Acoustic Mechanical Feedthroughs

Stewart Sherrit, Phillip Walkemeyer, Xiaoqi Bao, Yoseph Bar-Cohen, Mircea Badescu
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr. Pasadena, CA, 91109-8099

Abstract – Electromagnetic motors can have problems when operating in extreme environments. In addition, if one needs to do mechanical work outside a structure, electrical feedthroughs are required to transport the electric power to drive the motor. In this paper, we present designs for driving rotary and linear motors by pumping stress waves across a structure or barrier. We accomplish this by designing a piezoelectric actuator on one side of the structure and a resonance structure that is matched to the piezoelectric resonance of the actuator on the other side. Typically, piezoelectric motors can be designed with high torques and lower speeds without the need for gears. One can also use other actuation materials such as electrostrictive, or magnetostrictive materials in a benign environment and transmit the power in acoustic form as a stress wave and actuate mechanisms that are external to the benign environment. This technology removes the need to perforate a structure and allows work to be done directly on the other side of a structure without the use of electrical feedthroughs, which can weaken the structure, pipe, or vessel. Acoustic energy is pumped as a stress wave at a set frequency or range of frequencies to produce rotary or linear motion in a structure. This method of transferring useful mechanical work across solid barriers by pumping acoustic energy through a resonant structure features the ability to transfer work (rotary or linear motion) across pressure or thermal barriers, or in a sterile environment, without generating contaminants. Reflectors in the wall of barriers can be designed to enhance the efficiency of the energy/power transmission. The method features the ability to produce a bi-directional driving mechanism using higher-mode resonances. There are a variety of applications where the presence of a motor is complicated by thermal or chemical environments that would be hostile to the motor components and reduce life and, in some instances, not be feasible. A variety of designs that have been designed, fabricated and tested will be presented.

Keywords: Actuators, Piezoelectric Devices, Acoustic Mechanical Feedthroughs, Feedthru

INTRODUCTION

In previous work we looked at the potential to transmit electrical power by converting it to mechanical power in the form of a stress wave which propagates across a structure and then is converted back to an electric power via piezoelectricity. A variety of situations exist where power or information is required to be transmitted across a physical barrier without perforating the barrier. If the barrier material is thin or transparent to electromagnetic waves in the frequency of interest this can be accomplished optically or with magnetic coupling. If on the other hand this is not the case then other means are required to accomplish this task. The idea of using elastic or acoustic waves to transfer useful power was initially suggested by Y. Hu, et al.[1]. In the system they investigated a transmit and receive piezoelectric transducer were separated by a sealed armor (wall). A sinusoidal voltage is applied across the transmitting piezoelectric at a known frequency generating acoustic waves that travel through the armor into the receive piezoelectric where the stress wave generated a sinusoidal voltage. This approach has been used to transmit up to 1 kW power with up to 87% efficiency[2],[3],[4],[5]. In other recent papers[5], [6] we developed a single actuator rotary hammer drill where we designed ultrasonic horns to produce both a rotation and hammering in the base of the drill bit. The prototype actuator is shown in Figure 1 along with the FEM model. The groves in the horn cause the tip of the horn to extend and twist at the resonance frequency of the actuator (12 kHz). The bit is vibrated and spins at substantial rotational speeds up to 200 RPM. After designing, building and testing the horn shown in Figure 1 we realized that horn has a nodal plane for mounting and that this is a position of minimal displacement and we could treat the nodal plane like a wall. This means that the Single Piezo-Actuator Rotary-Hammering Drill SPARHD drill was in effect an existence proof of the idea of pumping mechanical energy across a structure to do useful mechanical work. In the rest of the paper we discuss the design of resonant structures that can create high frequency displacements that can be used to rotate a rotor or move a linear stage. Useful work is done directly on a rotor or linear stage without first converting to electric power. A similar configuration to the one we described is shown schematically in Figure 2. In the configuration shown a backing layer has been added to the system in an effort to increase the efficiency by moving the acoustic energy towards the stator. Although one could model this using the wave equation directly an alternative approach based on network equivalent circuits[7],[8] can easily be modified to account for the resonant structure and for additional acoustic elements. All the possible loss mechanisms of the solution can be accounted for and introduced into the model by using complex coefficients. The circuit model allows for the calculation of power and both linear and angular displacements in the forward direction. This system allows for the avoidance of cabling or wiring or perforating the structure. The technology is applicable to situations where the transfer of mechanical power for actuation or other tasks inside sealed containers and vacuum/pressure vessels is required, or where perforating the structure or operating in the internal environment is prohibited. A schematic diagram of the model for the system shown in Figure 2 and a generic network model for this system is shown in Figure 3.

