# USE OF PROGRAMMED PIEZO CRYSTAL FLEXURES FOR ECONOMIC VAPOR DEPOSITION OF PARYLENE HT® ON UNLIMITED LENGTHS OF MAGNET WIRE

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## KEYWORDS

High Temperature Electronics, Parylene, Magnet Wire

## ABSTRACT

The electronics industry recognizes the need for high-temperature electronics (HTE) particularly for aerospace and geothermal applications. HTE is generally defined as robust operation in temperatures up to 300ºC. A major constraint to HTE is high temperature magnet wire which is pervasive in electronic component windings and signal wire for sensors. The magnet wire constraint is caused by the temperature limits of the thin Polytetrafluoroethylene (PTFE) and Fluorinated Ethylene Propylene (FEP) coatings applied to HT magnet wire that limits the operating temperature to 220ºC. [1], [2] There are coatings, particularly parylene-based coatings such as parylene HT®, that would greatly improve HT magnet wire, signal wire, and create the potential for subminiature thermocouple (TC) sensors; however, the slow vapor deposition process required to apply parylene is generally thought impractical for use in pore-free coating of long lengths of small diameter wire. For this research, experiments were first performed coating small diameter, wire product prototypes in standard batch vacuum chambers utilizing static fixtures. Finding this approach impractical we devised a new process utilizing a piezo-crystal electrodynamically actuated fixture of 14” diameter by 18” height that supports a web of one 24,500’ long, continuous small-diameter wire. A prototype dynamic fixture was built and a trial run successfully coated a 1500’ length of 0.005” diameter copper wire with Parylene HT®. This successful demonstration was the basis for a DOL Phase I SBIR to explore the feasibility of electrodynamically actuated devises that would synchronize horizontal and vertical actuation to drive horizontal motion to the wire web to enable a continuous reel-to-reel operation for parylene vapor deposition. This is discussed in future work.

## INTRODUCTION AND BACKGROUND

An essential part of engine and turbomachinery testing is the need to route signal wire to connect imbedded sensors to data acquisition systems. SBIR research work [3] designing a miniaturized slip ring for High-Speed, High-Temperature (HSHT) operation required small diameter (<0.005”) electrically isolated wire in tight confines at 800ºF (427ºC). Finding no commercially available product, we sought a method of producing custom HT, pliable, small diameter wire. A survey of available dielectric coatings and application processes came up with half of a solution. Parylene HT® was identified as an exceptionally suitable coating in terms of its material properties but its vapor deposition application method is extremely expensive and unsuited to coating long continuous lengths of wire [4][5][6].

Specialty Coating Systems (SCS) was contracted to supervise engineering batches of small lengths of signal wire and uncoated thermoelectric wire spot welded to create small diameter uncoated thermocouples (TC’s). It proved impossible with the static fixturing used in the batch vapor deposition process to coat lengths of wire greater than 4’ in a standard vacuum chamber. The coated TC junctions which were successfully used in an engine test, however, demonstrated a flexible subminiature sensor that could be easily installed and imbedded in locations inaccessible to commercial HT, TC sensors. Thus these trials demonstrated 1) the usefulness of the product produced, 2) the impractical high cost of the product, and 3) the inability of the process to produce coated wire product of any significant continuous length. However, the potential disruptive impact on high-temperature electronics (HTE) of an economic process for slow vapor deposition coatings on unlimited lengths of wire (parylene HT®) invited further development work.

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## PARYLENE HT® AND DEPOSITION PROCESS

Parylene forms a gas impervious, micropore-free coating with a dielectric strength of 5,400 V/mil with as little thickness as 0.2 µm. Parylene HT® can be used in short-term, high temperature applications up to 450ºC after which it degrades by degenerating into an inert powder thus making it an exceptional candidate for coating magnet wire, signal wire, or thermoelectric wire (TC's) for HTE applications. The challenge barring its use is the parylene application process.

Parylene is deposited in a batch vapor deposition process which requires substrate exposure of 4-6 hours in the parylene dimer partial vacuum to deposit a 3-5 µm thickness. One of parylene's "defining characteristics" is its extreme penetration ability. "Because parylene is applied as a gas, the coating effortlessly penetrates crevices and tight areas on multi-layered components." The films are described as growing a "molecule at a time" [4].

