Honeywell

Review of 8-mm Piezoelectric Motor Connection Methods

Federal Manufacturing & Technologies

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Topical Report

C. P. Mentesana, Project Leader

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Abstract

This report presents the design and evaluation of electrical connection methods for driving an 8-millimeter traveling wave piezoelectric ring motor. This proved to be a difficult problem because many of the electrical leads and the bonds attaching them to the PZT ceramic were subject to breaking due to resonant vibrations as the motor was run. Methods investigated to provide electrical leads to the PZT ceramic ring included discrete wires, custom-designed cables, and a fixed ceramic ring. Bonds to the ceramic ring were made using three conductive adhesives, thermosonically bonded gold jumper wires, and soldering. A scanning laser Doppler vibrometer was used to evaluate the resonance in the electrical leads. Finite element analysis was used to help guide the design of a new cable to eliminate the resonance problems.

Summary

Delivering power through a conductor system to properly run piezoelectric traveling wave ring motors requires consideration of both electrical and mechanical issues. Typically, the geometries of the leads providing the electrical power have multiple natural resonant vibration modes. If any of these resonance modes are near the drive frequency of the motor, the same vibrations that drive the piezoelectric traveling wave motor drive large resonant vibrations in the electrical leads. These vibrations cause fatigue failures in the electrical leads or in the bonds that connect the leads to the PZT piezoelectric ceramic.

Although it was understood in the beginning that resonant vibrations in the connections could cause failures, many iterations of different conductors and attachment schemes were needed to achieve electrical connections that would not fail as the motor was run. Motors were powered by discrete wires connected to the PZT ceramic, cables made at Federal Manufacturing & Technologies (FM&T), and cables made by Pioneer Circuits in Santa Ana, California. Some of the later attempts of powering the motors took advantage of finite element modeling of the cables' designs and testing on a scanning laser

Doppler vibrometer. These results showed that to prevent resonance in the unsupported length of a cable or wire electrical lead, the lead needs to be as short as possible. The purpose of making the leads short is to raise the natural resonant frequency of the lead well above the drive frequency of the motor.

The first attempt at driving the motor was with discrete 0.010-inch diameter solid copper insulated wires bonded to the PZT using a Ciba-Geigy conductive epoxy. The resonance in the wires coupled with the brittleness of the conductive epoxy caused these connections to break the epoxy bonds when the motor was run. One variation that worked relatively well involved threading 0.010-inch diameter insulated copper wire through holes in the web of the stator before conductive epoxy bonding the wires to the PZT ceramic. With this configuration, the motors ran a long time without failures at room temperature. (Some failures were noted in the epoxy bonds during elevated temperature testing.) Based on the lessons learned from the finite element analysis and the relative success of motors made by threading 0.010-inch diameter copper wire through the large holes in the stator web, two motors were made by threading insulated 0.005-inch diameter solid copper wire through a series of closely spaced holes placed in the stator web. By keeping the unsupported length of the wire short, this method was successful at eliminating the resonances in the leads. This was confirmed by testing using the scanning laser Doppler vibrometer.

The grounding connection on all of the flexcable designs was made by one or more copper wires soldered through via holes and conductively epoxied to the web. The first flexcables made at FM&T had gold-plated pads terminating inside the PZT ring of the motor. Thermonsonically bonded gold wires, conductive epoxy-bonded gold ribbons, and conductive epoxy-bonded solid copper wires were used to bridge between the pads and the PZT ring. In all of these cases, either the conductor or the bond failed due to resonances as the motor was run.

The second cables made at FM&T contained tabs to be bonded with a conductive adhesive or soldered to the PZT ceramic ring. Most of these cables turned out very poorly. A few of the best ones were soldered to the PZT ceramic using tin lead solder, but the sputtered gold on top of the PZT ceramic dissolved into the solder, and the tabs peeled loose from the PZT when the motor was run. Some experimentation was done with different solder alloys that would not dissolve the gold and with nickel or platinum boundary layers. The other soldering alloys were soft and weak and broke easily, but the nickel and platinum boundary layers looked very promising as a method to allow tin lead soldering of cable or electrical leads.

The next cable was designed at FM&T and made by Pioneer Circuits, Inc. of Santa Ana, CA. To increase cable flexibility and conformity to the stator web, while providing a large area for bonding to the PZT ceramic, this design featured laser-cut slits through the Kapton. These cuts allowed the power conductors to bend and contact the PZT elements on the outside perimeter and the ground conductors to contact the web on the inside. Because the long curved length of the outer leads looked like floppy rabbit ears, this design was nicknamed the "rabbit-ear" design. Another change incorporated with this cable was the use of more flexible conductive adhesives to attach the leads to the PZT and the grounding wires to the stator web. Initial testing showed that with this design the grounding leads would break near the via holes. Viewing the vibration with a scanning laser Doppler vibrometer showed large resonances in these leads as the motor was driven. In order to eliminate the resonance problems, a small amount of RTV adhesive was used to bond the grounding leads down to the web. Although the addition of the RTV adhesive was crude, and it was difficult to apply, this system was successful at eliminating the breakage problem. This configuration was used on the CX3 group of motors shipped to Sandia National Laboratories. The motors built with this process withstood running tests at elevated temperatures and shock and vibration tests.

To better understand the resonance problems with the current design, and guide the design of a cable without these problems, a finite element analysis was conducted. Based on this analysis, a new flexcable with short conductor lengths was designed and validated before being made. The configuration of this cable looked like a T-shirt, and the design was nicknamed the "T-shirt" design. These cables were also made by Pioneer Circuits and used on the CX4 group of motors shipped to Sandia. These cables were bonded to the motor using the newer flexible conductive adhesives.

Beginning work was initiated on two methods, using a cable to bring the electrical power to the center of the stator and then using a different method of supplying the power out to the PZT ceramic ring. The first method would use a ceramic ring clamped below the stator web with very short (to eliminate vibration resonance problems) thermosonically bonded gold ribbons bridging between the ceramic collar and the PZT. The second method, needing future work, (called the conformal coating method) consists of applying an insulating coating below conductor leads applied directly to the web of the stator.