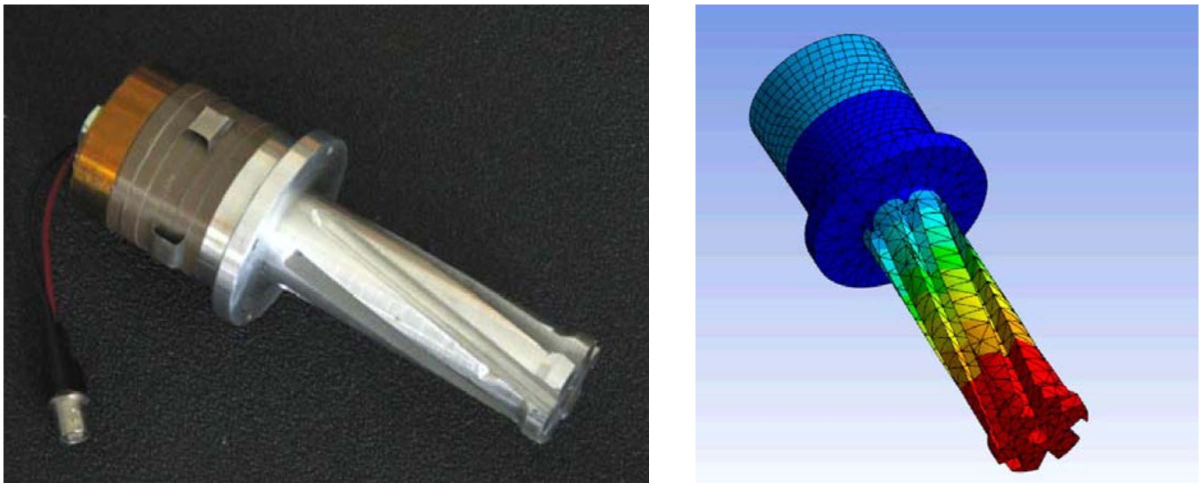

Figure 1. Photograph of the webbed horn actuator (left). Angled cuts extend only partway through the horn to leave a webbing ring connecting individual horn tines. A Finite Element Modal analysis of selected transducer design (right). Dark blue represents areas of minimal motion at resonance, while red as see at the tip represents areas of maximum displacement. The angled cuts in the horn cause the tip to rotate counter-clockwise as it extends in resonance.

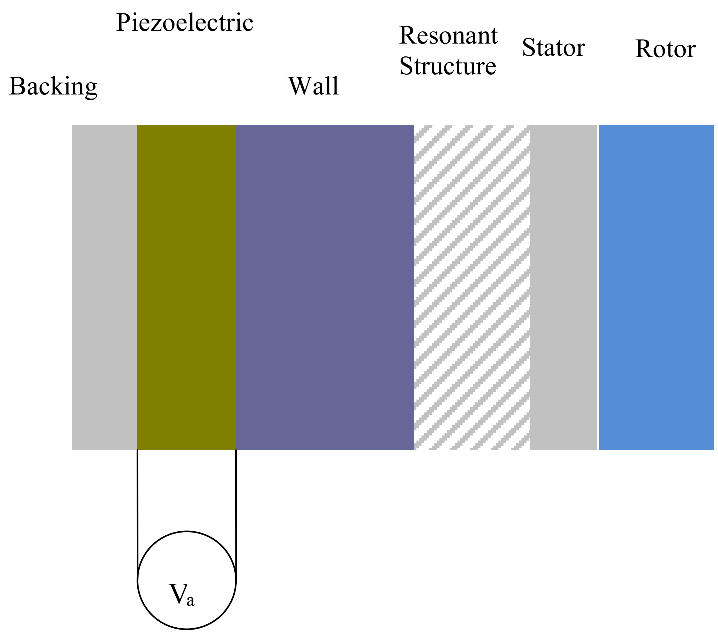

Figure 2. Schematic of the acoustic-mechanical feed through system with a piezoelectric generator and resonant structure on the other side of the wall to produce rotary motion. The acoustic wave is converted to twisting motion at the stator and this drives the rotor.

