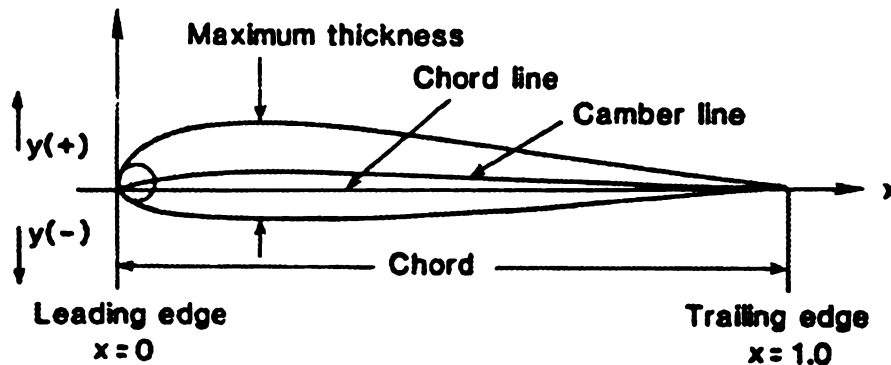


Figure 2: Important Airfoil Geometric Quantities

The purpose of an airfoil is to generate a mechanical force as a result of relative motion between it and a fluid. Relative motion implies that either the wing is stationary (airplane) or the fluid is stationary (helicopter). The primary force generated by an airfoil is called **lift**. Secondary forces also generated by an airfoil are **drag forces** and **pitching moments**. These forces are shown in Figure 3. The point of application of the resultant force is at the one-quarter chord point on the airfoil.

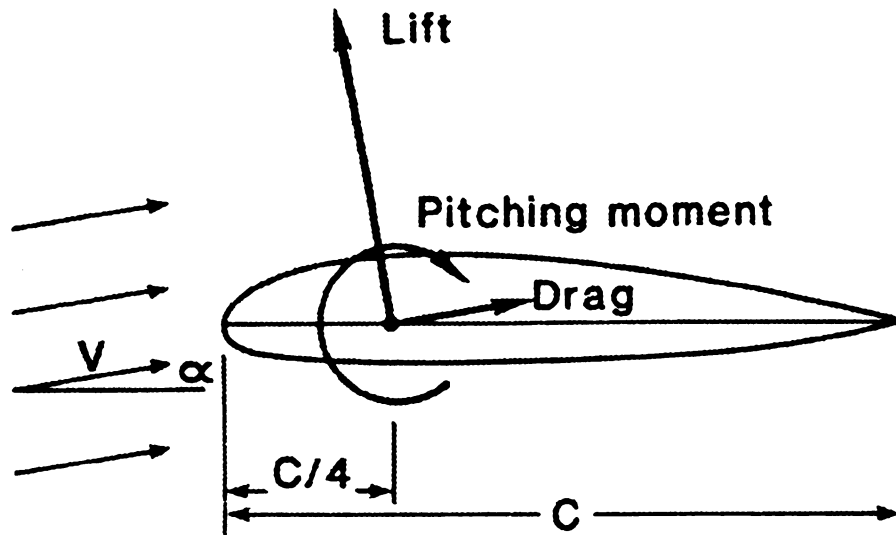


Figure 3: Aerodynamic Forces Developed by the Airfoil

It is recommended to select a symmetric airfoil for an ER blade to simplify tooling. Also, it may be beneficial to select an airfoil with a relatively small thickness. This would enhance the ER effect since the moment of inertia of the blade would be less. One possible airfoil is NACA 0012. This designation indicates that the maximum thickness of the airfoil is 12% of the chord, which is the lowest of standard airfoils.

Root End

The root end is the portion of the blade which transitions from the constant cross-section region to the hub interface hardware. There are several different methods

of attaching the blade to the hub. The most common in use are the "wrap around lug" concept and the simple "bolt through" concept. Regardless of the attachment method, the transition from the blade airfoil and root should provide a smooth and continuous path for the centrifugal forces, twist forces, bending moments and drag forces. A root end for an ER blade will require provisions for the lead wires to be routed from the electrodes to the electrical circuit at the hub.

Blade Tip

Blade tips are important because they sustain the highest dynamic pressures, are at the origin of the formation of the tip vortices, and generate most of the rotor drag and noise. The concepts used for attaching the tip caps all fall under the category of mechanical fastening or adhesively bonding. Either of these techniques should be suitable for an ER blade.

Tip Weight

Tip weights are needed to move the center of gravity of the blade near the one-quarter chord which is needed for stability and also to give the blade adequate rotary inertia capability to lift the helicopter. For the non-rotating tests that the ER blade went through, the requirements of a

tip weight do not exist hence the ER blade does not have a tip weight. Generally, tip weights are machined out of a metal such as brass.

Aspect Ratio

The aspect ratio of the blade is the radius of the blade divided by the chord (r/c). This generally falls within the range of 10-18. Many performance requirements influence the optimal aspect ratio.

DESIGN CONCEPTS

Based on all of the design issues discussed and the physical attributes described, three different configurations of an ER fluid-filled composite rotor blade have been conceptualized. The features of these blade concepts may be interchanged resulting in a multitude of design possibilities. Also, some features may be eliminated. For example, a spar may not be needed for spanwise stiffness depending on the stiffness of the ER fluid mechanism. The concepts consist of cross-sections only. It is not necessary to focus on the blade tip and root end until a working cross section is discovered. The blade only needs to be adequately fixtured to the appropriate test stands. These concepts consist of the following:

1. Continuous skin blade/urethane filler/integral ER cavity.
2. Continuous skin blade/polymethacrylimide filler/separable ER cavity.
3. Modular blade with composite spar/trailing edge skin/separable ER cavity.

Continuous Skin Blade/Urethane Filler/Integral ER Cavity

Figure 4 shows the concept of a continuous skin wrapped around a urethane filler with an integral ER cavity. The skins are continuous around the airfoil and are fabricated as a detail as is the composite spar. A tip weight is machined to fit in between the composite C-spar and the skin. The electrodes and spar are fixtured and suspended within the airfoil and urethane rubber poured in around the electrodes to serve as a filler. There is a filler material of some sort in between the electrodes during this operation to keep the ER cavity empty. The filler material could be sheet metal or sheet wax. Once cured, the filler is removed (or melted in the case of sheet wax) and the space between the electrodes is filled with an ER fluid and sealed off. The leading edge of the blade has a formed titanium detail bonded on. Advantages of this configuration are that the continuous skins do not require any mechanical fastening or bonding, both of which add cost and uncertainty. The integral ER cavity makes fabrication easier but does not facilitate easy service as a modular unit would.

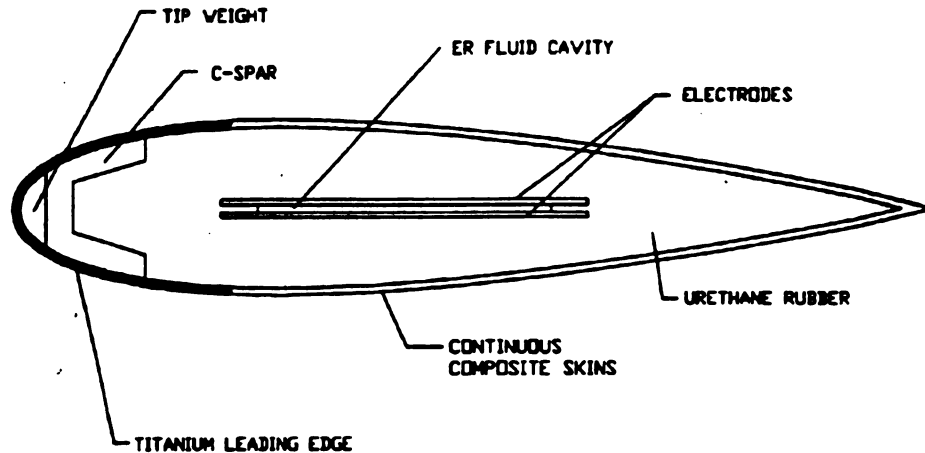


Figure 4: Continuous Skin Blade/Urethane Filler/Integral ER Cavity

Continuous Skin Blade/Polymethacrylimide Filler/Separable ER Cavity

Figure 5 shows the concept of a continuous skin wrapped around a polymethacrylimide foam filler and a separable ER cavity. The electrodes are encapsulated in an ER "cartridge" made of urethane rubber with a rectangular cross section. The cartridge is placed inside a molded cavity within the polymethacrylimide foam. The solid composite D-spar with molded-in tip weight and the foam are used as a mandrel for the continuous skin plies. After curing the skins, the ER cavity is installed. Finally, a coating of epoxy-based silicon carbide is sprayed on the leading edge for erosion protection. In addition to the advantages achieved with continuous skins, the ER cartridge can be slid out of the blade for servicing. This concept is more

difficult to manufacture than the previous concept due to the premolding and bonding of the foam and spar.