Discussion

Scope and Purpose

This paper presents a review of the electrical connection methods considered for power delivery to run an 8-mm piezoelectric traveling wave ring motor manufactured by Honeywell Federal Manufacturing & Technologies (FM&T) in Kansas City, MO, for Sandia National Laboratories, Albuquerque, NM. The piezoelectric material used in these motors is a lead-zirconate-titanate (PZT) ceramic. It is intended as a knowledge preservation document, not only to describe work performed up to the present, but also to convey problems and their causes encountered during motor development work. The reader is assumed to have a basic understanding of the theory and operation of piezoelectric traveling wave ring motors. Basic background and supplemental information are listed in the references.[1-4]

Delivering power through a conductor system to properly run piezoelectric traveling wave ring motors requires consideration of both electrical and mechanical issues. Insulated electrical paths must be provided to small, thin, closely spaced parts of the motor. Micro-elliptical motion of the PZT surfaces created by traveling waves must be accommodated by the connection method. Robust electrical and mechanical bonding methods (soldering or adhesives) must firmly attach conductors to the metalized PZT elements and the stator without coming apart during operation. Design geometries must minimize self-destructive resonant vibrations of free-span conductors at and near motor operating frequencies. To prevent restricting the traveling wave motion of the motor, the added mass and stiffness of the conductors and bonds must not impede the resonance of the PZT stator system. With these criteria in mind, the goal was to design a thin, low-mass, flexible cable assembly, with short conductor runs. The design was to have good isolation and intra-conductor high-voltage standoff capability. Additionally, it was desired to solder or adhesively bond the cable to the PZT element to withstand normal handling and motor operation, as well as operational tests at elevated temperatures and shock environments.

Activity

Early Work

Early in 1995 the first attempts to devise power cables for piezoelectric motors involved simple and direct schemes. Small wires were soldered or bonded directly to the PZT elements and the stator web. This worked for experimental motors, but was neither practical nor strong enough to build production motors. Various specially shaped flexcables were considered (e.g., cables with tabs, cables with pads); all were limited in their success due to material processing limitations, conductor failure, or bond failure. Due to their small size, each flexcable had to be carefully prepared and attached to the motor under a microscope. Following are a description of the main schemes considered and the reason for not using each.

Wires Attached With Conductive Epoxy

Small, discrete wires were bonded to the PZT elements and the stator with Ciba-Geigy Epibond 7002 conductive epoxy paste. (See Figure 1.) This allowed the motor to run, but resonance in the wires coupled with the brittle nature of this conductive adhesive caused the adhesive connections to break when driven. The lack of strain relief also made the connections susceptible to handling damage.

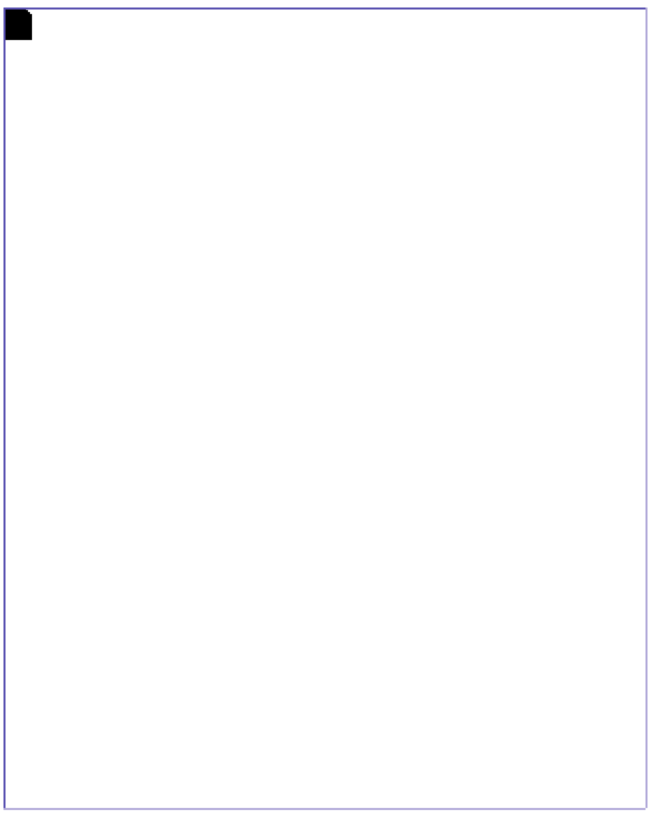

Figure 1. Epoxy Bonded Wires on PZT Elements

Ring-Tab Flexcable

To increase strength, a tabbed flexcable with a ground pad was designed. As can be seen in Figure 2, conductor tabs extended radially outward from the center of the cable and reached out over the PZT elements. Parallel gap welding would attach the tabs to the PZT elements. A 30-gage copper wire

(0.010-inch diameter), soldered through the via pad and conductively epoxied to the web, would make electrical and mechanical connection to the stator web. To achieve a good PZT bond, the tabs had to be completely free of Kapton material. This would be done using eximer laser ablation. The equipment for this process was available; however, the process had not been done in a number of years and would require many weeks of development time. Consequently, this ring-tab cable design was rejected.

Figure 2. Ring-Tab Flex Cable

Ring-Pad Flexcable With Gold Wire Bonds

To avoid the need for eximer laser technology, a ring-pad flexcable was designed and made with bonding pads substituted for tabs. See Figure 3.

Figure 3. Ring-Pad Flex Cable

Gold jumper wires, 0.001-inch diameter, were used to make electrical connections to the PZT elements. As can be seen in Figures 4a and 4b, thermosonic bonds were used with two connections made on the cable pad (right) using ball bonds, and terminating on the PZT element (left) with wedge bonds. During motor operation, resonant vibration in the soft, gold wire loop caused fatigue and failure just above the ball bond. Finite element analysis of a different product with similar gold wire bonds confirmed that stresses were highest in the short-radius bend area of the wire above the ball bond. To try to alleviate this problem, the next attempt was made by changing the jumper conductor from thermosonic gold wire to conductive epoxy bonded gold ribbon.

Figure 4a. Gold Wire Bonds to PZT Elements

Figure 4b. Wedge Bonds Left, Ball Bonds Right

Ring-Pad Flexcable With Conductive Epoxy Bonded Gold Ribbons

The same ring-pad flexcable was used as before, except 0.003-inch thick x 0.025-inch wide gold ribbon was substituted for the gold wire bonds. Gold ribbons were epoxy bonded from the cable pads to the PZT elements with Ciba-Geigy Epibond 7002 conductive epoxy paste. See Figures 5a and 5b.

Figure 5a. Gold Ribbon Bonded With Conductive Epoxy

Figure 5b. Closeup of Gold Ribbon Bonds

The through-hole ground connection was made as before, which provided electrical and mechanical connection to the web. Ribbon connections were used on several motors. However, after operation, the ribbons came off due to broken epoxy bonds as can be seen in Figure 6.

Figure 6. Gold Ribbon Epoxy Bond Failure

Ring-Pad Flexcable With Copper Wire Bonds

Another idea used the same ring-pad flexcable, but the gold ribbon was replaced by 0.005-inch diameter copper wire. See Figure 7. The wire was bonded to the cable and PZT elements using the Ciba-Geigy Epibond 7002 conductive epoxy paste. The motor ran, but the wire broke from fatigue due to resonant vibrations. Cracks were also observed in some epoxy bonds.