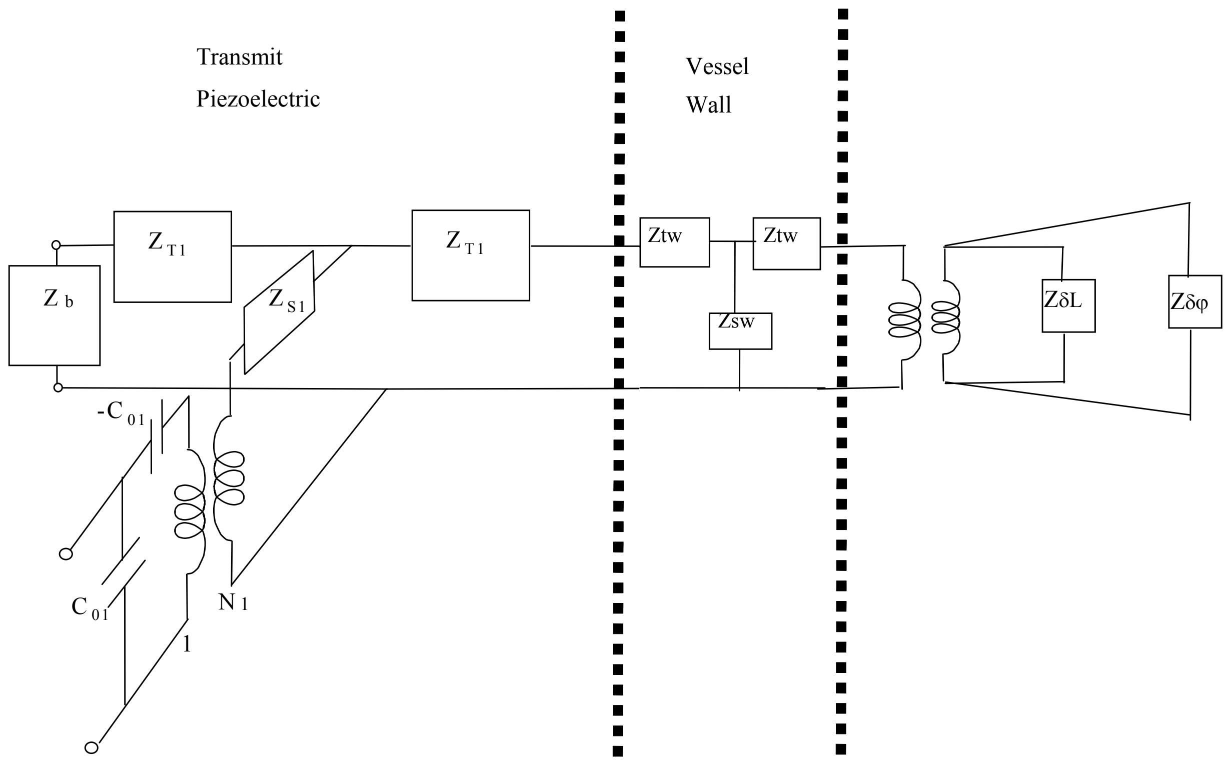

Figure 3. Schematic of the network equivalent circuit for the physical system shown in Figure 2. The delivered power is consumed in the impedance of the piezoelectric and converted to stress waves. The stress waves travels across the wall were it is converted to extension of the stator surface into the rotor (ZδL -friction) and angular movement of the stator with respect to the rotor (Zδφ -rotation).

The model parameters for the network circuit shown in Figure 3 are listed in Table 1. These models have been widely used for backed/matched and mass loaded resonators[9], transient response[10], material constant determination[11], and a host of other applications[12].