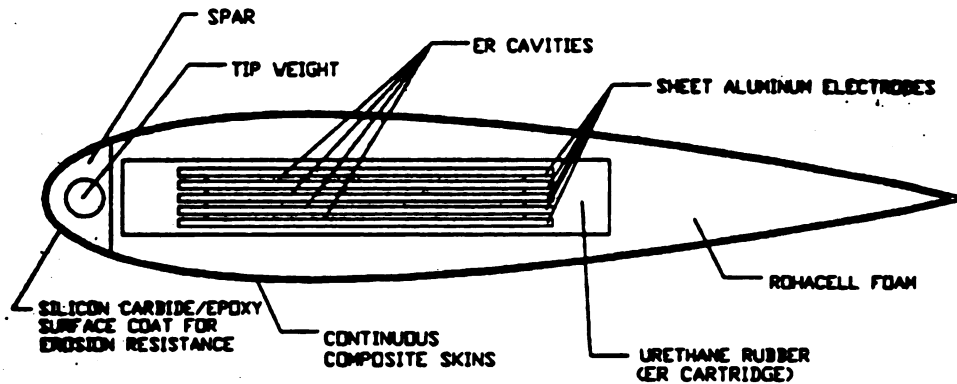


Figure 5: Continuous Skin Blade/Polymethacrylimide Filler/Separable ER Cavity

Modular Blade With Composite Spar/Trailing Edge Skin/Separable ER Cavity

Figure 6 shows the modular blade concept a composite spar, trailing edge skin and a separable ER cavity. This concept is totally modular with the trailing edge composite skins, kevlar/epoxy leading edge with tip weight, ER cartridge and aft honeycomb or foam filler all being separate pieces which are prefabricated and assembled together. The primary advantage is serviceability. The tooling and processing is more complex due to the separate pieces and the need to mechanically fasten the skins to the leading edge.

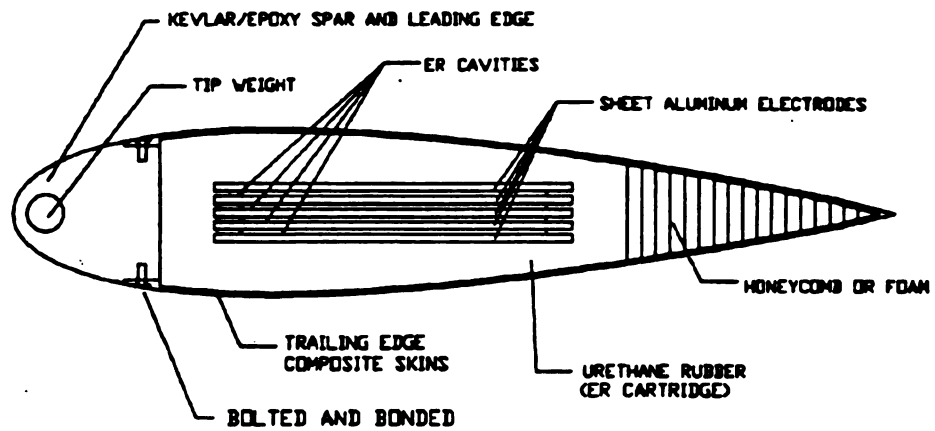


Figure 6: Modular Blade with Composite Spar, Trailing Edge Skin and Separable ER Cartridge.

ELECTRORHEOLOGICAL ROTOR BLADE CONSTRUCTION

The design issues and concepts were evaluated and a first iteration ER fluid-filled rotor blade was conceptualized and defined in terms of its physical attributes. These attributes are described in this section. Figure 7 Below shows a cross-section of the blade.

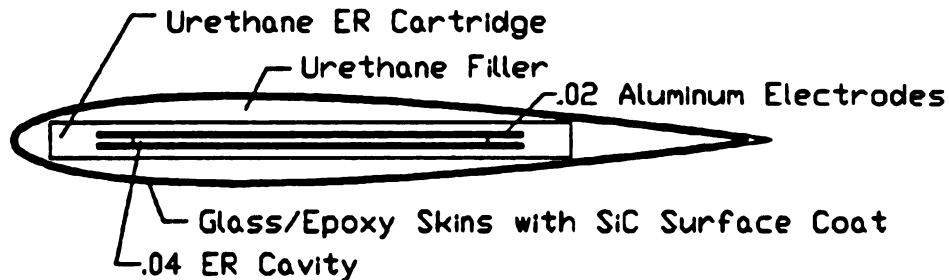


Figure 7: ER Fluid-Filled Rotor Blade Cross-Section

For various reasons, some of the attributes were not incorporated into the ER blade. These are the spar, root end, tip cap and tip weight. The ER blade does not have a spar because it was desired to maximize the effect of the ER mechanism had on overall blade stiffness. The ER blade was made to evaluate non-rotating vibration tests only, hence, it did not need a root end. A root end for an ER beam being used for rotating tests will require provisions for the lead wires to be routed from the electrodes to the electrical

circuit at the hub. The existence of a tip cap would not have had any bearing on achieving vibration control with ER fluids. Tip weights are needed to move the center of gravity of the blade near the one-quarter chord which is needed for stability and also to give the blade adequate inertia capability to lift the helicopter. For the non-rotating tests that the ER blade went through, the requirements of a tip weight do not exist hence the ER blade does not have a tip weight.

Electrorheological (ER) Cartridge

The design presented in this paper utilizes an electrorheological cartridge. The cartridge is the core of the blade and is a separate assembly which is fabricated and tested independently prior to encapsulating it into the blade. Since a blade of this nature has never been designed or fabricated before, it was desirable to have a somewhat modular design which would facilitate easy design verification and change implementation. The cartridge consists of two electrodes made out of .020" 6061 aluminum sheet and a gap of .040". The electrodes are separated by silicone sheet strips around the periphery. The entire assembly is encapsulated in castable urethane rubber and the finished cartridge has a rectangular cross section. The urethane is cast on the four lengthwise edges and one end

simultaneously. Figure 8 shows a cross-section of the ER cartridge.

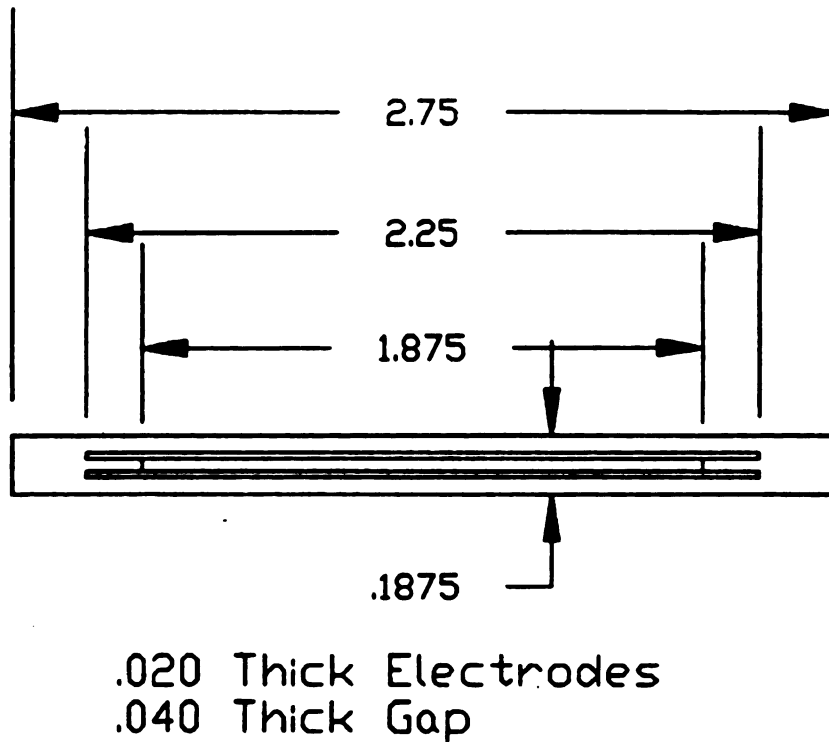


Figure 8: ER Cartridge Cross-Section

Aluminum was selected for an electrode material because of its cost, availability and electrical conductivity. The electrodes have tabs at the root ends to allow for attachment for lead wires. The gap of .040" was selected to facilitate filling the cavity with the ER fluid and make it more difficult for the electrodes to touch during testing. Prior work has proven that gap dimensions up to .040" can exhibit the ER effect and that this effect deteriorates with larger gap sizes. Silicone sheet was used for a

separation/insulation material because of its insulation properties, cost, availability, and consistent thickness. The sheet was cut into .1875" strips and bonded to the electrodes around the periphery with an epoxy-based glue. For testing purposes, a fourth strip was placed between the electrodes at the root end after filling and clamped in place to act as a seal for the fluid cavity. The electrode assembly was encapsulated in urethane to isolate the cartridge from all other materials in the blade. The urethane is a two-part, castable material.

Silicon Carbide Leading Edge

The coating selected for the rotor blade is a silicon carbide surface coat. The surface coat is applied to the female mold which forms the blades skins and leading edges prior to laminating. During the cure, the silicon carbide flows partially into the first few plies and becomes an integral part of the laminate. The coating can also be applied using a spray-on method. This coating is also easily repairable as it can be splined on the leading edge and will cure at room temperature. This type of coating will be used as the erosion resistant leading edge due to its easy application method, repairability, and cost. No additional tooling (form dies, etc) will be needed. In addition, it is currently being used in production military

helicopter parts as an erosion coating. The exact identification of this product is Ren Plastics RP 3260.

Glass/Epoxy Skins Composite Skins

Due to the fact that the stiffness of the ER cartridge with and without voltage applied across it is basically uncharacterized, there was no logical basis for choosing a particular fiber type and orientation. The skins were constructed of two plies of bidirectional glass cloth. At this point, it was desired to have minimum stiffness contribution from the skins so that the ER effect from the cartridge could be maximized. To eliminate the problems associated with the transition from the leading edge to the airfoil, continuous skins around the entire airfoil are used versus a bonded leading edge for instance. The matrix selected was XR100-317 epoxy resin made by REN Plastics.