Figure 7. 0.005-Inch Diameter Copper Wire Replacement

Hole-Threaded Discrete Wires

Early in 1996, the stator web underwent design changes to improve motor performance. Eight (and later nine) holes were drilled equidistantly around the web floor to lessen web stiffness. To reduce wire fatigue and breakage, 30-gage (0.010-inch diameter) insulated copper wire was woven through several web holes, run to the edge, and bonded to the PZT elements using Ciba-Geigy Epibond 7002 conductive epoxy paste. The weaving constrained the wires from flopping around and produced less stress on the epoxy bonds. The ground connection was made with the same type of wire, wound around and bonded to a rib between two successive web holes. (See Figure 8.) When power was applied, the motor ran well without any failures at room temperature. This method worked well for development, but the epoxy bonds failed during testing at elevated temperatures. This created a need to develop electrical connections that would survive the operation at elevated temperature and shock tests and be more suited for production motors.

Figure 8. Woven Wire Connections

Recent Work

Late in 1997, new ideas and materials were used in tackling the piezo motor connection problem. A printed circuit ceramic collar was designed to interface between a fixed cable and the moving PZT elements. Suspended under (and free from) the moving web and stator, the collar offered a solid base for bonding Kapton flexcables, gold wires, or ribbons. Several flexible conductive adhesives were obtained which yielded crack-resistant, vibration-tolerant bonds for moving electrical connections. Soldering was investigated to attach copper leads to PZT elements. New concentrically slit flexcables were designed to incorporate shape-conformance and flexibility, thus reducing stresses on conductors and bond points. Cables were designed in-house and purchased commercially to obtain small features like slits, short-radii curves, and Kapton ablation over copper paths. Ablating a small area of Kapton over a copper trace allows soldering the copper to the metal below for an improved bond. It was decided that small, thin, symmetric Kapton cables with minimal mass offered the best solution for electrical connections. Following are discussions of the work performed.

Fixed Ceramic Collar

The fixed ceramic collar design was intended to reduce contact with the moving web of the stator. Figure 9 shows a thin round ceramic collar, supported in the middle by a metal spacer and washer, providing centering and standoff of the collar, below the web. In Figure 10, Kapton cable connections and wire or ribbon bonding to the PZT elements were to be made to the printed circuit trace pads on the collar. To determine whether resonances at the motor driving frequencies were likely to break the ceramic collar or the gold wire or ribbon, finite element analyses were done of the collar and various gold wire and ribbon geometries. The analysis of the ceramic collar eliminated the resonance concern for it. Based on the analysis results of the ceramic collar, the first vibration mode occurs at 116.7 kHz and the three-wave mode occurs at 204.2 kHz. The three-wave mode used to drive the stator (occurring at about 50 kHz for phosphor bronze material and about 69 kHz for a stainless steel material) is far too low to be expected to excite the three-wave mode of the collar. The driving frequency of the motor is also different from, and far away from, the first mode of vibration of the collar. The analyses of the gold wire and ribbon showed that (as confirmed by the previous failures in the gold ribbon and wire connected to motors) the geometry of the ribbon or wire can cause severe resonance problems in the gold conductors. By making the connections out of a short, wide ribbon, these problems can be avoided. Based on the analysis, the preferred geometry was a 0.005-inch wide by 0.001-inch thick gold ribbon with a distance between connections of about 0.020 inch. With this geometry, the first resonance mode of the ribbon was raised to about 200 kHz. This is far above the 69-kHz drive frequency of the stainless steel stator and prevents the motor from driving natural resonances in the gold ribbon.

Figure 9. Fixed Ceramic Collar Scheme

Figure 10. Details of Ceramic Collar and Cable Attachment

Various trace patterns on the collar could accommodate different PZT polling configurations. A six-segment PZT element collar is shown in Figure 11. Several ceramic collars were laser-cut out of a sheet of commercial ceramic material, but due to the development effort required, this method was suspended to concentrate on flexcables and conformal coating efforts.

Figure 11. Six Segment PZT Element Ceramic Collar

Asymmetric Tab Flexcable Designs

For simplicity and ease of manufacturing, it seemed that the most direct way to power a ring motor was with some kind of flexcable. Using the old ring-tab flexcable idea, a symmetric design was first proposed which used a single-sided, 1-oz. copper Kapton cable. The cable was to fit around the center hub of the motor and was to be secured by three holes in the web--two for electrical grounding and one for mechanical support. Bare copper tongues, ablated free of Kapton, were to be bonded to the two halves of the PZT ring to power the motor. For assured conductivity, additional gold ribbons would be thermosonically bonded from the top of the tongues to the PZT. Considering the geometry of the 4-3 polling pattern of the ring’s two halves, it was thought the node locations with the least vertical motion (and thus minimal bond and conductor stress points) occurred at the 2, 4, 6, 7, 9, and 11 o’clock positions around the ring. To match these nodes, the tongue locations were made at the asymmetric 11 and 2 o’clock positions. This can be seen in Figures 12 and 13.

Figure 12. Asymmetric Flexcable with Tabs in 11 and 2 O'clock Positions

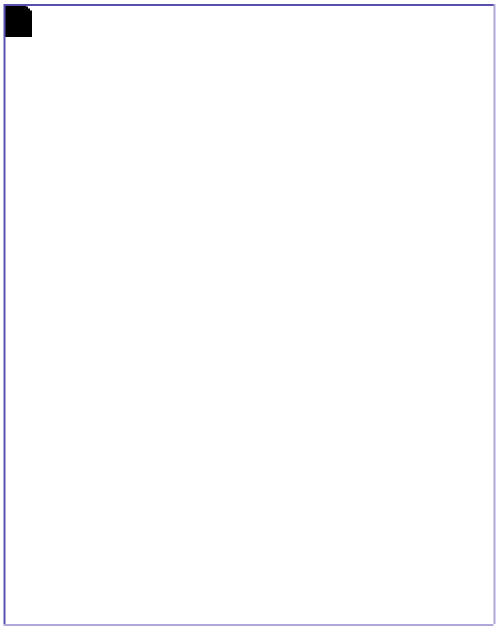

Figure 13. Asymmetric Cable Connection to Web

The asymmetric design was made in-house with unimpressive results. Cutting out the cables from the etched panels proved difficult since the shapes were small and intricate and the ability to make cables had dwindled over the years. The only laser available to do small cutting and ablating was a CO_2 laser, which proved too cold for this application. It scorched and melted the material, making it ragged and rough, and left melted Kapton whiskers hanging off of edges. The cables had to be plasma cleaned to remove the residue. Since laser cutting was not working well, mechanical routing was the only other timely means available to cut out cables. This was painstakingly slow, with much work and modest success. The cables had irregular edges with some edge-cuts even encroached into conductor paths.