In previous work we have shown that the Mason's equivalent network models produced results identical with the solution to the wave equation in layered structures[7] if the loss was treated in a similar fashion for each model. The solution to the model proceeds as with any network solution. In this representation, the voltage on the mechanical side of a transformer corresponds with the force and the current corresponds with the velocity of the surface. Voltage is multiplied by the transformer ratio N when moving from the electrical to mechanical side of the transformer while the current is divided by N. When moving from the mechanical side to the electrical side the voltage is divided by the transformer ratio N and the current is multiplied by N. These models can be used to guide the FEM design and characterize Acoustic Mechanical Feedthroughs. The current through the output impedance is related to the speed of the specific displacement. The current through the ZδL is proportional to the speed of the linear displacement at the surface of the resonance structure while the current through Zδφ is proportional to the twist velocity. It is clear that we require the resonance structure to engage the rotor to create friction and then to twist to drag the rotor and finally move back releasing the friction and resetting the twist. This means the surface displacement should undergo an elliptical motion at the contact point between the stator and the rotor or an off angle extension that always produces a clockwise or counterclockwise rotation as is shown in Figure 4. The top section is a rotor that is mechanically engaged to the horn via a spring. The bottom section is an ultrasonic horn that has been designed to have off angled extension at the contact points or elliptical motion.

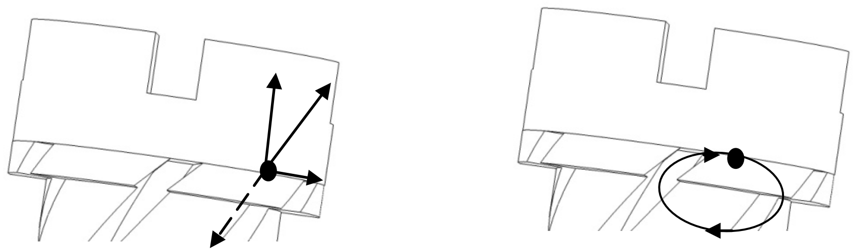