Urethane Rubber Filler

Most of the discussion on traditional fillers such as honeycomb and foam fillers above does not apply to the ER blade because the ER cartridge occupies most of the space. For compatibility and processing reasons, what little space there is between the inside of the skins and outside of the cartridge is filled with the same urethane rubber used in the cartridge. Using rubber rather than honeycomb or foam

reduces the stiffness which further enhances the contribution of the ER cartridge to the overall stiffness.

Airfoil

The airfoil selected for this blade was the NACA 0012. There are two reasons for this selection. First, the number 0012 indicates that the maximum thickness of the airfoil is 12% of the chord, which is the lowest of standard airfoils. Minimizing the thickness of the blade reduces the moment of inertia hence the stiffness. Thus, the ER cartridge will have more influence. Second, this airfoil is symmetric. This is advantageous from a tooling and fabrication standpoint. Data on the NACA 0012 airfoil is in Appendix A.

Aspect Ratio

The aspect ratio of the blade is the radius of the blade divided by the chord. This generally falls within the range of 10-18. The ratio used for the ER blade was 12 simply for convenience. The chord is four inches and the radius (length) is 48 inches.

ER CARTRIDGE FABRICATION AND TESTING

The overall sequence in fabricating the ER blade as described consisted of first manufacturing an ER cartridge which exhibits the ER effect by itself. Once that was accomplished, the rotor blade tooling was made. The cartridge was then incorporated into an actual blade. Finally, testing of the finished blade was done.

The ER cartridge presented previously is the result of two iterations of design, fabrication and testing. The first cartridge consisted of multiple layers of electrodes and ER fluid cavities. It was unsuccessful in that it was so stiff by itself, applying voltage to the ER fluid had no affect. This section describes the fabrication and testing of the multi-layer design as well as the existing single layer design. It is believed that with additional development, the multi-layer cartridge may have potential applications. The fluid used in all testing was made from 55% by weight Dow Corning Diffusion Pump Fluid #704 (Silicone Oil) and 45% corn starch.

Multi-Layer ER Cartridge

The original concept for the ER cartridge was to make it as thick as possible and still fit into a realistic airfoil shape. The cartridge consists of five electrodes made of .050" 6061 aluminum and four cavities as shown in Figure 9. The total thickness was 1/2" and the airfoil was NACA 0018 (maximum thickness equal to 18% of the chord - 50% thicker than the NACA 0012). This was the desired airfoil to provide room for an ER cartridge which could occupy as much of the cross-sectional space as possible. A chord of 6" was chosen for the cartridge as dimensioned below to fill most of the cross-sectional area.

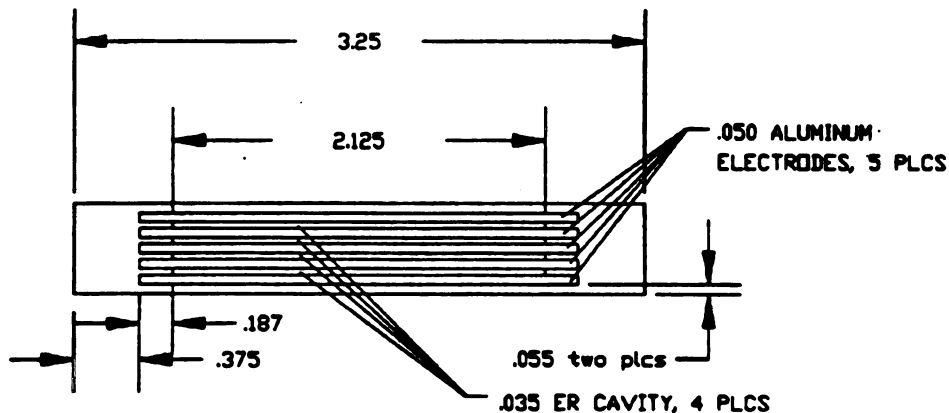


Figure 9: Multi-Layer ER Cartridge

A rectangular mold was made to cast the electrodes in the urethane to achieve the dimensions shown above. Figure 10 shows a bottom side view of the mold and electrodes prior to pouring. For the first attempt, sheet aluminum was used

as the spacer material. The ER cavity area of the electrodes was taped off and all bonding surfaces were lightly sandblasted. The assemblage of electrodes and spacers was lowered into the mold. While the sandwich of sheet metal was held centered in the mold, bolts were tightened through the side walls of the mold against the electrodes to hold the electrodes and spacers tightly together to eliminate any seepage of the urethane in the ER cavity. Conathane TU-65 urethane was then poured around the electrodes to encapsulate the edges. Figure 11 shows the electrodes suspended in the mold immediately after pouring. After the urethane was cured at room temperature, the cartridge was demolded. At this point, it was discovered to be impossible to remove the sheet metal spacers. The second attempt at fabricating this configuration utilized .035" sheet wax as spacer material. The sheet wax was cut and placed on the cavity area of the electrodes. Figure 12 shows the assembly of electrodes and wax prior to closing the mold and pouring. After encapsulation in urethane, the cartridge was placed vertical with the open end down in an oven at 200°F. The wax melted and flowed out at this temperature. This process produced a very cosmetically appealing cartridge.

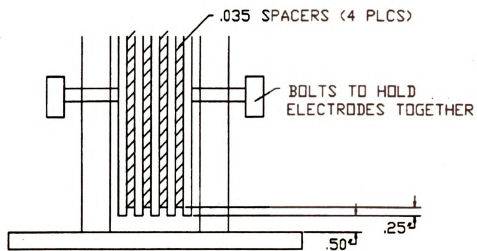


Figure 10: Bottom Side View of Multi-Layer ER Cartridge Prior to Pouring

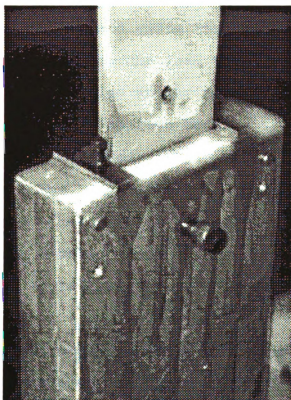


Figure 11: Multi-Layer Cartridge After Pouring

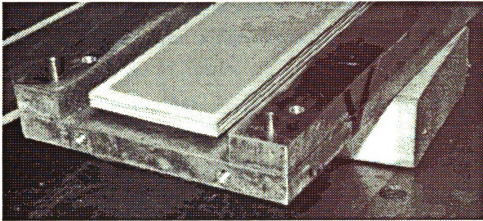


Figure 12: Multi-Layer Cartridge Assembly Showing Sheet Wax Spacers Prior to Pouring

Once fabricated and filled with fluid, the cartridge was fixtured to an exciter (shaker). The natural frequency was found to be 20 Hz. Lead wires were then attached. The first sequence of attaching the lead wires was +, -, +, -, +. Excitations were applied at the natural frequency and a voltage of 2000 volts was applied and the tip deflection and velocity curves were observed. There was no change in either parameter. The lead wires were then hooked up +, -, skip, +, -. Again, there was no difference with or without voltage. Appendix B shows plots of input versus output for both combinations of lead wires and with and without voltage.

The conclusions made from this experiment were that it is now desired to have as flimsy a cartridge as possible to maximize the ER effect. This desire also applies to the rotor blade itself. For this reasoning, the cartridge was

changed to a single layer as shown in Figure 2 and the airfoil was changed from a NACA 0018 to a NACA 0012.

Single Layer ER Cartridge

The single layer cartridge was fabricated slightly differently than the multi-layer cartridge. The aluminum electrodes were .020" 6061 aluminum sheared to 2.25" x 48 ". The ER cavity area which was 1.875" wide centered on the electrodes was taped off and all bonding surfaces of both electrodes were lightly sandblasted. Strips of .040" thick silicone rubber sheet were cut to .1875" wide. The strips were adhered with epoxy around the edges of the cavity side of one of the electrodes. One of the ends was left without silicone to facilitate filling. Once cured, a bead of epoxy was run along the opposite side of the silicone strips and the other electrode was placed on top of the epoxy. The assembly was lightly clamped together and the epoxy was allowed to cure. Once cured, the exterior surfaces were wiped with solvent to facilitate bonding.

A rectangular mold was made by sandwiching two four foot long pieces of metal .1875" thick with a separation of 2.75" between two pieces of metal 4" x 48". The two .187" pieces were temporarily bonded with polyester filler to one of the side plates. The opposite side plate was removed and the mold was placed horizontally on the table. The mold was filled with a .055" layer of Conathane TU-65 urethane

rubber. The electrode assembly was placed centered on top of the bed of urethane. The assembly was then covered with another layer of .055" urethane. The other side plate was placed over the urethane and the entire mold was clamped together. The mold was then positioned vertically and after settling, additional urethane was poured in the end around the electrode assembly to ensure a void free ER cartridge. Once cured, the cartridge was carefully demolded.

The cartridge was extremely flimsy and was not self-supportive. The stiffness was not great enough to hold the entire cartridge up while constraining it at one end.