The same thing happened when ablating Kapton for the bare copper tongues along the cable top. The CO_2 laser was too cold to completely vaporize and remove the Kapton from the copper trace ends. Scorched and melted material was left on the copper surface and in some instances discolored the tongue. Again, plasma cleaning had to be used to remove residue from the copper. Most of the tongues looked bad and were unusable.

A few in-house cables were good enough to try on motors. See Figure 14. A parallel gap welder was used as a method of controlling the soldering process. The bare copper tongues were soldered at the 11 and 2 o’clock positions on the metalized chrome/gold layer of the PZT elements. Because tin lead solder readily absorbs gold, the joints were weak and exhibited low peel-strengths of approximately 7 to 10 grams. One joint measured 20 grams. When run, the tabs quickly peeled loose from the PZT ceramic element. The in-house production problems, low peel-strength, and cable appearance demanded a new cable design.

Figure 14. Soldered Asymmetric Ring-Tab Cable

"Rabbit-Ear" Flexcable Designs

The ring-tab cable design was again modified so that the cable conductors entered the top of the PZT ring in one small area (at the 12 o’clock position) and continued around (in each direction) to offer better bonding areas on each element. It was believed this would reduce both bond stress and cable stress. This cable design was nicknamed the "rabbit-ear" cable due to the long leads that look like floppy rabbit ears. It consists of ½ ounce per square foot copper (0.0007-inch thick) bonded to 0.001-inch thick Kapton with 0.0005-inch thick adhesive. In some areas, a 0.0005-inch thick cover layer of Kapton is bonded on top with 0.001- inch thick adhesive. The center section that attaches to the stator and the leads that connect to the PZT ceramic element were designed to be very flexible, and do not include the top layer of Kapton. This design has two wires that act as the pins that attach and ground the cable to the center web of the motor. The original version of this "rabbit-ear" design had bare copper next to the PZT elements and no soldering holes in the top Kapton layer. For development, a conductive adhesive bond would be used to attach the cable to the PZT elements. For production, it was preferred to reduce or eliminate organic materials contained in epoxies and adhesives from the motor fabrication process, to reduce long-term outgassing and aging deterioration. The cable ears were thus designed to allow soldering in the future. To increase cable flexibility and conformity to the stator bottom, three concentric slits were laser-cut through the Kapton cable, between the conductors. See Figure 15. These cuts allowed the power conductors to bend and contact the PZT elements on the outside perimeter and the ground conductors to contact the web on the inside, with minimal mutual stress to both. To allow soldering, four access holes were ablated through the top Kapton layer over each ear of the cable. See bottom of Figure 15. Either adhesive film or soldering could be used to bond the cable with this method. This seemed to be the best combination of flexibility and strength for getting power to the moving PZT ring. These cables were fabricated by Pioneer Circuits, Inc. of Santa Ana, CA.

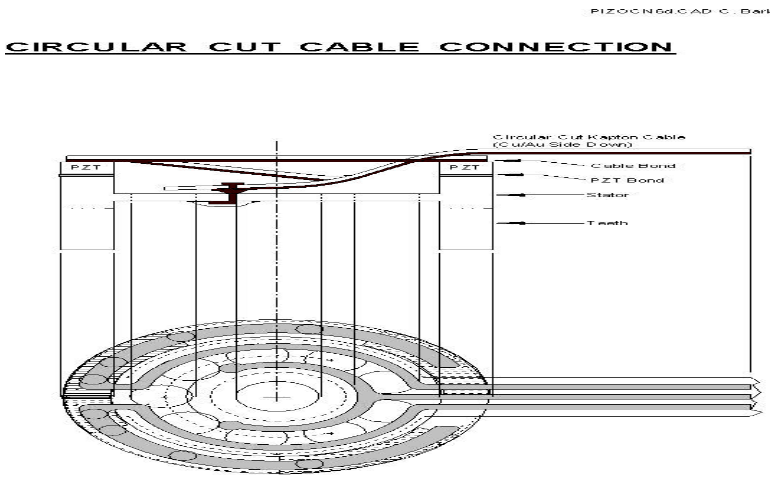

Figure 15. "Rabbit-Eared" Cable With Circular Cuts

A typical soldering attachment method, shown in greater detail in Figure 16, would allow the tip of a soldering iron to contact the inner copper conductor of each ear and promote better heatflow for a good solder joint. The gold metalization on the PZT elements would need to be changed to prevent the gold from being absorbed into the tin lead solder. Some positive preliminary results were obtained by sputtering nickel and platinum barrier layers on top of the gold metalization.

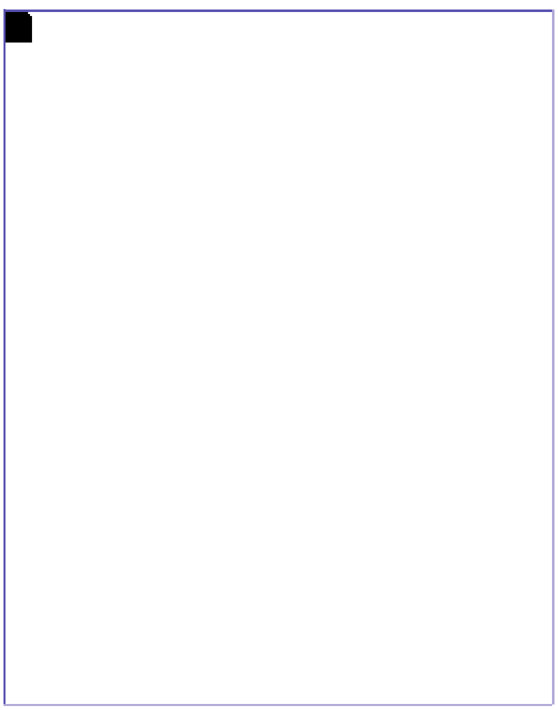

Figure 16. Detail of Cable Attachment Method

The "rabbit-ear" leads of the cable were designed to allow them to be cut to the desired length or left full length to bond along both sides of the ceramic ring element. A major change in the attachment of these leads was the use of new more flexible conductive adhesives. Figure 17 shows the ears trimmed short at the second hole down and bonded to the PZT elements with 0.002-inch thick, Ablefilm 5025E, flexible conductive adhesive film (Ablestik Labs). Electrical ground and mechanical connections were made through two, 0.012-inch diameter drilled holes in the web. A pair of 30-gage (0.010-inch diameter) copper wires was soldered to the cable's ground pads, inserted through the drilled web holes, bent over, and conductively bonded to the tooth-side of the web, using Albebond 976-1, silver-filled, flexible conductive epoxy paste. The ground conductor (middle copper path on the cable) splits into two circular paths next to the center hub, each terminating with a via pad. The soldered wires can be seen as two bright spots close to the center hub. The bent-over ground connections are on the opposite (toothed) side, away from view.