Parylene is widely used to coat high performance *components*, mostly electrical, in medical, military & aerospace, and automotive applications. The per-component cost is driven by two things. The first is the cost of the batch time. The second is the cost of the parylene dimer. The parylene will deposit on any hermetically exposed surface within the vacuum chamber, thus it is desirable to have as much target surface area as possible per batch. Both cost drivers lead to trying to place as many components (maximizing target surface area) in each batch as possible. This is facilitated by designing static fixtures to hold the maximum possible components per batch within the typically cylindrically-shaped vacuum chambers.

## ENGINEERING TRIALS WITH STATIC FIXTURES

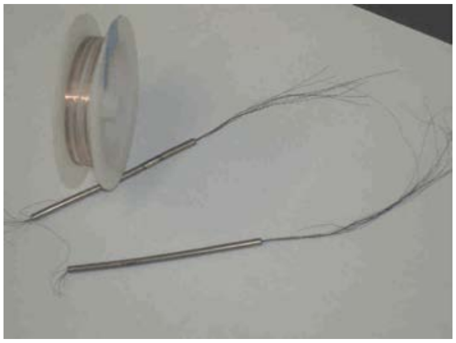


**Figure 1 – Parylene coated product from engineering trial, Top-50' spool of 0.005" dia. wire, Bottom 3' tubes with 10 wires passed through the ID.**

Three experiments were run in one engineering-batch run of parylene HT®.

**Uncoated small diameter wire TC Junctions:** TC junctions were formed by spot welding small diameter N and P thermoelectric wire. The TC's were hung in a V shape with their leads taped to a fixture toward the top of the chamber so that the junction dangled downwards in open space. This immediately demonstrated the impracticability of the process in two ways. First the lead lengths were limited to the vacuum chamber height and secondly it is very difficult to hang any economic quantity of devises in the chamber such that they do not contact each other.

*Results:* Several of the TC's became unattached from their fixture and fell to the base of the vacuum chamber during the trial run. This was ascribed to the extreme penetrating power of the parylene vapor as it coats any hermetically exposed surface and often insinuates itself under vacuum tape and lifts it off. The surviving TC's were successfully used in an engine test that showed the usefulness of these subminiature flexible TC's if there were a practical way to make them. The most practical way to make them would be to devise a process of coating unlimited lengths of thermocouple wire and making TC's on demand with lead lengths as required to the application.

**50' spool of 0.005" diameter copper wire (fig.1):** It was speculated that the extreme penetrating power of the parylene vapor might allow coating of spooled wire directly.

*Results:* The 50' spooled wire represented overlays of wire only 2-3 deep which would be miniscule compared to spools containing any quantity of wire. The result was that while the parylene appeared to penetrate everywhere, it fused wire to wire and wire to spool at their contact points. This was considered an unacceptable result as the integrity of coating at spots where fused wire had to be separated was questionable.

**Strands of uncoated wire through long, small inside diameter tubes (fig. 1):** In this experiment two 3' tubes with 0.085" ID's were packed with 10 each of 0.005" OD uncoated wire. This experiment again tested the penetrating power of the parylene vapor.

*Results:* After coating, the wire bundles were "wrung out" electrically for shorts to each other or to the tube that they were coated in. Only one wire was found to short to the tube. The tubes were then heated to 800°F (427ºC) for one hour and retested. The result was the same as before heating where only one wire had a short. This demonstrated both that ability of parylene HT to operate at 800 °F and the extreme penetration power of the parylene vapor since the midpoints of the tubes represented a 211:1 length to diameter ratio and each tube was packed with ten 0.005" OD wires so that the coating had to follow a very long and tortuous hermetic path.

**Overall results and conclusion:** The three experiments combined indicated that in a static situation continuously coated lengths of wire could only be assured where the wire could be kept from contact with other wire or the static fixture. They also showed that, for use as TC's, magnet wire, or signal wire, an economic method would have to be devised to coat long lengths of wire. If a continuous long length of wire were to be coated in the confined area of a vacuum chamber, the length of the wire, the required exposure time, and the coating cost all indicate that a high density web of wire would have to be contained in the vacuum chamber so that static contact is never made between the wire to itself or to any static structure. This means that either the fixture containing the wire web, or the wire, or both must be in near constant motion.

## DEVISING THE DYNAMIC WIRE WEB

The fundamental design challenges to coating long lengths of wire are:

(1) A great quantity of wire has to reside in the vacuum at all times both for economics and to accommodate the long exposure time necessary for the slow deposition process.
(2) The wire resident in the vacuum cannot have long contact time with itself or with any fixturing that can cause the coating to fuse and disturb the integrity of the coating when the wire is pulled apart and removed.
(3) The extreme penetrating power of the vapor will coat any hermetically exposed surface and potentially foul any mechanism in the vacuum such as bearings, wheels, or motors.
(4) Small diameter copper wire has low tensile strength (less than 1lb).