The cartridge was filled with ER fluid and a seal was clamped between the electrodes at the fill end to keep the fluid from leaking. The cartridge was placed on the shaker. Mounting the cartridge consisted of fixturing it so that only 12" of the 48" extended past the shaker. The other 36" was supported on the opposite side. The natural frequency was found to be 7 Hz. This natural frequency was then used as the exciter frequency to yield maximum deflection. After 2000 volts were applied across the fluid, the amplitude of the tip reduced by approximately 33%. Figure 13 shows input versus output for no voltage. The peak on the bottom graph (output) is at approximately 4.2 volts which is equal to 4.2 mm of deflection (.165"). Figure 14 shows the same graphs generated while applying 2000 volts. The peak on the output graph is at approximately 2.8 volts equal to 2.8 mm deflection. After the voltage was applied, the deflection

was $2.8/4.2 = 67\%$ of the initial deflection with no voltage.

Once this ER effect worked, a spanwise elastic modulus was determined. The cartridge was fixtured as a cantilever beam with a length of 12". A load of .3249 lbs (147.5 grams) was applied and different voltages were induced. The deflection for a 12" portion for any voltage was .242". Using $E = (PL^3)/(3vI)$ yielded an elastic modulus of 516,000 psi. The cartridge was then fixtured for a 3-point bend test with a span of 16". A load of .6498 lbs (295 grams) produced a deflection of .047". Using $E = (PL^3)/(48vI)$ produced a spanwise elastic modulus of 787,200 psi. This was done for no volts and 3000 volts. A conclusion was made at this point that the ER effect is a dynamic phenomenon and cannot be detected in static tests.

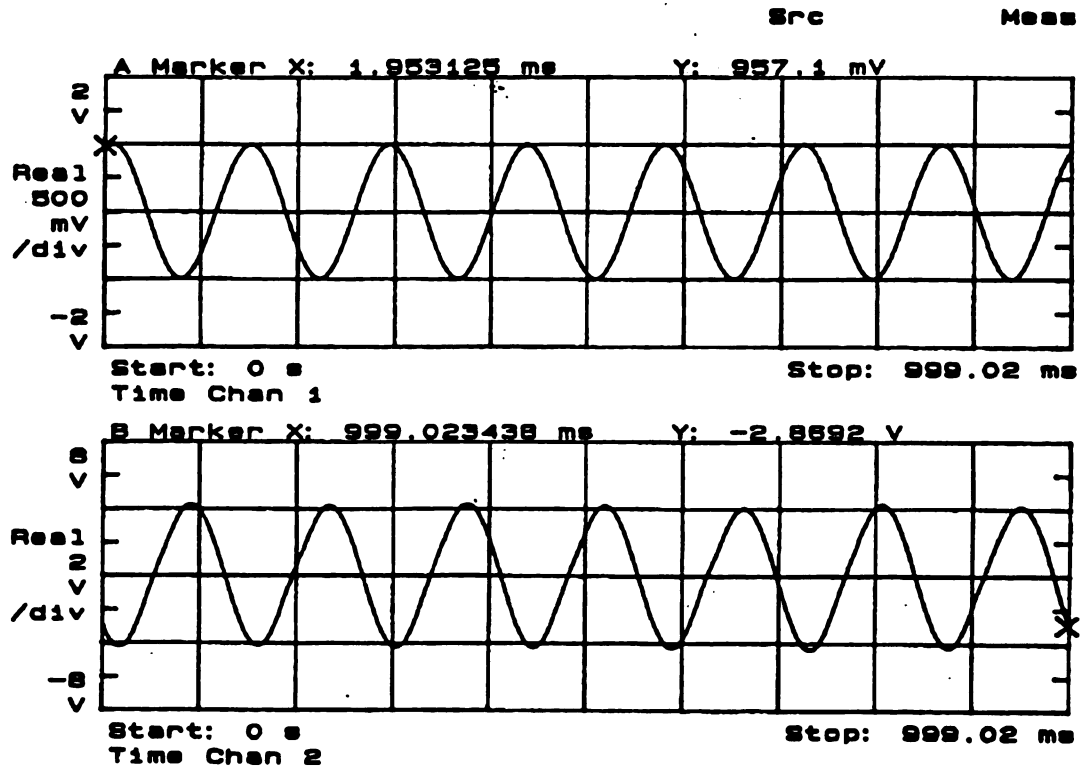


Figure 13: Single Layer Cartridge Response - No Voltage

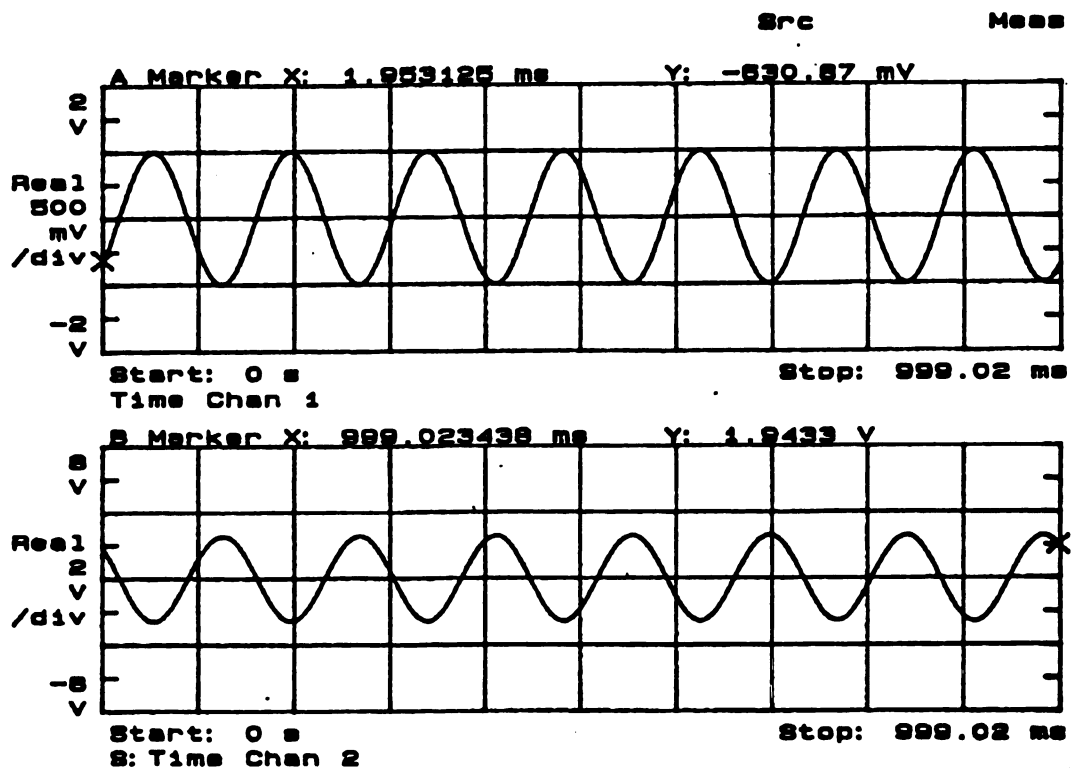


Figure 14: Single Layer Cartridge Response - 2000 Volts

ROTOR BLADE TOOLING FABRICATION

Aside from the ER cartridge molds, the tooling required to encapsulate the rectangular ER cartridge into an airfoil shape consists simply of a pattern and two mold halves. Since the airfoil is symmetrical, both mold halves are identical. This section explains the procedure for fabricating both the pattern and the mold halves.

Pattern

The pattern was basically half of the airfoil and served as the form to cast the mold halves. The first step consisted of machining 18 templates as shown in Figure 15 below.

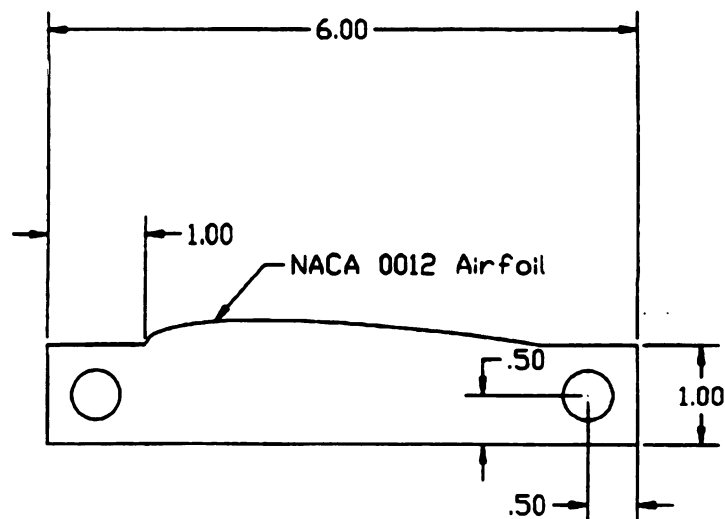


Figure 15: Pattern Template

The templates were made of .080" steel. All 18 pieces were rough cut, stacked together and positioned on a CNC mill. CNC code was written in SmartCAM software and downloaded to the mill to machine the profile on the templates.

Once the templates were machined and deburred, two pieces of 54" long .500" diameter rod were slide through the .501" holes in the templates. The templates were distributed every 3" along the rods. A piece of 1" x 4" wood was cut into 17 pieces, each piece being 3" long. The wood pieces were placed between the templates. The templates were then clamped tightly against the wood pieces and hose clamps were tightened onto the ends of the rods to hold everything tightly together. The entire assembly was then fastened to a piece of 1" x 10" wood 5' long. This assembly is shown in Figure 16.