Figure 17. Cropped "Rabbit-Ear" Cable Bonded to Motor

Due to time constraints of proving design feasibility, cables were only bonded to the PZT elements with flexible conductive adhesive film. The soldering capability of the ears remained unused. Again, vibration resonances caused fatigue failures in the connections to the PZT ceramic and in both ground paths adjacent to the ground pins. Although the cables failed due to resonance, the flexible conductive adhesive did not fail.

Vibration Analysis and FEA Modeling

Evaluations of the "rabbit-ear" cable with the scanning laser Doppler vibrometer clearly showed the resonances in the cable as the motor was driven. To prevent this resonance from breaking the grounding connections, the center section of the cable was bonded down to the stator web using a flexible RTV adhesive. This process worked well enough to prevent any failures from occurring in the motors undergoing the operational testing at elevated temperatures and shock tests. Although the "rabbit-ear" cables and this method of bonding the center of the cable were used on all of the CX3 motors shipped to Sandia, this method was crude and the adhesive was difficult to apply. A better cable design was desired. To evaluate the problems in the "rabbit-ear" cable design and guide the design of a new cable to eliminate these problems, a series of finite element analyses was performed.

Analysis of Existing "Rabbit-Ear" Cable Design

A three-dimensional finite element model was created and natural frequency analysis performed. This analysis determined the various vibration frequencies and mode shapes of the cable, including the modes that were breaking the cable at the 69-kHz motor driving frequency. Restraints were applied to the finite element model at the end of the cable and to the leads that connect to the motor at their attachment points. Due to the long, thin geometry of the longest unrestrained section of the cable, the first vibration mode (fundamental mode) occurred at about 1.2 kHz, with many vibration modes between this mode and the 69-kHz drive frequency. There were two modes near the 69-kHz motor drive frequency which were likely to cause the breakage in the cable connections. If possible, the most effective changes in the cable design for eliminating any vibration modes near the driving frequency would be to cause the first vibration mode of the entire cable to be significantly above the 69-kHz driving frequency. Although this is the desired solution, it isn’t possible to modify the cable enough to make this happen, because the fundamental vibration mode occurs at such a low frequency. It is feasible, however, to significantly eliminate the breakage in the cable connections by changing the cable design in a way which will keep the short leads that attach to the PZT ceramic from resonating until beyond the 69-kHz driving frequency. The resonant frequencies of the short leads of the cable may be raised by increasing their stiffness. This may be accomplished for the same cable materials by changing the thickness or shortening the length of the leads. The second phase of the design analysis process focussed on determining a representative cable thickness and length that would work for the leads.

Determination of a Workable Length and Thickness for Cable Leads

Based on the theoretical solution of the vibration of a transverse bending beam, the resonant frequencies (of the various modes of vibration) vary linearly with the thickness of the beam and as a squared function of the length. The assumptions in the derivation of the theoretical solution are that the beam is long and slender, made from a uniform linear elastic and isotropic material, and that it only undergoes small displacements. Although the cable is not made from a single linearly elastic material, it was expected that it would still follow closely the same variations in resonant frequencies with respect to thickness and length. In order to verify these relationships for the cable and to establish a starting point for designing the cable, a "test case" finite element model was created of a long, thin strip of the same configuration used in the long leads ("ears" of the "rabbit-ear" cable design). This model was originally 0.200-inch long, with fixed restraints at each end. From this analysis, the fundamental vibration mode for this configuration occurs at 3.9 kHz. Shortening the length of the model to 0.100 inch confirmed the squared relationship between vibration frequency and length as the fundamental frequency was raised to 15.6 kHz. Based on these results, the expected fundamental frequency for the same cable with a length of 0.050 inch would be about 62 kHz. Although large gains were made by shortening the length of the leads that attach to the PZT ceramic, 0.050 inch is about the shortest length feasible. To finish raising the fundamental frequency of the leads above 69 kHz, the thickness of the cable could be increased. To minimize the effects of the leads on the vibration of the motor, the leads used in the "rabbit-ear" cable design were very thin and flexible. This lead thickness could reasonably be doubled in the new design without becoming too rigid for the motor to function well. To incorporate these changes, the next cable was designed to be twice as thick with the leads having a maximum unrestrained length of about 0.050 inch.

Development of the New "T-Shirt" Cable Design

To keep the leads short, the new cable design was shaped like a T-shirt. See Figure 18. The "neck" of the "T-shirt" was a center ring with three wires that attach to the center web of the stator. This design incorporated an optional fourth conductor to accommodate a feedback element made into the PZT ring. Looking like a small driving element, the feedback segment acts like a microphone, picking up the resultant vibrations of the traveling waves and converting the energy to a small varying voltage. This voltage is used by the drive electronics to control the signal frequency furnished to the motor. The control circuit can thus track and compensate for temperature, impedance, and torque-load changes experienced by the motor during operation. The short leads that attach to the PZT ceramic form the "sleeves" of the "T-shirt," with one center lead attaching to the feedback segment of the new PZT ceramic element design. With this design, loads in the cable are absorbed by the three wire attachments in the "neck" area that act as a strain relief to protect the leads. To verify that this design accomplished the goal of raising the resonance of the leads of the cable above the 69-kHz drive frequency, a three-dimensional finite element model was created of the new "T-shirt" cable design. The two resonance modes closest to the drive frequency found by the finite element model were at 64.2 kHz and 72.6 kHz. The 72.6-kHz mode has no significant vibration of the leads. With the exception of the 64.2-kHz mode, the first significant vibration in the leads was found to occur in the center lead connected to the feedback segment of the element at 90.6 kHz. The 64.2-kHz mode was a resonance in the large square "shoulder" of the "T-shirt." There were duplicate vibration modes at this frequency, one for each "shoulder." This mode would cause serious resonance problems in the leads that attach to the PZT ceramic. Although this was a serious problem with the first iteration of the "T-shirt" design, it was caught by performing the finite element model before making any actual cables. The fact that the "shoulders" in the first "T-shirt" design were so large and square accounts for this mode of resonance at 64.2 kHz. As previously discussed, the frequency of resonance varies as a square function of the unsupported length between the attachment points on the lead and the square corner of the "shoulder." Fortunately the "shoulders" of the first iteration design were much larger than needed, and when coupled with the squared relationship between this length and frequency, this resonance was eliminated from occurring anywhere near the 69-kHz drive frequency by a significant rounding of the "shoulders" on the next iteration of the "T-shirt" cable design.