Many ideas were proposed and rejected and it was supposed that the design challenges were innately insurmountable. For example, any static fixture supporting a long length of wire can be rejected out of hand for violating (2). The ideas of having fixtures and mechanisms that keep the wire continuously moving so as to avoid (2) invariably come up against (3) and (4). Reel-to-reel (R2R) processes in addition to adding the necessity of vacuum pass-thru's still have to meet (1) so that a large serpentine of moving wire must be supported in the vacuum, again coming up against (3) and (4).

Finally the idea emerged to consider using fixture vibratory motion with stationary wire rather than wire motion in a static fixture. It was reasoned that if the fixture supporting the wire vibrated with accelerations exceeding gravity, the wire would spend most of its time in space and hence with the "molecule at a time" nature of the vapor deposition it would not fuse with the fixture thus overcoming (2). Further if the fixture were made to support a very long length of wire to form a wire "web", it would fulfill (1). Then it was further supposed that if the vibration were instigated by inertial piezo stack expansion and contraction, (3) and (4) could be overcome.

The final concern was how to configure the web fixture to make it practical to string the long wire into the web. This was answered with a system of interlocking struts as shown in fig. 3. In this system struts are first inserted into the circular base plate to form a circular row toward the center of the baseplate. The base plate is placed on a lazy Susan so that it can be rotated to wind wire along the circular row of struts from a spool of wire. Each strut has notches spaced along its length that point outward creating a shelf for winding many rows of wire along its length. Once the inner-most circular row of struts is wound another circular row of struts is inserted. The struts are designed (fig. 3) so that the inner diameter side of each circular row of struts closes off the grooves of the previous circular row of struts enclosing the inner wound wire in a spatially generous window.

As designed in fig. 2, a dynamic wire web having a 14" diameter and 18" height that fits easily into a small vacuum chamber would accommodate 24,500' of wire. The surface area of 0.005" OD wire would be 4,618 in$^2$ while the surface area of tank walls of a 16" diameter by 20" high vacuum chamber would only be 1,709 in$^2$. Thus the ratio of target surface area to vacuum chamber area is about 2.7:1.

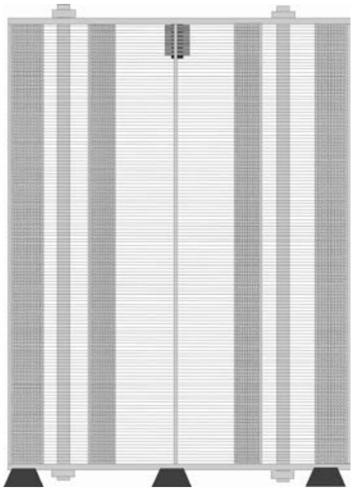


**Figure 2 – Dynamic wire web**

## PROTOTYPE DYNAMIC WIRE WEB TRIAL

### Construction and Test

A smaller version of the dynamic wire web concept shown in fig. 2 was constructed. Fig. 3 shows the interlocking struts being set into the base. Fig. 4 shows wire being wound onto the web. Once wound, the central cylinder shown in fig. 4 is removed and the top plate, also visible in fig. 4, is placed on top of the struts locking everything into place.