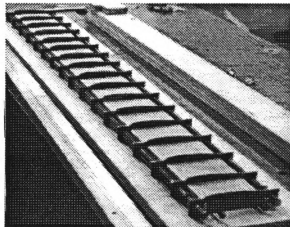


Figure 16: Pattern Assembly

Next, glass microballons were added to room temperature curing epoxy resin to make a paste-like, low density sandable filler. This syntactic foam was splined between all 18 templates with a straight edge using the templates as guides. Once cured, the entire surface was covered with a thin layer of polyester filler. The filler was rough sanded to remove the high spots, followed by a wet sanding operation to make a very smooth pattern surface. Once the entire surface was wet sanded to the templates, the pattern was complete. Refer to Figure 17.

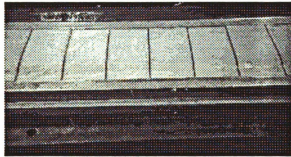


Figure 17: Pattern Assembly After First Spline

Molds

The molds were made out of a mixture of sand and resin with a surface coat on the mold surface. In order to cast a mold half, the first step was to build a box around the pattern. This was done by screwing 1" x 6" boards tightly around the sides of the pattern. Once the box was made, the molding surfaces of the side boards and the pattern were

sealed with paste wax and the same surfaces were coated with a release agent.

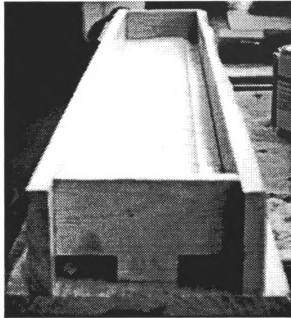


Figure 18: Pattern Box Prior to Surface Coat

The first step in casting the mold was to coat the insides of the pattern box with a graphite-filled, black, high-temperature surface coat. The product used was REN CGL1320 made by REN Plastics division of Ciba Giegy. The surfaces included the wet sanded surface on the pattern and the inside surfaces of the side rails. The thickness of the surface coat was .050" - .100". The pattern was left alone for several hours to allow the surface coat to become tack-free.

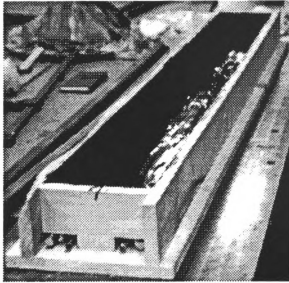


Figure 19: Pattern Box After Surface Coat

Once tack-free, a mixture of three parts-by-weight sand to one part high temperature laminating resin was used to fill the pattern box. The resin system used was RP4005/1500 made by REN Plastics division of Ciba Giegy. Once the box was half full with the sand mixture, two pieces of 1" square tubing were placed in the sand. The tubing was covered with the sand/resin mixture and the mixture was added until the entire mold box was filled. Refer to Figure 20. The purpose of the steel tubing was to provide additional stiffness in the mold. The mold was left to cure at room temperature for 24 hours. Once cured, the box was disassembled and the mold was removed from the pattern.

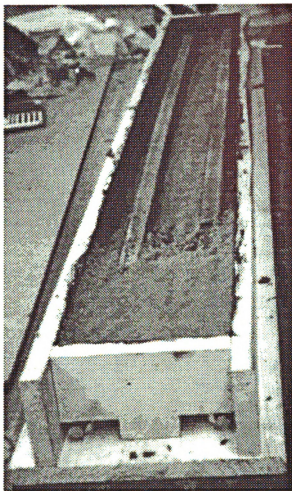


Figure 20: Casting Sand/Resin in Pattern Box

The boards and pattern were thoroughly cleaned and reassembled. Paste wax and release agent were applied as before. The entire process of applying surface coat and filling with sand/resin was repeated and a second identical mold half was produced. Figure 21 shows both mold halves.

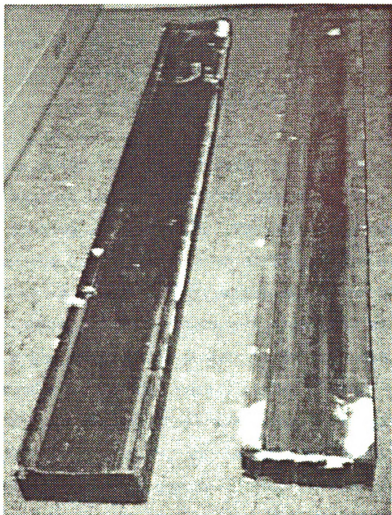


Figure 21: Both Mold Halves After Demolding

ROTOR BLADE FABRICATION

At this point, the ER cartridge was fabricated and proven to exhibit the ER effect by itself. Also, all necessary tooling was complete. The next step was to encapsulate the cartridge into an airfoil shape with fiber reinforced skins on the outer surface which had an abrasion resistant coating. The manufacturing sequence was to first encapsulate the rectangular shaped cartridge solely into urethane rubber so the end result has an airfoil shape. Next, the rubber airfoil shape was wrapped with fiber-reinforced skins. Finally, an abrasion resistant coating was applied to the outer surface. This section describes in detail these three processes performed to fabricate the rotor blade.

Cartridge Encapsulation

The process used to encapsulate the cartridge into an airfoil shape was similar to that used initially to encapsulate the electrodes into a rectangular cartridge. The main difference was a rectangular mold was used for the initial encapsulation and the airfoil shape sand/resin molds were used for the final encapsulation.

The first step consisted of applying sheet wax to the mold surfaces to compensate for the skin thickness. The airfoil of the rubber must be smaller than the final airfoil, the difference being the thickness of the outer skin. Since two plies of glass/epoxy at .010" per ply thickness were used to wrap the blade, the sheet wax used on the mold surface was .020". With the airfoil of the rubber portion .020" smaller than the mold, upon wrapping it with .020" of glass/epoxy skins, the mold will provide a tight encapsulation of the entire assembly. The sheet wax was carefully placed over the entire mold surface and trimmed with a utility knife to the leading and trailing edges.

The mold halves were then aligned and clamped together. Both mold halves were positioned vertically. A metal plate was bonded with polyester filler to the bottom of the mold segments to prohibit leakage of the urethane. The mold was then filled half full with urethane by pouring it into the open end on top. The outer surfaces of the cartridge were lightly abraded with coarse sandpaper and cleaned with acetone. A 1.5" wide x .035" piece of sheet aluminum was slid into the ER cavity of the cartridge so that the gap will be maintained during encapsulation. Without this filler piece, there would be a strong possibility of the walls of the cartridge being pushed in by the urethane causing the electrodes to come in contact. Once the cartridge was prepared, it was simply pushed down into the mold. As it was forced down, the urethane in the mold was

gradually displaced around the cartridge and flowed towards the top of the mold. The cartridge was pushed down until only the ends of the sheet aluminum electrodes and a short portion of the cartridge remained above the top of the mold. Prior to this point, the urethane reached the top of the mold, ensuring that the entire mold was filled. The assembly was left overnight to allow the urethane to cure. Once cured, the mold halves were separated and the part removed. Figure 22 shows the cartridge after demolding. The molds were then cleaned and stripped of the sheet wax. The surfaces were coated with release agent and the mold was ready for the next operation.

The part itself captured the airfoil as defined by the molds and sheet wax very well. There was thin flashing on the leading and trailing edges which was cut off with scissors. The part was prepared as before with a light abrasion using sandpaper followed by a thorough acetone wipe.

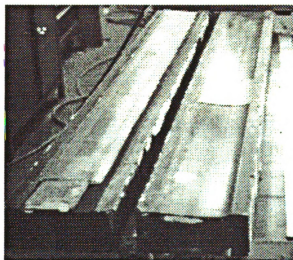


Figure 22: Cartridge After Encapsulation into Airfoil

Skin Layup

The mold surfaces and outer surface of the part were coated with a light application of REN Plastics XR100-317 laminating epoxy resin. Bidirectional glass fabric style 120 was spread out on cardboard and saturated with the resin. The part was placed at one end of the fabric. The end of the fabric was held against the part and the urethane assembly was simply rolled into the fabric. The rolling process was continued until the thickness of the skins was equal to two plies (the blade cartridge was flipped four times). Once wrapped, the assembly was placed onto one of the mold halves and covered with the other. The molds were then clamped together. The .035" piece of aluminum was still inside the part to maintain the gap. The part was left in the mold overnight to allow the resin to cure.

After the cure was complete, the part was demolded and all of the flash was sanded off. The metal spacer was pulled out of the blade. The blade seemed to have a desirable amount of flexibility upon an intuitive evaluation. Refer to Figure 23.

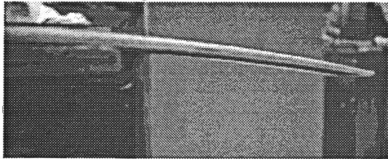


Figure 23: Blade Droop and Flexibility After Demolding

Silicone Carbide Surface Coat Application

The final step in fabricating the blade was applying the exterior abrasion resistant surface coat. The blade was thoroughly rinsed with acetone and the ends of the electrodes were covered with masking tape. REN Plastics RP3260 surface coat was mixed per manufacturer's instructions. The surface coat was then put into an agitating spray gun and thinned with methyl ethyl ketone (MEK). Several light coats were sprayed onto the part until a thickness of approximately .005" was achieved. The part was placed in an oven at 175°F for 2 hours to cure the surface coat. The part was removed from the oven and the masking tape was taken off. This concluded the fabrication of the blade. Figures 24, 25, and 26 show a plan view, root end view and tip view of the finished blade.