Figure 4: View of the two potential horn motions (helical extension or bending) that can develop an extension and torque at a point (black dot) on a rotor. Black arrow and ellipse show contact. Contact pushes the rotor up and drags it to right in each case. The normal force is much lower on retraction or on the bottom portion of the ellipse. The net force on the left can produce a prolonged rotation of the rotor as well. The bending ellipse shown on the right produces a rotation. A mode that rotates in the opposite direction around the ellipse would induce reverse rotation.

Table 1. The coefficients and model parameters of the network equivalent shown in Figure 2.

Material Properties	
$\boldsymbol{\varepsilon}_{33}^{T}$ effective free complex permittivity	
$\mathbf{s}_{33}^{E}$ effective short circuit complex elastic compliance	
$\boldsymbol{k}_{33}$ complex electromechanical coupling	
$\boldsymbol{k}_{33}^{2} = \boldsymbol{d}_{33}^{2} / \mathbf{s}_{33}^{E}\boldsymbol{\varepsilon}_{33}^{T}$	
$\boldsymbol{d}_{33}$ effective piezelectric charge coefficient	
Mason's Model (Generator) ρ=density, t= thickness, A=area	
$\mathbf{C}_{01} = \dfrac{\boldsymbol{\varepsilon}_{33_1}^{S} A_1}{t_1}$	$\mathbf{N}_1 = \mathbf{C}_{01}\boldsymbol{h}_{33_1}$
$\boldsymbol{Z}_{01} = \rho_1 A_1 \mathbf{v}_{\mathbf{1}}^{\mathbf{D}} = A_1\sqrt{\rho_1 \mathbf{c}_{33_1}^{D}}$	$\boldsymbol{\Gamma}_1 = \dfrac{\omega}{\mathbf{v}_{\mathbf{1}}^{\mathbf{D}}} = \omega\sqrt{\dfrac{\rho_1}{\boldsymbol{c}_{33_1}^{D}}}$
$Z_{T1} = i\mathbf{Z}_{01}\tan(\boldsymbol{\Gamma}_1 t_1 / 2)$	$Z_{S1} = -i\mathbf{Z}_{01}\csc(\boldsymbol{\Gamma}_1 t_1)$
Wall Properties ρ=density, t= thickness, A=area	
$Z_{tw} = i\mathbf{Z}_w \tan(\boldsymbol{\Gamma}_w t_w / 2)$	$Z_{sw} = -i\mathbf{Z}_w \csc(\boldsymbol{\Gamma}_w t_w)$
$\boldsymbol{Z}_w = \rho_w A_w \mathbf{v}_{\mathbf{w}}^{\mathbf{D}} = A_w\sqrt{\rho_w \mathbf{c}_w^{D}}$	$\boldsymbol{\Gamma}_w = \dfrac{\omega}{\mathbf{v}_{\mathbf{w}}^{\mathbf{D}}} = \omega\sqrt{\dfrac{\rho_w}{\boldsymbol{c}_w^{D}}}$
backing properties ρ=density, t= thickness, A=area	
$Z_b = i\mathbf{Z}_R \tan(\boldsymbol{\Gamma}_R t_R)$ termination impedance	
$\boldsymbol{Z}_R = \rho_R A_R \mathbf{v}_{\mathbf{R}}^{\mathbf{D}} = A_R\sqrt{\rho_R \mathbf{c}_R^{D}}$	$\boldsymbol{\Gamma}_R = \dfrac{\omega}{\mathbf{v}_{\mathbf{R}}^{\mathbf{D}}} = \omega\sqrt{\dfrac{\rho_R}{\boldsymbol{c}_R^{D}}}$