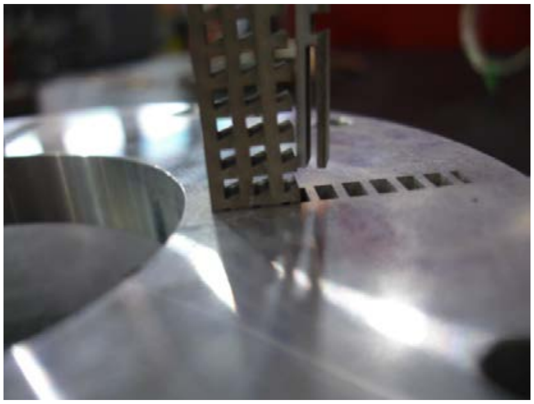


**Figure 3 – Interlocking struts**

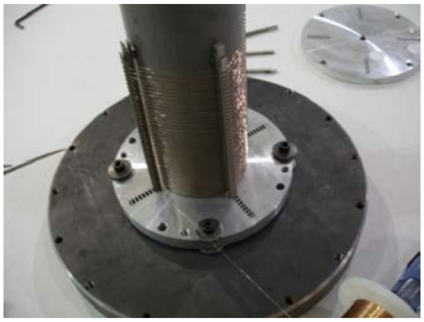


Figure 4 – Winding the Web

Fig. 5 shows acceleration testing of the web structure (minus struts and wire) with a laser vibrometer and three-axis accelerometers. The piezo crystal electrodynamic actuator is shown mounted to the top plate in fig. 5. During actual operation in a vacuum chamber it is mounted so that it hangs down from the top plate occupying the space in the ID of the web. Fig. 6 is the acceleration-frequency sweep of the web structure as measured by the laser vibrometer and accelerometers. The piezo stack actuator was able to achieve about 60 g's of fixture acceleration at its apparent natural frequency of 3500 Hz.

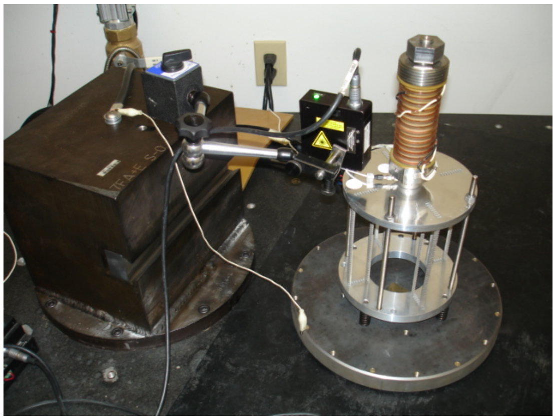


Figure 5 – Acceleration testing

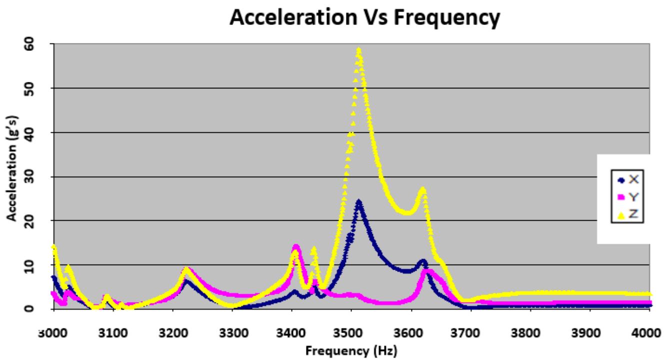


Figure 6 – Web structure acceleration

**Parylene Application Trial**

1500' of bare copper 0.005" wire was loaded onto the dynamic web. A vacuum chamber witness port was replaced with a port that allowed pass through of power for the piezo dynamic actuator and sensor signals. Accelerometers were installed on the upper and lower plates of the dynamic web and a TC was placed on the actuator to monitor its operating temperature.

There were a number of concerns that we hoped that the engineering run would answer. Among these were:

- Would the actuator excite the web fixture with greater than 1g acceleration as it accumulated parylene coating?
- Would the actuator heat up due to lack of convective cooling in the vacuum or would radiant and conductive cooling be sufficient?
- Would the rubbing of parylene on parylene cause static electric build up sticking the wires to the fixture or each other?

Table 1 – Temperature and acceleration monitoring data

**Parylene Application Trial**

| Time | TC °F | Top Accel g's | Lower Acel g's |
|---|---|---|---|
| Initial | 104.3 | 21.8 | 20.5 |
| 30 min | 101.1 | 24 | 19 |
| 60 min | 94.6 | 6.3 | 20.5 |
| 90 min | 92.6 | 37.2 | 20.6 |
| 120 min | 92.1 | 36 | 29 |
| 140 min | 89.6 | 36.2 | 30.8 |
| Final | 88.5 | 26.3 | 18.3 |

As indicated by the monitoring data shown in table 1 the actuator did initially heat up slightly but then cooled to a steady-state temperature of around 89ºF (32ºC). Also accelerations were well beyond 1g for the entire test. The trial run took over 12 hours and a witness strip placed in the chamber indicated that about 5 µm coating thickness was achieved. In the main the wire came off freely from the web structure showing no adherence or fusion. The only minor disappointment was that wire fused to wire in 6 locations so that in pulling it apart the coating was felt to be compromised. This could be fixed in the future by allowing less slack in the wire. Resistance checks where made from point to point along the wire with all showing open line resistance. Overall for the 1500' of wire, the run was felt to be a success demonstrating the feasibility of producing very long lengths of parylene HT coated magnet wire or thermocouple wire.