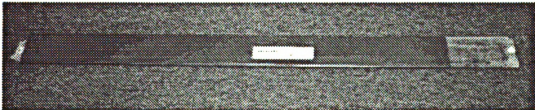


Figure 24: Plan View of Blade

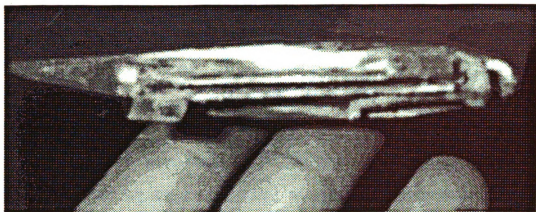


Figure 25: Root End View of Blade

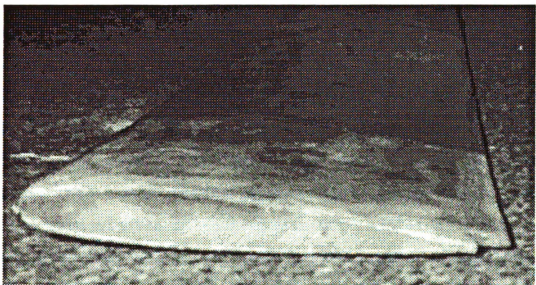


Figure 26: Tip View of Blade

ROTOR BLADE TESTING

Before the blade could be tested on the exciter, fixturing had to be fabricated to properly constrain the end of the blade. The fixturing was made in two parts. First a metal plate having a hole pattern matching that of the exciter was covered with a thick (3/4") layer of polyester filler. Before allowing the polyester to cure, the blade was treated with a release agent and was pushed into the polyester so that the polyester would capture one half of the airfoil shape. Once cured, the fixture half was coated with a release agent and a second metal plate was coated with the polyester. The other side of the blade was then pushed into the polyester on the second fixture plate and bolts were tighten in each corner of the plates, drawing the plates towards the blade. The polyester was then allowed to cure. This fixuring was lightweight, captured the entire airfoil on the blade for approximately three inches and easily bolted to the exciter.

The blade was filled with ER fluid of the same concentration as used on the cartridge (55% Silicone Oil, 45% Corn Starch). A piece of sheet rubber was cut to the same width as the ER cavity, positioned in between the electrodes at the opening and a spring clamp was used to

hold the electrodes tightly against the rubber, eliminating the possibility of leakage. The blade was secured to the exciter with the fixturing and the lead wires were attached to the electrodes.

A random input was first used to find the natural frequency. The natural frequency was found to be 13 Hz. This natural frequency was then used as the exciter frequency to yield maximum deflection. The first parameter evaluated was the vertical velocity of the tip. Figure 27 shows the tip velocity with no voltage (top graph) and the velocity after applying 3000 volts. The peak with no voltage is approximately 160 mV or .160 v which equates to .16 m/s. After applying 3000 volts, the peak reduced to 110 mV (bottom graph) or a velocity of .11 m/s. The velocity was reduced by 31% by applying 3000 volts.

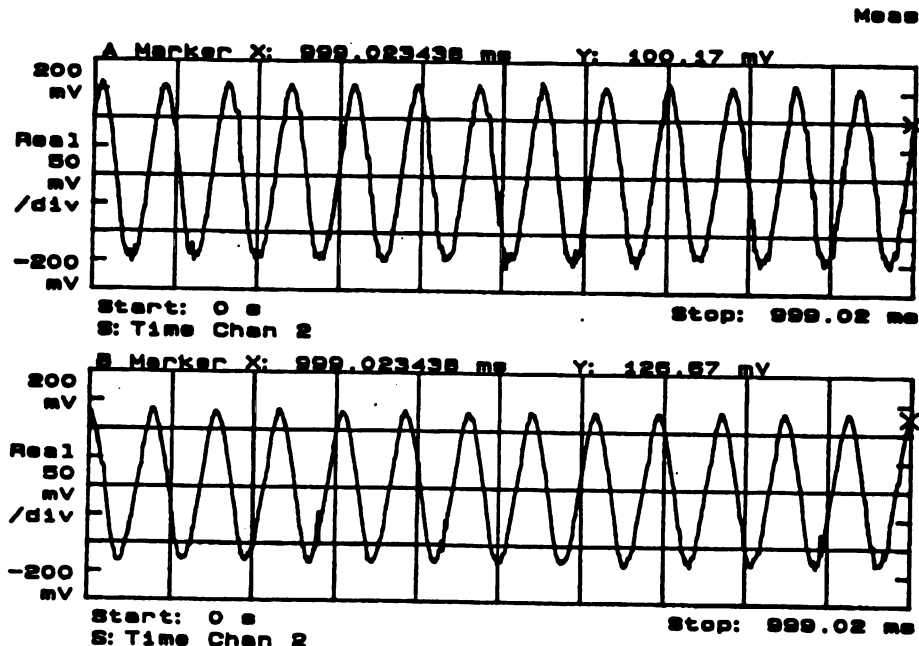


Figure 27: Blade Tip Velocity - No Volts, 3000 Volts

Figure 28 shows the same graphs generated by applying 2000 volts rather than 3000 volts. The velocity decreased from .16 m/s to .13 m/s for a reduction of 19%. The final parameter evaluated was tip deflection.

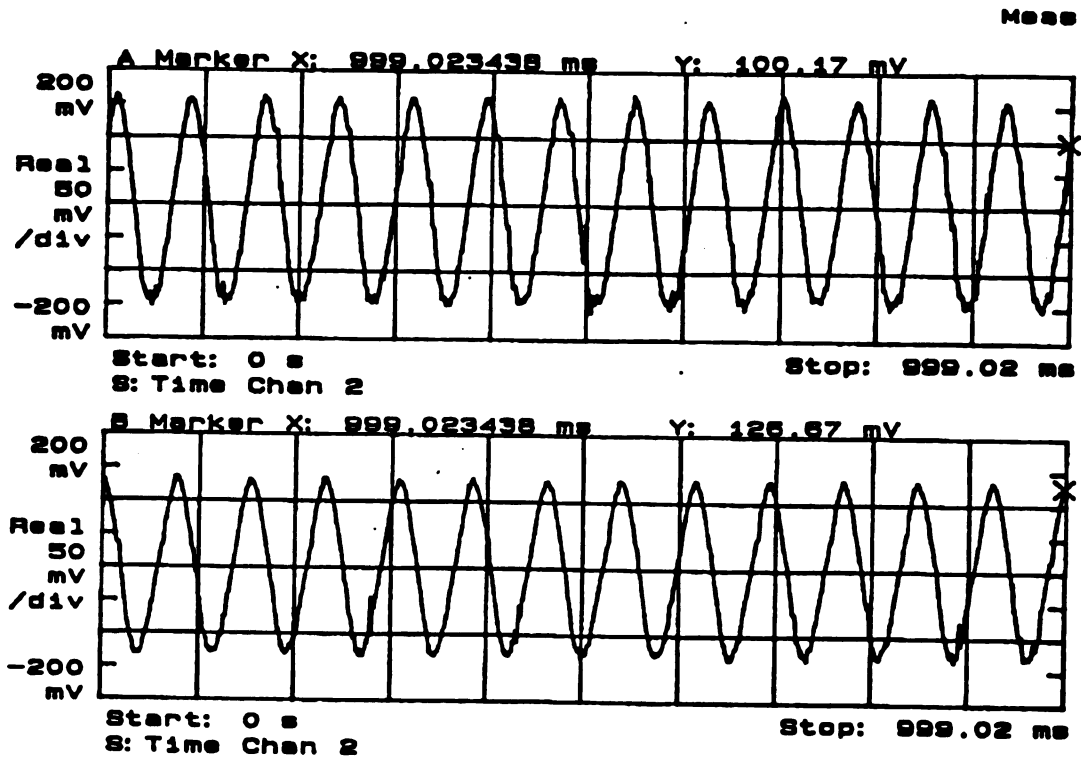


Figure 28: Blade Tip Velocity - No Volts, 2000 Volts

Figure 29 shows tip deflection with no voltage (top) and after applying 3000 volts. The deflection is approximately 2.2 mm with no voltage and 1.9 mm after applying 3000 volts. The reduction of .3 mm (.012") equates to a 14% reduction of tip deflection.