An example of a potential application is shown in Figure 5. An actuator on the outside of a pipe that can be bolted on or removed when not in use is excited electrically at a predetermined frequency. The actuator generated stress waves that travel into the resonant structure and the high frequency micro displacements rotate the rotor which may be used to control a valve or port. No electrical leads are required inside the pipe. As well, the resonance structure does not require insulation or magnetic materials that can have issues operating in caustic or high temperature environments.

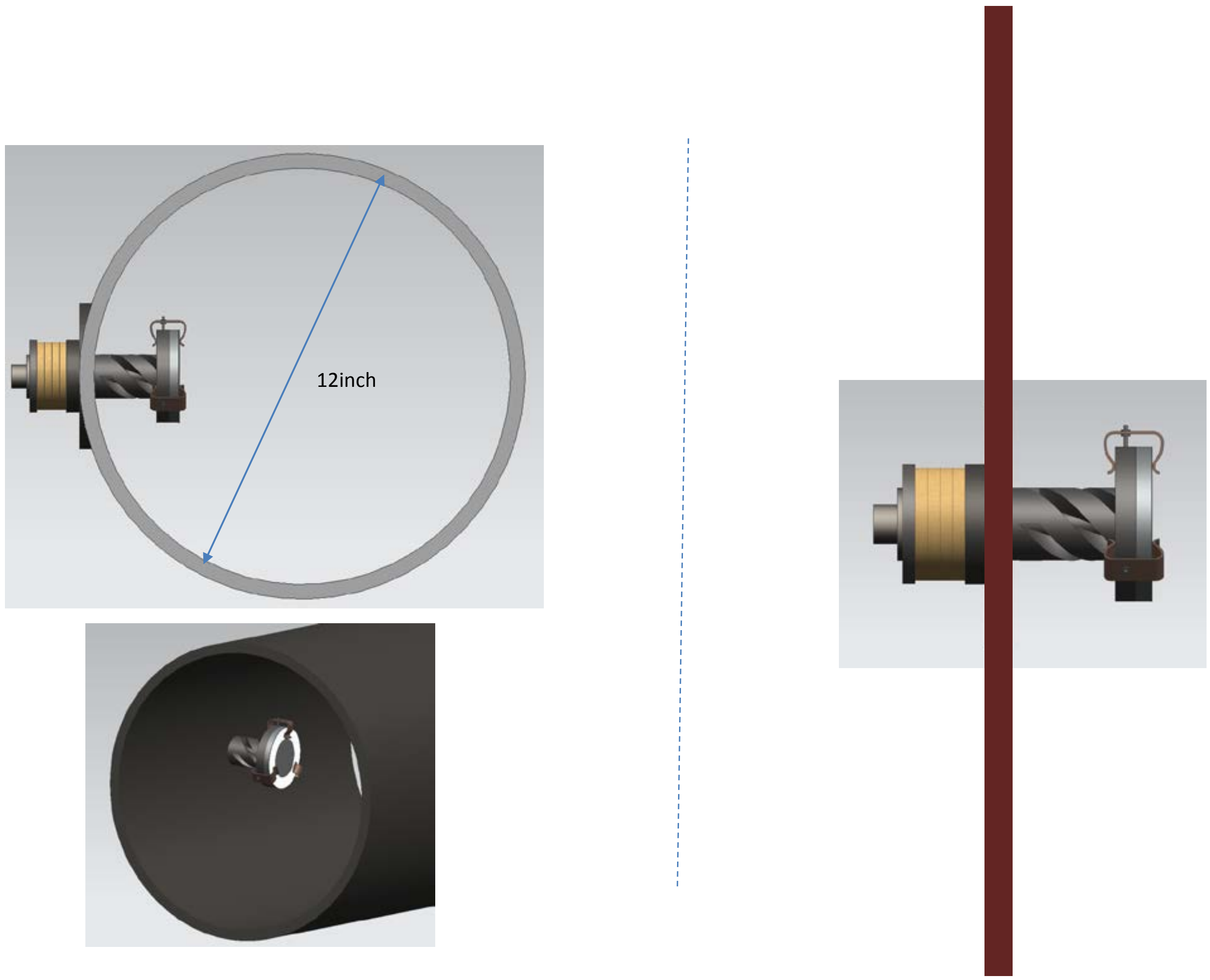

Figure 5: View of a potential application for the Acoustic Mechanical Feedthrough. The left figure shows an actuator on the outside of the pipe. The acoustic wave excites the horn inside the pipe which causes the rotor to turn. The figure on the right shows a similar structure on a planar wall.

RESULTS

In order to evaluate the utility of this approach we looked at older methods of producing ultrasonic motors and found the Kumada motor design[13],[14] highly adaptable to produce the required motion across the structure. The motor has a body and a slot cut into the body that causes a twisting motion and extension motion in bars that are 90 degrees out of phase and in contact with the rotor. By adjusting the slots, bar and the length of the body one can match the resonance in the actuator such that sufficient rotation occurs in the rotor. The first design that produced the correct motion is shown in Figure 6. In order to get the motion required we increased top plate thickness, increased the thickness of 45deg bar and increased its height. The contact area of the connecting pads was also increased while the thickness of the slot separating the top plate from the base of the horn was decreased. The PZT

(Lead Zirconate Titanate) stack was shortened. The second design we investigated that produced the correct motion is shown in Figure 7. It is called the 4 bar stator. The design is similar to the Kumada horn but has 4 bars that produce a more stable stator. The final design that we tested is shown in Figure 8 and is called the flexure finger design.