## DEVISING DYNAMIC WIRE MOTION FOR R2R

Given that the feasibility of vapor coating long lengths of wire in a batch process was demonstrated, the next step is to explore the feasibility of converting the batch operation to a continuous reel-to-reel (R2R) process. However, to accommodate the required R2R horizontal wire velocity, our previously mentioned four fundamental design challenges reemerge. The ingenuity of the dynamic web concept is that prolonged static contact between the wire and the fixture is avoided by the vertical oscillation of the fixture which keeps a long length of wire mostly suspended in space for its retention time in the vacuum. The length of the wire that must be accommodated by the web is determined by the R2R wire speed as incoming wire must reside in the vacuum 4 hours before exiting. Pulling the long length of wire through a complex web serpentine is challenged by the wire's low tensile strength. Also any propelling or friction reducing mechanisms within the vacuum invite fouling due to parylene penetration.

Fortunately, modern sophisticated motor controls are available that can operate in a constant low torque mode (regardless of velocity) to accommodate the low tensile strength of the wire, but such low torque "tugging" of the wire by the take up reel will not generate significant velocity. *Therefore the challenge is to get the dynamic web itself to generate the horizontal motion.*

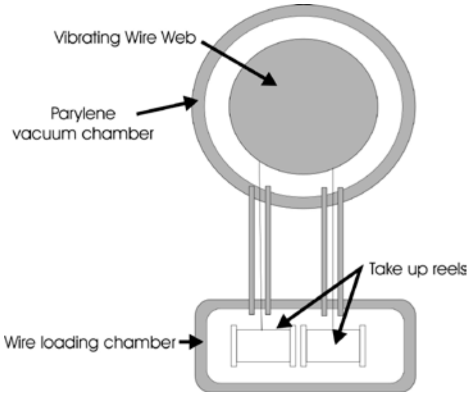


**Figure 7 – Reel-to-reel system with dynamic wire web**

### Synchronized horizontal and vertical motion concept

This approach henceforth examined, explores using piezo-stack driven flexures to create synchronized horizontal and vertical motion in the web. Piezo stacks are commercially available that multiply the expansion and contraction of piezo crystals to a given voltage by stacking them between electrodes. Piezo crystals are better at expansion than contraction so they are generally mated with some kind spring system that provides a contraction force when the excitation voltage is lowered. Many stacks come with position feedback.

Piezo stacks placed in flexures with springs can provide kinematic mechanisms that can leverage the piezo stack expansion/contraction motion without any independent moving parts, joints, wear, or lubrication, thus making them ideal candidates for placement within the deposition vapor. Dynamic piezo-actuated, flexures have been used for nano-positioning, and have been leveraged for longer "stroke motion". Electronic amplification systems have been designed to capture the "circulating" power of the flexures as they go through expansion and spring retraction cycles. [9], [10], [11], [12].

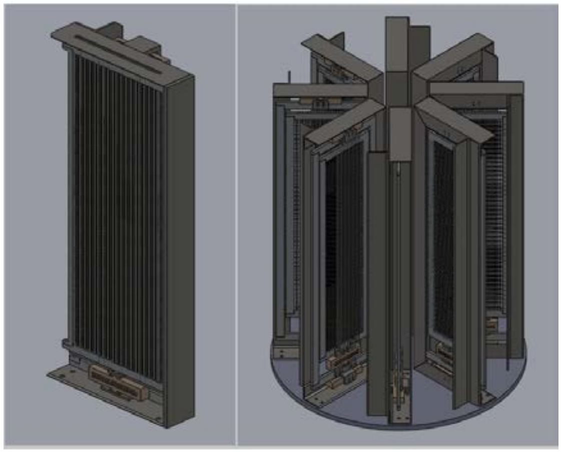


**Figure 8 - Independent acting frames**

### Tandem dual overlap motion

The vertical motion of the frame provides the same function as it did in the dynamic wire web structure, that is, it keeps wire mostly suspended in space so that it can receive continuous coating without fusing to the fixture. In this case however, there is also synchronized horizontal motion. The horizontal motion goes "forward" at the desired wire horizontal velocity when the wire is in contact with the frame and resets itself "backwards" while the wire is in space. Thus it is envisioned that the frame will generate forward horizontal velocity in the wire in the same way as slip-stick vibratory bowels or as "walking beam" mechanisms. The dual overlap concept is the idea of having 2 frames working in concert so that one is up and moving forward while the other is down and resetting. And thus the wire is always resting on a frame going forward at the desired horizontal R2R velocity.