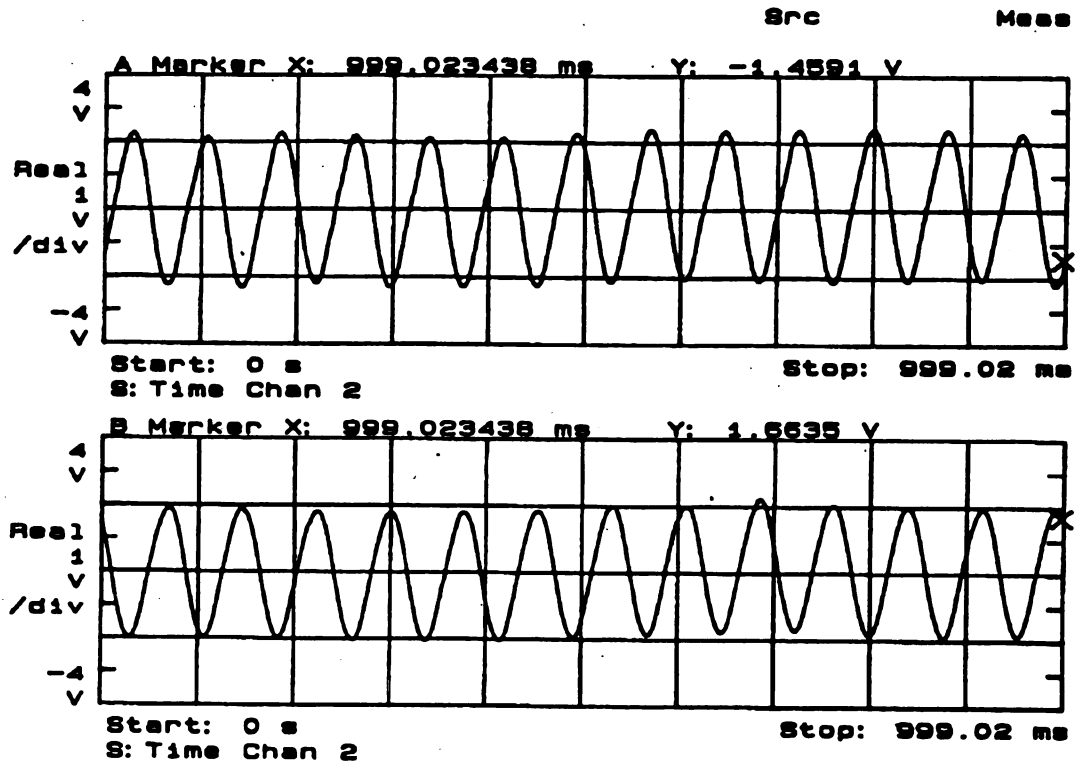


Figure 29: Blade Tip Deflection - No Volts, 3000 Volts

MANUFACTURING ISSUES

The final segment of the research effort involved highlighting some of the manufacturing issues that would mandate further evaluation as this application of ER fluids advances towards production. This section discusses the manufacturing issues involved in the specific processes used in fabricating an ER blade in a production environment, the tooling and equipment needed and finally, the quality control aspects.

Manufacturing Processes

The production processes used to fabricate a blade similar to the laboratory blade would basically be the same as those described. These processes are cartridge fabrication, cartridge encapsulation, skin layup and abrasion resistant coating application. Also described are other components and processes that would be needed on a production blade, but were not implemented on the model blade. The materials used on the model blade were not optimized as there has only been one blade fabricated and tested. These manufacturing steps will require a re-evaluation upon material or process substitution.

Cartridge Fabrication. The manual method of partially filling the mold with urethane, positioning the electrode assembly, filling with urethane and closing the mold worked fine for a development blade. However, it was time consuming and produced air bubbles. An alternative method to encapsulate the electrode assembly in urethane is via a Resin Transfer Molding (RTM) process. The electrode assembly would be fixtured in a constrained position in the center of the mold. Resin would ingress in one end and would be forced through the mold around the electrode assembly with a vacuum source at the other end. This process would be more adaptable to production than the pouring method. Also needed in production is a removable cap for the ER cavity with provisions for lead wires to be easily attached to the electrodes. The model blade has a temporary cap which was clamped in place.

Cartridge Encapsulation. Similar to encapsulating the electrode assembly, RTM would be a viable replacement for a production process. RTM for this process would work just as explained in the previous section. Also, the sheet wax procedure would not be needed in production since there would be two sets of molds, one made to the outside of the skin for the skin layup and the other made to the inside of the skin to encapsulate the cartridge.

Skin Layup. Production processes such as filament winding or automatic tape laying could perhaps replace the hand layup procedure. Also, high performance prepregs may be used for production blades. The layup process would be similar but the curing process for these materials would entail an autoclave rather than a room temperature cure.

Silicon Carbide Surface Coat Application. The process used to manually spray the surface coat on was inexpensive and easy. The uncertainties are longevity compared to alternatives such as an elastomeric sheet and dimensional conformance after spraying. If the coating is functionally adequate, the method of applying the surface coat to the mold surface rather than spraying it on the mold would make a superior part since the flow surface would now be defined by the mold and the surface coat would be allowed to crosslink with the skin plies making it an integral part.

In addition to the processes described above, a production blade would inherit additional processes. These are due to attributes not used on the laboratory blade but possibly necessary on production blades. These components include the tip weight, spar, tip cap and root end. Some of the considerations for fabricating these components are described below.

Tip Weight. The model blade did not have a tip weight because it would not have contributed to the objective of

evaluating the ability to control vibration with an ER fluid. To incorporate a tip weight would involve fixturing the piece of metal (machined or round) in the mold during the cartridge encapsulation operation. If properly fixtured, the weight will be cast in the correct location of the blade and all of the surface contact between the weight and the rubber should be sufficient to hold the weight in place without any mechanical fasteners.

Spar. It may be discovered that a spar is needed in addition to the ER mechanism. If so, it could be fabricated from unidirectional composite material and machined as a separate detail. The spar would then be fixtured and encapsulated (or bonded) at the leading edge in the same manner as the tip weight.

Tip Cap. The tip cap could simply be a flat laminated composite panel attached to the end of the blade. Inserts could be cast in the urethane to allow for mechanical fastening. An alternative approach is to mold the cap with a flange that captured the end of the blade. Inserts could be molded or potted in perpendicular to the flow surface and fasteners put through the flange. This approach would be less likely to fail since all of the axial load on the cap is transferred through the fastener to the skin.

Root End. The root end consists of the hardware and transition region in which the blade changes from a constant cross-section to the hub. Many of the traditional methods used on composite blades will work the same way on as ER blade as long as there are provisions for lead wires to unobtrusively be attached to the electrodes. One method is the "wrap-around-lug" concept. The outer skin plies gradually twist from the airfoil surface to wrap around cylindrical bushings situated perpendicular to the plane of the blade. The bushings are used to attach the blade to the hub. Employing this method would require complex layup molds with changing cross-sections.

Tooling and Equipment

Based on the construction of the blade and the process as described, there are several facets of tooling and equipment needed to fabricate a blade of this nature on a production basis. The tooling and equipment needed for fabricating the ER blade includes molds, fixtures, sheet metal equipment, mixing equipment, and aluminum surface prep equipment. Obviously, standard composite facility equipment such as autoclaves, clean rooms, and machining centers is needed. This additional tooling and equipment are described in this section and the list is not an all inclusive as there are always tools unanticipated at the concept phase in any composite part program of this complexity.

Molds. A mold is needed anytime it is desired to have an uncured material conform to a shape while curing. For this blade, it is necessary to have at least three molds.

The first mold is the rectangular cross-section mold needed to cast the ER cartridge. It is simply four lengthwise pieces of metal bolted and doweled together with a base plate. Fixturing is needed to hold the electrode assembly centered in the mold during the urethane ingression.

The second mold needed is a mold to encapsulate the cartridge into an airfoil shape. This can be machined aluminum or composite and the contour will need to be the desired airfoil offset inboard the skin thickness. Fixturing is necessary to constrain the cartridge in the proper location during the urethane ingression.

The final required mold is the layup mold which the urethane wrapped in composite is placed in to form the final airfoil. It will be identical to the mold described above only will contain the true airfoil. Both the second and third molds will have the root end incorporated as specified by the design.

If a composite tip cap and spar are to be used, separate layup molds will be needed for each of these. The spar mold can be machined metallic or composite and the tip weight mold can be a flat metal plate with any necessary steps or contours machined into it.

Fixtures. There will be several fixtures needed to fabricate the ER blade. Aside from the fixtures needed to constrain the cartridge and electrodes during encapsulation, there may be electrode bonding fixtures, spar fixturing, tip weight fixturing, tip cap fixturing, and root end fixturing.

There will need to be fixtures to hold the trimmed metal electrodes directly over each other while bonding in the silicone strip without closing the ER fluid cavity.

Spar fixturing and tip weight will include trim fixtures to cut the pieces to length, machining fixtures as needed, and constraining/locating fixturing to accurately locate and hold the pieces while being encapsulated in urethane.

Tip cap fixturing will consist of a periphery router/machining fixture to machine the edges and drill and holes needed for mounting.

The root end fixturing will involve fixturing to drill bushing holes in either the composite or molded-in metal bosses.

Sheet Metal Equipment. Since the sheet metal components used for the electrodes are not used on conventional composite blades, equipment to fabricate these details is needed. For flat electrodes, a sheet metal shear will be adequate. For cambered blades requiring contoured electrodes, either draw dies or roll form tooling will be

also required. A brake may be needed for any sections of the electrodes requiring bends.

ER Fluid Mixing/Dispensing Equipment. Electrorheological fluids have two components which must be mixed within a certain range of ratios to work properly. To perform this, automated mixing and dispensing equipment is available and needed to be efficient for a production application.

Aluminum Surface Preparation Equipment. Prior to encapsulation in rubber, the aluminum will undergo certain processes which will require additional equipment. First, the aluminum must be mechanically abraded in the areas that get encapsulated. This can be done with conventional sandblasting equipment. The aluminum will have to be free of all contaminants before bonding. This may be done with either a trichloroethane vapor degreaser and/or an etch or anodic treatment followed by application of a corrosion resistant primer.

Quality Control

The aspects of quality control and inspection will have added responsibility and complexity resulting from incorporating ER fluids in rotor blades. These additional responsibilities fall into the categories of Receiving/In-Process Inspection and Non-Destructive Evaluation (NDE).

Receiving/In-Process Inspection. Receiving inspection will be mandated to trace certifications of all new materials including the aluminum, ER fluid components (corn starch and silicone oil), rubber encapsulant and all hardware associated with the electrodes such as lead wires and connectors. Certifications may include physical, chemical, and mechanical test data. In-Process inspections will need to be performed on the cartridge assembly or other equivalent ER fluid-filled mechanism prior to integration into the final assembly to ensure proper response prior to integrating it into a rotor blade. This will require sophisticated testing equipment such as customized rotating shakers to simulate flight conditions.