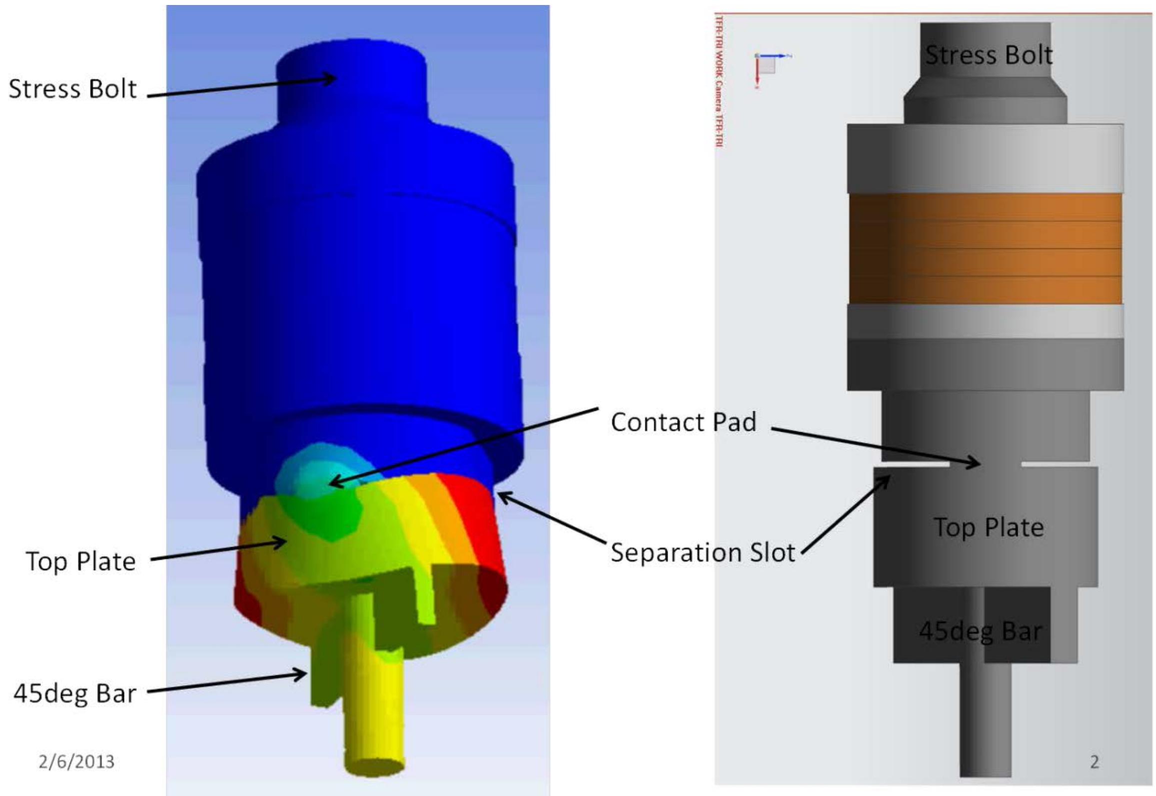

Figure 6: View of the Kumada design. The bar is at 45 degrees to the slot. FEM modal simulations showed the appropriate elliptical motion at about 16 kHz.

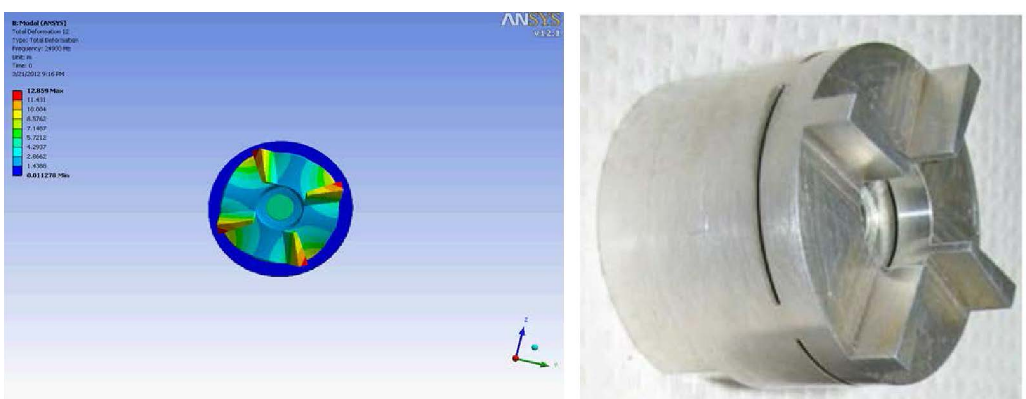

Figure 7: Head on view of the 4 bar stator design. FEM modal simulations showed the appropriate elliptical motion at about 25 kHz. Photograph of the fabricated 4 bar stator part.