### Flexure kinematics

As expected, there appears to be no suitable commercially available flexures. Economic calculations were made that indicated a target horizontal R2R velocity of 40"/s. For design a piezo-stack with a total stroke of 0.010" was chosen. To be practical, this had to be highly leveraged so that the horizontal flexure would have a stroke of 0.100". The kinematic diagram for the horizontal flexure is shown in fig. 9. The kinematic diagram includes springs so that the fixture kinetic energy is kept in the system as the motion reciprocates. Calculations based on weight estimates of the wire and fixture indicate that the piezo stack cannot generate enough force to accelerate to the R2R velocity in a single cycle. A simulation of the horizontal drive velocity is shown in fig. 10. It predicts that it will take 17 cycles or about 0.18 s to achieve full speed. Fig.11.

shows the steady state drive cycle and fig. 12 shows dual tandem steady-state cycles.

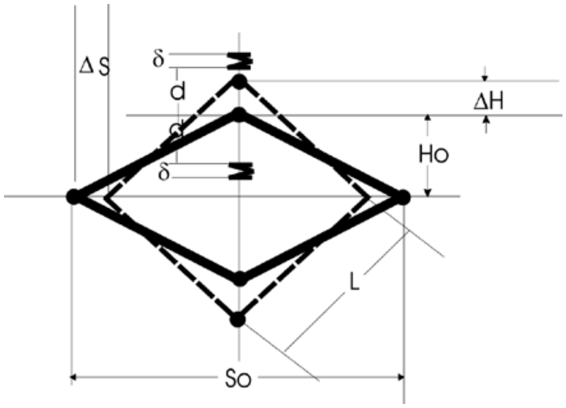
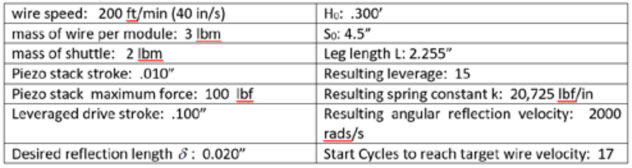


Figure 9 – horizontal flexure kinematic diagram

Table 2 – Kinematic diagram specifications



| | |
|---|---|
| wire speed: 200 ft/min (40 in/s) | H₀: .300′ |
| mass of wire per module: 3 lbm | S₀: 4.5″ |
| mass of shuttle: 2 lbm | Leg length L: 2.255″ |
| Piezo stack stroke: .010″ | Resulting leverage: 15 |
| Piezo stack maximum force: 100 lbf | Resulting spring constant k: 20,725 lbf/in |
| Leveraged drive stroke: .100″ | Resulting angular reflection velocity: 2000 rads/s |
| Desired reflection length $\delta$ : 0.020″ | Start Cycles to reach target wire velocity: 17 |

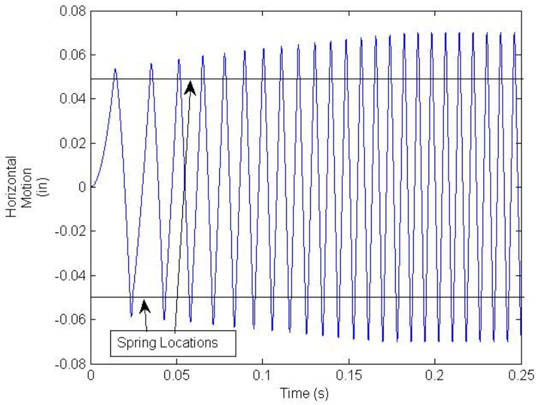


Figure 10-Horizontal time-displacement simulation

Table 2 shows the piezo stack specifications, spring constants and required flexure dimensions. None of which are unreasonable.