Figure 18. First "T-Shirt" Cable Design

Final Design of the New "T-Shirt" Cable

The final design of the "T-shirt" cable included the rounding of the "shoulders" to eliminate the resonance near the motor driving frequency. The feedback lead was also moved to the center to create a more symmetrical design of the cable. Many of the corners of the leads were radiused, and the pads at the attachment points to the PZT ceramic were rounded to eliminate the stress concentrations of sharp corners. The windows around these pads and around the through holes in the copper for the pins were redesigned so that there is a solid surface area for the Kapton and adhesive to attach to. The final "T-shirt" cable was designed at FM&T and fabricated by Pioneer Circuits, Inc. of Santa Ana, CA. As can be seen in Figure 19, three sequential hole-pads (around the "T-shirt" "neck") form a strong mechanical and electrical ground connection for anchoring the cable to the inner stator web. The connections to the drive phases ("T-shirt sleeves") and feedback element ("T-shirt chest") are small, situated over the ring elements, and are located on the same side of the stator ring as the ground pins. Three ablated windows over the pads, in the top and bottom Kapton covering, are provided to expose the bare copper of the drive and feedback connections. Each window area is cut smaller than the pad area to improve bonding strength and reinforce the pads. This feature allows either adhesive bonding or tin lead soldering of the pads to the PZT elements. A three-sided relief cutout (forming a tongue) frees up the feedback pad in the middle of the cable, while maintaining a high resonant frequency of the feedback conductor. Four oblong windows (similarly cut like the pads) are provided to attach the cable to a PWB or similar application. See the Appendix for the Piezo T-Shirt Cable Attachment Process.

Figure 19. Final "T-Shirt" Cable Design

Constrained Threaded Discrete Wires

Vibration analysis and FEA modeling proved the importance of minimizing long conductor lengths and stiffening conductor runs when dealing with vibrating piezo elements. Thus, the goal was to design a conductor with a natural resonant frequency (of any vibrating member) much higher than the motor operating frequency. Ideally, a conductor should ride the moving web, run from inside the web to the outside, and terminate on the outer PZT elements. An attempt was made to do this by drilling several 0.010-inch diameter holes in the web, between the large holes, and forming a lacing path for wires leading to the outside elements. Insulated 36-gage (0.005-inch diameter) copper wire was then woven through the holes and soldered to each element. To prevent problems with gold dissolving into the solder, a 97% indium,

3% silver solder was used to attach the wires to the gold sputtered PZT. This solder is very soft and weak, but the gold does not dissolve into it, and it allowed the wires to be soldered for this evaluation. As mentioned previously, a long-term solution for soldered leads could be obtained by applying a thin nickel or platinum boundary layer on top of the gold. Two bonded stators were fabricated by this method and tested with the scanning laser Doppler vibrometer. See Figure 20. The first stator was assembled by threading the wires through the small drilled holes and then stripping the ends of the wire and soldering it to the PZT. Because of the small size of the stator, stripping the wires the right length was very difficult, and one of the loops of wire making a connection to the PZT was too long. This resulted in large resonant vibrations in this loop of wire when the stator was driven during testing with the scanning laser Doppler vibrometer. To fix this problem, the second stator was assembled by stripping and soldering the wire connections to the PZT before threading the wires through the holes in the web. Scanning laser Doppler vibrometer tests confirmed that the second stator was very successful at eliminating resonances in the wire. The disadvantages to this system are the crude esthetics, the complexity of threading wires through the holes, and possible wear and abrasion problems between the wire insulation and the holes as the motor is run.

Figure 20. Constrained Threaded Discrete Wires

Motor Imbalance

An investigation into the effects of imbalance on the performance of the piezoelectric motors was performed and published under topical report KCP-613-6279, *Imbalance in Traveling Wave Piezoelectric Motors*.[4] This work proved that the 4 left-3 right polling pattern, used on PZT elements of existing motors (four sections on the left half, three on the right), produced a double-hump mechanical impedance behavior over the operating frequency range. The four-element side had a resonant frequency hump peak a few 10’s of hertz above the three-element side. The energy contribution to a common traveling wave from two unequally patterned sides resulted in motors with an interesting and sometimes strange behavior. These motors would lose torque, make strange noises, stop, or even run in reverse. This was known as the "squirrelly region" of motor performance. It was theorized that as motors ran and heated up, the dielectric properties of both element halves changed in a parallel manner. If the pair of impedance humps was either both below or both above the drive signal frequency, the motor behaved normally. However, if the humps drifted to straddle the drive frequency, operation was in the squirrelly region and behavior was indeterminate. Since no attempt was made (using feedback or motional current sensing) to lock onto (track) this drift behavior, motors sometimes ran OK and sometimes not.

As continued running generated more heat, some motors would pass through and out of this region to again behave normally. Some motors never exhibited odd behavior, presumably because straddling never occurred. For these, it was thought that unintentional manufacturing and processing tolerances created error stackups in a direction favorable to align the two humps more closely or cause smaller frequency drifts. These motors always behaved normally.

Due to this investigation, PZT element polling patterns are now being made symmetrical (3 left-3 right

PZT element polling pattern) and tolerances of PZT element fabrication are more stringent. Steps are being taken to minimize variances in the manufacture and assembly of motor components. These efforts are aimed at making each PZT ring-half contribute energy equally and coincidentally to the traveling wave at all operating frequencies. In other words, the same (one) impedance hump is desired for both element halves over the same frequencies. Eliminating the double hump and thus the "squirrelly region" will boost output torque for all motors and make them easier to control.

Accomplishments

The design and attachment of electrical leads to drive the vibrations that operate the 8-mm piezoelectric ring motors is difficult. These vibrations result in destructive mechanical resonance of the conductor traces and the bonds to the PZT elements.

To eliminate the resonance problems in the electrical leads, the unrestrained sections of the wires and electrical leads were designed to have a natural resonant frequency above the drive frequency of the motor. To accomplish this, the stiffness of the leads needed to be increased. Small increases in stiffness can be gained by increasing the thickness, or large gains in stiffness can be obtained by shortening the length. As a result, trace lengths inside the stator ring were kept short and distances between fixed grounding wires and moving contacts were minimized. Cables were made thick enough to accommodate operational stresses and normal handling, yet flexible enough not to hinder motor operation. With these criteria, a "T-shirt" cable design was developed, based on finite element analysis and modeling techniques.