Non-Destructive Inspection. Adding ER fluid to rotor blades does impose additional non-destructive inspection (NDI) requirements. These include surface inspection of the aluminum with fluorescent penetrant techniques, inspection of all bond lines for voids and other defects and a final test inspection of the completed blade performed on the rotating shaker mentioned above.

CONCLUSIONS

This paper presents one of the most advanced attempts at controlling vibration in rotor blades by utilizing ER fluids. A fiber-reinforced ER fluid-filled composite helicopter rotor blade was designed, fabricated and tested. Also, many design and manufacturing issues were explored. Although there are many differences between a scaled down rotor blade and an actual one, this study will provide some ground work for future advancements in this area. Based on the design, manufacturing and testing of the ER fluid-filled helicopter rotor blade as described in this paper, the following conclusions can be made on the feasibility of utilizing ER fluids to control vibration in rotor blade applications:

1. It is possible to achieve vibration control with ER fluid-filled, fiber-reinforced composite helicopter rotor blades on scaled-down blades with construction representative of actual parts. The tip velocity of the presented rotor blade was reduced 33% by applying 3000 volts and the deflection was reduced by 14%. These reductions could be increased by optimizing the design.
2. The blade was purposely made with some flexibility to ensure realization of the ER effect. If the blade was made with sufficient stiffness to meet the functional requirements of an actual rotor blade, it may have been too stiff to exhibit vibration control using ER fluids as utilized in the design presented. To overcome this,

the ER cavity needs to be located off of the neutral axis. Future work should focus on this idea.

3. An ER component made of layers of electrodes can be easily and accurately manufactured. Although the multi-layer cartridge did not work as attempted in this study, additional development may make this idea more feasible than single-layered components for some applications.
4. Utilizing ER fluids for vibration control adds many new design and manufacturing issues. Advancing ER fluids towards production applications will require extensive evaluation of these issues.
5. Many new quality control issues will be required for ER fluid-filled rotor blade fabrication and sale to an end user. These issues will involve creation of many new testing procedures and material and process specifications.
6. An important issue in ER rotor blade design involves characterizing the ER fluid mechanism. Many physical and mechanical properties need to be determined at an early stage in a research program. These properties include optimal electrode material, thickness, size, spacing, stiffness, etc.

APPENDICES

APPENDIX A: NACA 0012 AIRFOIL DATA

<u>X (upper)</u>	<u>Y (upper)</u>
.00000	.00000
.01250	.01894
.02500	.02615
.05000	.03555
.07500	.04200
.10000	.04683
.15000	.05345
.20000	.05738
.25000	.05941
.30000	.06002
.40000	.05803
.50000	.05294
.60000	.04563
.70000	.03664
.80000	.02623
.90000	.01448
.95000	.00807
1.00000	.00000

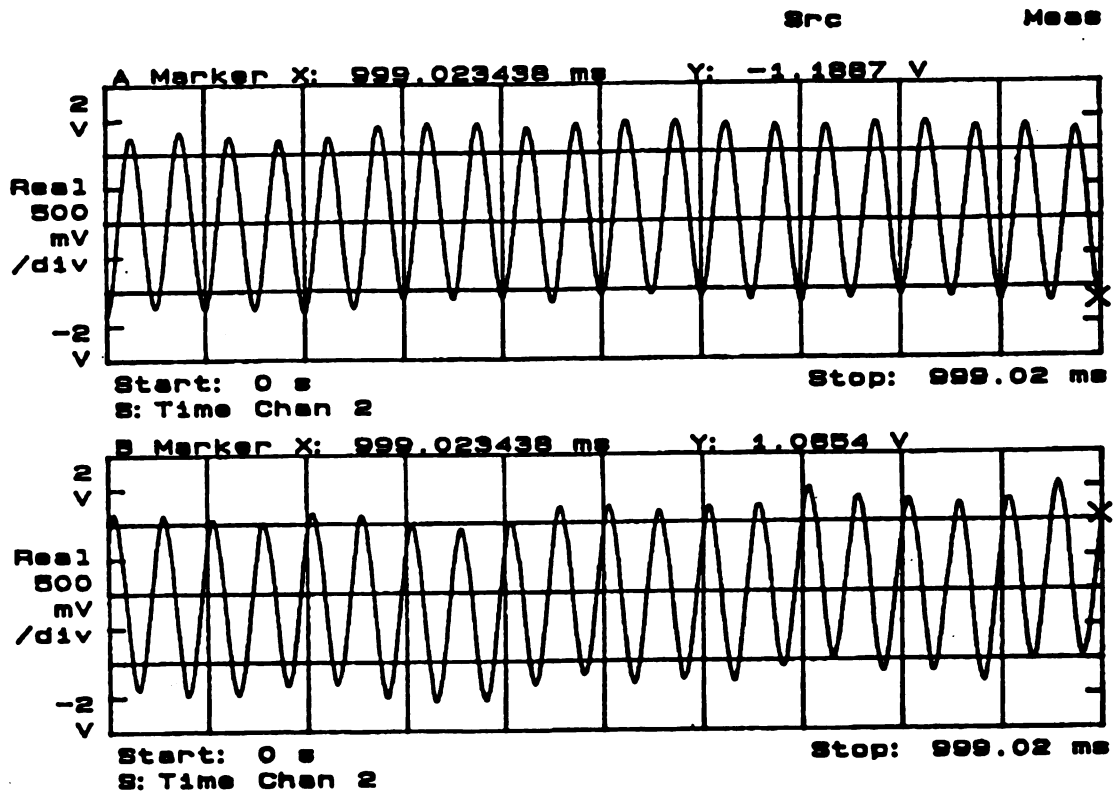
leading edge radius = 1.58

slope of radius = 0.00

airfoil is symmetrical - lower = upper

data is per unit chord

APPENDIX B: MULTI-LAYER ER CARTRIDGE RESPONSE



GENERAL REFERENCES

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1. Immen, Frederick H. and Raymond L. Foye, "New Insights in Structural Design of Composite Rotor Blades for Helicopters," Proceedings of the Fourth International Conference on Composite Materials, Tokyo, Japan, 1982.
2. Foye, R.L., et al, "Mechanics Problems in Composite Main Rotor Design," U.S. Army, Research, and Technology Laboratories, 1983.
3. Hahn, M., "Design for Repairability of Helicopter Composite Blades," DTIC report number AD-A178 691, 1987.
4. Holmes, R.D., "S-Glass Reinforced Plastic Adopted for Helicopter Rotor Blades," SAMPE Quarterly, October 1975, pp 28-41.
5. MIL-S-8698
6. Goldstein, G., "Electrorheological Fluids: Applications Begin to Gel," Mechanical Engineering, October 1990, pp 48-52.
7. Marsh, G., "Plastic Tiger," Aerospace Composites and Materials, Vol. 3, March/April 1991, pp. 4-7.
8. Adelman, H.M. and W.R. Mantay, "Integrated Multidisciplinary Design Optimization of Rotorcraft," NASA Tech. Mem. #101642, 1989.
9. Law, M. and J. Williams, "The Influence of Helicopter Operating Conditions on Rotor Noise Characteristics and Measurement Repeatability," DTIC report number AD-A121426, 1982.
10. Nixon, Mark W., "Preliminary Structural Design of Composite Main Rotor Blades for Minimum Weight," NASA Technical Paper 2730, 1987.
11. Aerodynamics of Rotorcraft, AGARD report number 781, DTIC report number AD-A230 577, 1991.

12. Skinner, Gary L., et al., "Combined Preliminary Airworthiness Evaluation and Airworthiness and Flight Characteristics Evaluation of the UH-1H with Preproduction Hub Spring and Composite Main Rotor Blades Installed", AEFA Project #84-33 Final Report, 1988.
13. Miley, S.J., A Catalog of Low Reynolds Number Airfoil Data for Wind Turbine Applications, Department of Aerospace Engineering, Texas A&M University, February 1982.
14. Layton, Donald M., Helicopter Performance, Matrix Series in Mechanical and Aeronautical Engineering, Matrix Publishers, Beaverton, Oregon, 1984.
15. Bazov, D.I., "Helicopter Aerodynamics", NASA #N72-23024, May 1972.
16. Barrie, Douglas, et al., "Advancing Helicopters", Flight International, December, 1992, pp. 31-37.
17. Koliass, Alexander and Andrew Dimarogonas, "Rheology of Zeolite and Corn Starch Based ER Fluids at High Strain Rates," Proceedings of the Conference on Recent Advances in Adaptive and Sensory Materials and their Applications", Blacksburg, VA, 1992, pp. 548-557.
18. Morishita, Shin and Tamaki Ura, "ER Fluid Applications to Vibration Control Devices and their Adaptive Neural-Net Controller," Proceedings of the Conference on Recent Advances in Adaptive and Sensory Materials and their Applications", Blacksburg, VA, 1992, pp. 537-546.
19. Brooks, Douglas, "Applicability of Simplified Expressions for Design with Electrorheological Fluids," Proceedings of the Conference on Recent Advances in Adaptive and Sensory Materials and their Applications", Blacksburg, VA, 1992, pp. 524-535.
20. Weiss, Kenneth, et al, "Electrorheological Materials and their Usage in Intelligent Material Systems and Structures, Parts I and II, Proceedings of the Conference on Recent Advances in Adaptive and Sensory Materials and their Applications", Blacksburg, VA, 1992, pp. 507-520 , 605-617.

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