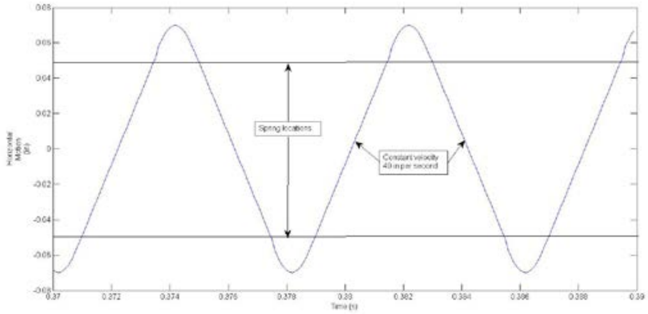


Figure 11-Steady state horizontal motion after 17 cycles

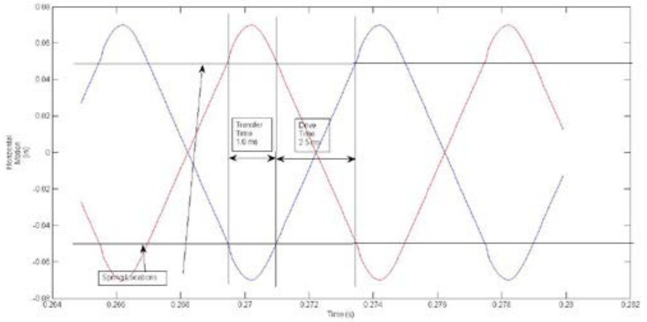


Figure-12 Dual horizontal flexures working in tandem

The kinematic diagram for the vertical motion generating flexure is shown in fig. 13 and works in a unique way. Its piezo actuator pushes it to its “up” position working against springs. When the time comes for the horizontal actuator to reset, the actuator is turned off and the springs drop it at greater than gravity acceleration and it bounces against the lower springs. Its motion is illustrated in fig. 14. The motion of tandem vertical actuators is shown in fig. 15.

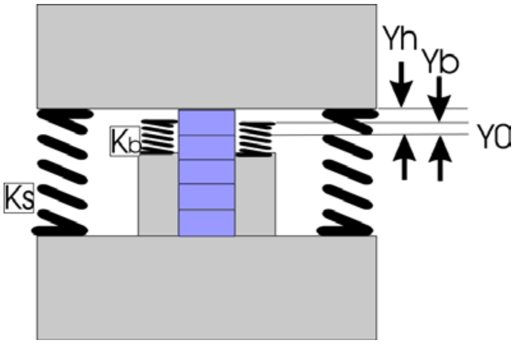


Figure 13-Kinematic diagram of the vertical motion generating device

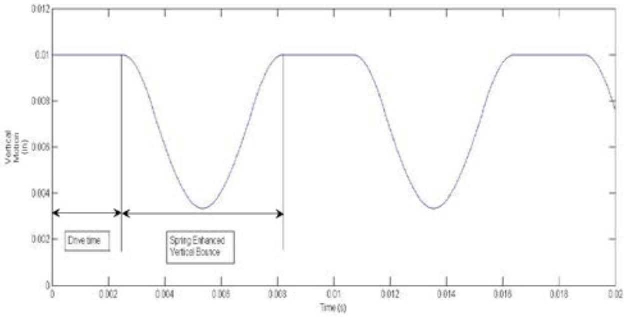


**Figure – 14 Vertical motion**

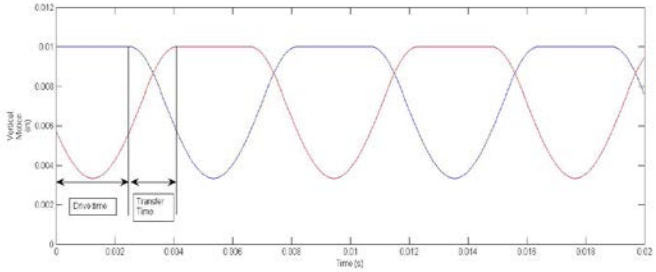


**Figure – 15 Dual vertical devices working in tandem**

Fig. 16 shows the combined duel overlap shuttle motion. Note how much larger the horizontal motion is compared to the vertical motion.

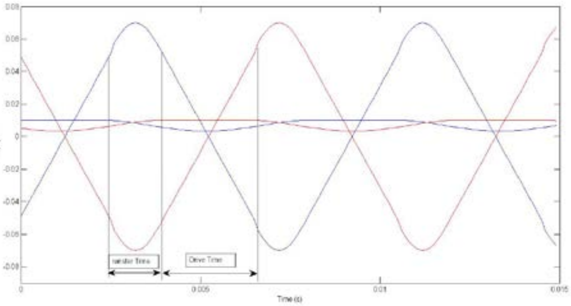


**Figure-16 Combined horizontal and vertical motion**

## Light weight shuttle/comb system

A concept for reducing weight and cost and adding flexibility is to break down the independent acting frames into a shuttle comb system. Only the motion of the horizontal members of the web frame motivate the wire while the vertical members serve only to separate the wires. Thus considerable weight can be removed from the dynamic portion of the frame if it is broken into a dynamically activated "shuttle" with only light weight horizontal wire separators as shown in fig. 18 and stationary combs performing the vertical separation. A combination of two dual overlap shuttles and two combs is shown in fig. 18. The weight of the dynamic part of the shuttle is estimated to be less than a pound.