Flexible conductive epoxy film adhesives were used for pad bonding. At this time their performance seems favorable if fresh adhesives are applied to clean surfaces and properly cured. Cable bonds to the PZT elements are flexible, conductive, and not detrimental to the chrome/gold layer covering the PZT ceramic. Future PZT ceramic elements will be coated with platinum or nickel to allow regular tin lead soldering of the cable.

PZT element polling pattern symmetry (left-to-right) is important for proper motor behavior. Mechanical (pattern) balance was found to be closely related to electrical impedance balance, which means the two motor halves must form a "single hump" impedance curve for the exact same frequencies. This will help to prevent unusual motor behavior in the "squirrelly region" characterized by noise, stopping, or running backwards. In addition, piece-part fabrication and assembly tolerances must be very tight and exact to achieve good balance.

The project investigated cable vibration problems, proper bonding materials and methods, and discovered the importance of symmetrical polling of the PZT elements. These issues will yield a more powerful motor and one that is easier to control.

Future Work

Conformal Conductors

Probably the best solution for powering moving motor elements (albeit the most difficult to accomplish) is to deposit insulated conductive traces onto the bottom of the stator using physical vapor deposition (PVD) methods. Conformal application of power conductors to the surface of the web and over the PZT elements can eliminate problems of destructive resonant vibrations and bond failures. Referring to Figure

21, a separate and insulated ground pad configuration is shown in the drawing. Before the PZT element is bonded to the stator, a flexible insulated base layer (e.g., Teflon or Pyralene) is applied over the entire bottom of the stator. A chrome/gold (Cr/Au) layer and narrow gold ground path and pad are concurrently deposited over this insulating layer. This forms an insulated (from the stator) ground path to the bottom of the PZT element. The PZT element is then bonded to the Cr/Au layer as usual. Next, a short, vertical intermediate insulation layer is applied in a narrow strip to the inner wall of the stator and the PZT element to isolate the signal path from the edge of the Cr/Au bonding layer. Finally, a gold signal path/pad is laid down over the intermediate and base insulation layers to provide connection to the top of the PZT element. Another pair of signal and ground connections is similarly formed on the opposite half of the stator to provide power for the other half of the motor. Because of the inner location of the signal and ground bond pads near the central mounting hole, web motion is relatively small. A simple four-conductor flex cable is required for connection to the bond pads. This cable should not see destructive resonant vibrations, bending fatigue, or bond failures as experienced by previous designs.

Figure 21. Conformal Coating Connections With Insulated Ground

Figure 22 shows a simplified, non-insulated ground configuration using the stator metal as common ground return for signals. The usual Cr/Au layer is deposited onto the stator ring top and the PZT element bonded to it as usual. A Teflon or Pyralene insulation layer is deposited down the inner side of the PZT element and stator wall, across the web floor, and over to a pad near the central mounting hole. Finally, a narrower gold signal path and pad are laid down over the insulation layer to provide connection to the top of the PZT elements. Another signal connection is similarly formed on the opposite half of the stator to provide power for the rest of the motor. A simple three-conductor flex cable is required for connection to the bond pads and one or two through-hole wires for grounding and strain relief. This connection scheme eliminates motion-related failures and is easier to implement.

At the time of this writing, a film of Teflon, 1.1-microns thick has been successfully PVD-deposited onto a 304 SS dummy stator as a base-insulating layer at Sandia National Laboratories/New Mexico. The clear film shows a peel strength of ~ 5 kpsi while flexure tests show good adhesion to the SS base metal and high crack and craze resistance. Teflon appears to be a favorable insulating material with a higher-than-expected standoff voltage of 400,000 volts/micron. To form the gold conductor path, a titanium adhesion layer, 500-angstroms thick, was applied over the Teflon, then 5000 angstroms of gold.

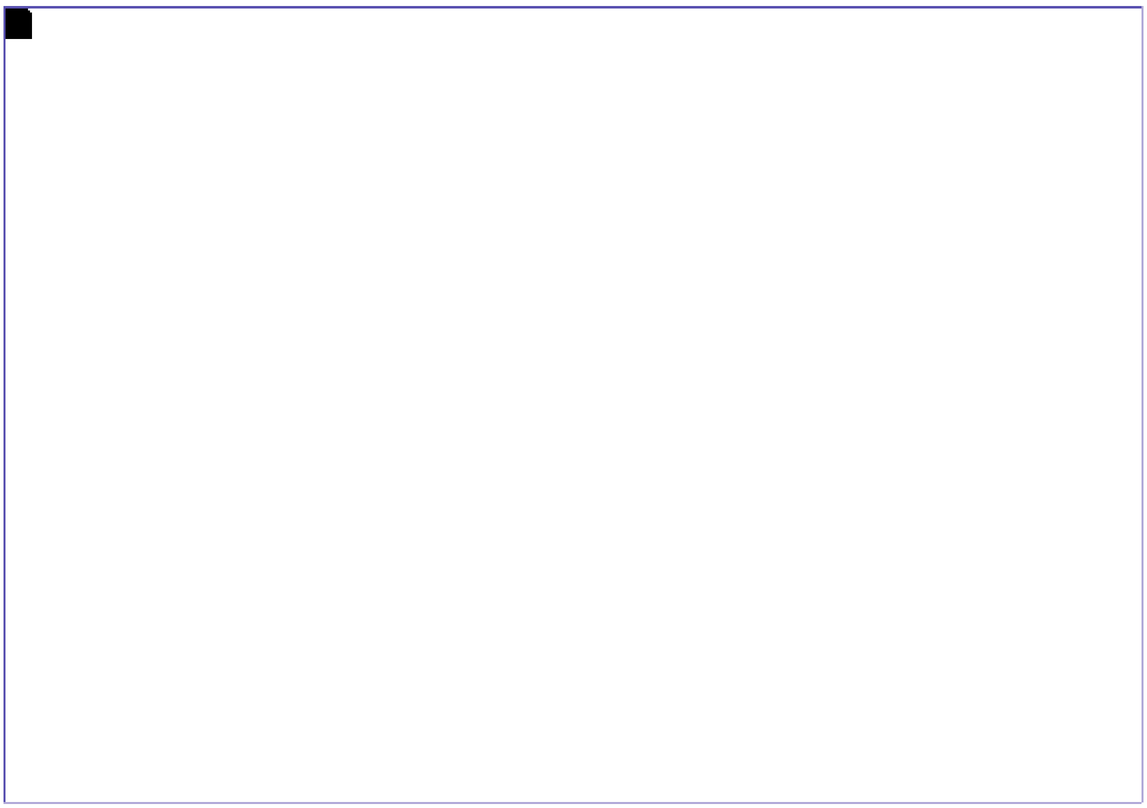

Figure 22. Conformal Coating Connections Using Stator as Ground

Several problems have arisen with the conformal coating process. The gold is easily scraped off in spite of the adhesion layer. Due to the small size, holding fabrication tolerances of the deposition mask becomes significant. Care must be taken when aligning the mask on the workpiece to prevent shadowing and inadvertent deposition problems. For example, on one stator, the gold path was accidentally deposited, slightly skewed from the Teflon/titanium path onto the SS base metal, causing a short.

More work remains to be done to find PVD materials that will bond well to Teflon and resist abrasion, twisting, and vibration of the stator. In spite of these problems, Teflon seems the insulating material of choice as it is flexible, tough, easily deposited, and has very good dielectric properties.

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Appendix

Piezo T-Shirt Cable Attachment Process III

Piezo T-Shirt Cable Attachment Process III

Stainless Steel Stator, 8mm Motor

This process is used to attach a T-Shirt-shaped Kapton cable to the element of an 8mm SS stator, Piezoelectric motor. **Ablestik 5025E**, Non-carrier, 2-mil thick, flexible adhesive film and **Ablestik 976-1**, Syringe-applied flexible conductive epoxy adhesive are used to attach the cable.

1. PREPARATION:

1.1 Solder three 32-gage wires into the inner holes of the cable. The wire should extend upward approximately 1/4" to 3/8" on the stator side of the cable. (Stator side is the same side as the four bare connector pads on the opposite cable end.) Assure that the wire sticks through each hole as close to flush as possible on the side that will be opposite the stator. Keep the solder fillet to a minimum. Clip the 3 free ends of these ground wires at a slight rake angle (5-10°) from the tooth-top plane to aid in web-hole insertion. These wires will make the common return connection to the stator. Thoroughly clean both sides of soldered areas with DI water then rinse with alcohol.

1.2 Assure that the attachment area on the element surface is clean and free of any excess epoxy from the element-to-stator bond process. Use a lint-free wipe and isopropyl alcohol to clean the surface. Allow adequate time for the alcohol to evaporate before proceeding.

1.3 Remove from freezer and cut a 1/8 x ½ " wide strip of **Ablestik 5025E,** Non-carrier, 2-mil thick, flexible adhesive film. Return rest to freezer. Slice the film into the following size pre-forms for each cable: (3) 15 x 48 mil

(2) 15 x 25 mil

(1) 15 x 15 mil

The pre-forms are cut in a manner that will allow the adhesive to reside completely inside and across (length-wise) the cable windows.

1.4 Remove the **Ablestik 976-1** Syringe-applied flexible adhesive paste from freezer storage. Extrude a small amount of paste onto a clean small box lid and return the 1-cc. syringe to the freezer.

1.5 Place (then tape down) the cable, ground wires UP, on a flat surface that has a layer of Kapton or Teflon tape on it. The tape will help protect the cable surface. Under a microscope, place two (2) 15 x 25 mil pre-forms in the "sleeve" windows and one (1) 15 x 15 mil pre-form in the "chest" window. Then place the three (3) 15 x 48 mil strips lengthwise across each window. Using a flat instrument covered with Kapton tape, firmly press each pre-form down against the Kapton and window to adhere it for further handling. Remove the cable from the flat surface.

2. CABLE Assembly

2.1 Hold the stator from the teeth side, through two adjacent web holes, with a pair of holding tweezers. Carefully align the 32-gauge wires and thread them into the three web grounding holes (longest wires first) from the element side of stator. Slide the cable down onto the motor until the windows touch the PZT elements. **DO NOT** push the cable or pull the wires snug below a flat configuration.

2.2 Remove the stator and cable from the holding tweezers and place it with stator teeth UP on a rubber pad on a flat surface. Trim excess wire lengths even with the stator teeth plane. **Without pulling the wires**, bend them radially outward and down against the corresponding ribs between web holes.

2.3 Using wire-cutting tweezers, trim the bent-over wires to a length halfway out the web hole diameters. **Be careful not to knick the ribs between the web holes.**

2.4 Using a microscope, insure that the film pre-forms (inserted previously) are still present under each window and are aligned properly. Adjust if necessary. If one or more pre-forms are missing, slip another pre-form under the window tab and gently press it down. Make sure that each pre-form is completely across each window and does not extend beyond the inside or outside edge of the PZT element. Make sure the adhesive does not bridge between segments.

2.5 If there are any areas on the surface of the PZT element that require patching, use the 976-1 adhesive paste to make the patch.

2.6 If patching is required, a layer of **Teflon** (not Kapton) **tape** should be applied to the patch-side surface of the red rubber cushion (in the next step). The tape will prevent the cushion from sticking to the repaired area.

3. CURE PREPARATION STACK-UP

3.1 Place a pressure plate (milled-out area DOWN) over the threaded boss on top of a Hex brass base covered with Kapton tape. Place a red silicone rubber, rosette-holed ring cushion on top of the pressure plate.

3.2 Place the motor/cable assembly (teeth UP) on the red rubber cushion. Thread a 0-80 x 0.300" hex socket-head screw down through each center hole of the stator, cushion, and plate. Start the screw (several turns) into the base but do not tighten yet.

3.3 Be sure the BLACK edge mark on the rubber cushion aligns with the feedback element (center of cable width). Shift or rotate the cushion as far as possible in the direction of the BLACK edge mark to apply even pressure over the three windows and clear the three ground-wire solder fillets. Adjust cushion position as needed.

3.4 Using a Hex-Allen "L" wrench and being careful not to disturb the stack, run the center screw down and tighten to slip-finger tight, then ½ turn more.

3.5 Under a microscope, using a 30-gauge wire, place a small amount of 976-1 adhesive paste on the three bent-over wires to form a small fillet around each grounding hole and wire. Minimize coverage in the area toward the center hole of the stator.

Curing Stack-Up

4. CURE

4.1 Place the base and motor assemblies into a room-temperature oven. Ramp the temperature to 150° C (over 30-45 min.) and hold this temperature for 2 Hrs.

4.2 Turn OFF oven and leave the motors in the oven for a minimum of 4 Hrs. to allow the temperature to ramp down. This will prevent thermal shock, which could depole the elements.

4.3 Remove the assemblies from the oven. Carefully disassemble the stack-up. The rubber ring cushion may be lightly stuck to the cable or pressure plate.

4.4 Under a microscope, examine the PZT element edges (inside and out) below the three window connections for excess adhesive film that may have run down over the edge and formed a short to the stator. Trim any excess off with an Exacto knife.

5. The motors are ready for testing.