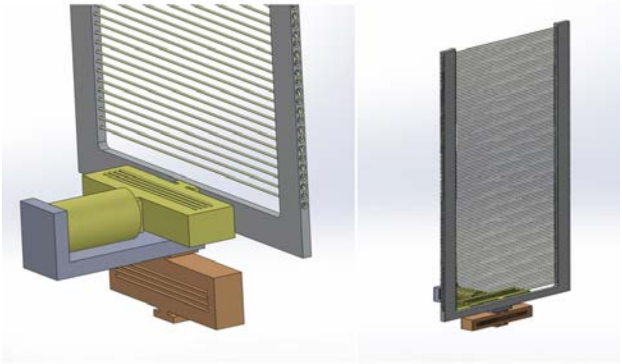


**Figure-17 Light weight shuttle system**

**Figure-18 Tandem shuttles combined with 2 combs**

## The complete system

The complete system is shown in fig. 19. It consists of a R2R system which is powered by DC motors controlled at constant torque keeping excess, wire slack from occurring in the wire web with the wire speed controlled by the dual-overlap, dynamic excitation of the shuttles so that the take-up reel is merely collecting the coated wire being fed out of the wire web rather than pulling the wire through the web. As the reels rotate, they generate horizontal motion distributing the wire evenly across the reel. Also shown are thin-tube wire pass-thru ports with pressure connections back to the system roughing pump. The only part not shown is the parylene vapor generation system and vacuum system.

Thus, this relatively compact and inexpensive system is made to work with standard parylene vapor generation equipment and a standard batch-size vacuum chamber and is designed to produce unlimited lengths of parylene HT® coated wire at 200ft/min (40in/s).

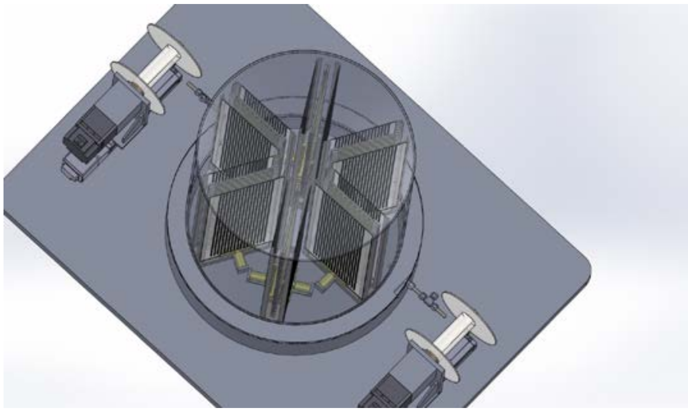


Figure-19 The complete system

## CONCLUSION

The value of being able to coat unlimited lengths of small diameter wire utilizing a vapor deposition process such as for parylene products, especially parylene HT®, has been established. Such a process would open the way for subminiature TC sensors, small diameter, pliable signal wire for testing in HT and chemically harsh environments, and lastly for HT windings meeting HTE goals of 300ºC.

Despite the apparent impracticalities of such a process, use of a piezo actuated, high density wire web structure has been devised, built, and demonstrated creating a batch of a significant length of 0.005" OD parylene HT® wire.

Building on the demonstrated batch process a continuous R2R process has been devised that promises to create a compact, relatively inexpensive process that works with standard batch-size vacuum systems to produce parylene coated wire at a rate of 200'/min.

## FUTURE WORK

Development of the devised R2R system requires the development of three major subsystems: a torsion-controlled R2R wire take-up feed system, a wire vacuum pass-thru system, and the motion-generating, dynamic high-density wire web system. The first two items are almost certainly practicable with existing technology. The motion-generating dynamic high-density wire web system is based on using piezo stack controlled flexures to create synchronized horizontal and vertical motions designed to generate a subminiature "walking beam" R2R velocity in the wire web. It is the most speculative and challenging part of the system and the success of the system depends on it. Therefore, future work would concentrate on this system which could be developed on a bench top outside the vacuum system. It is obvious next task.

## ACKNOWLEDGMENTS

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