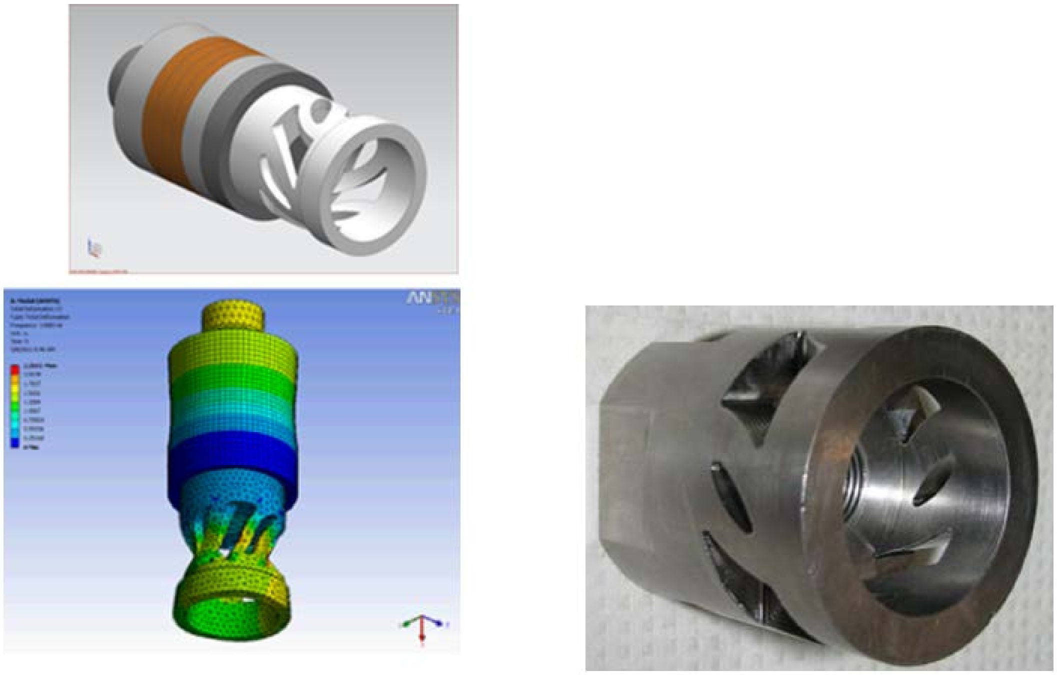

Figure 8: CAD view of the flexure finger stator design. FEM modal simulations showed the appropriate elliptical motion of a point on the horn tip at about 15 kHz. Photograph of the fabricated flexure finger stator horn.

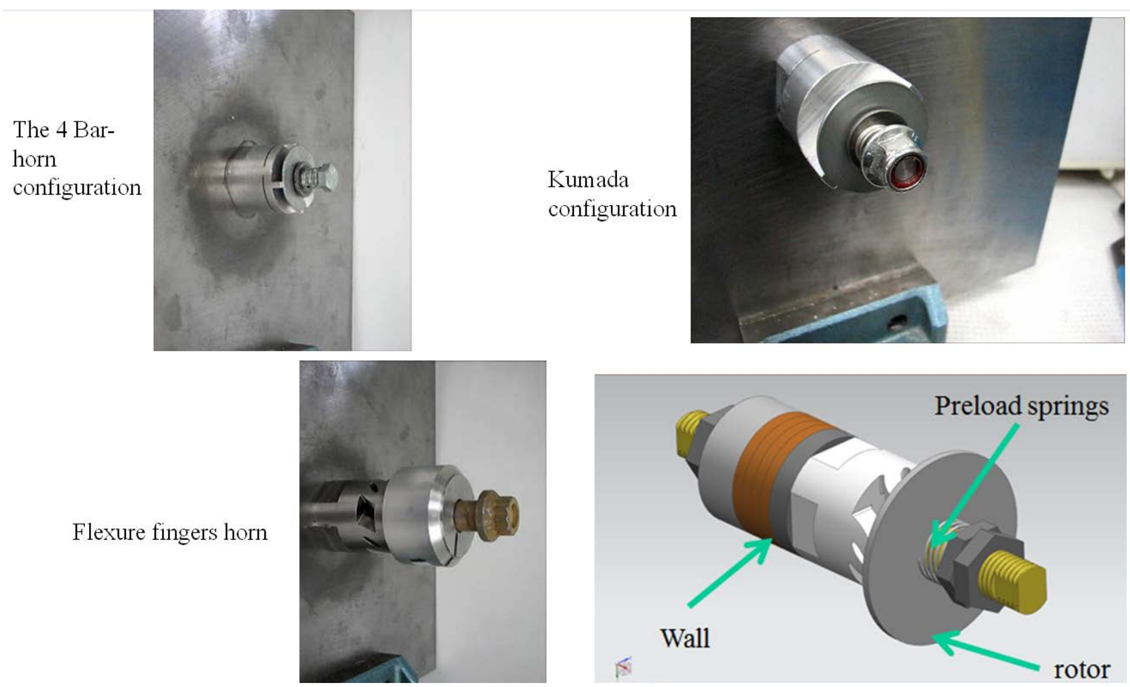

Figure 9. The three rotary motion AMF's studied mounted on the wall ready to test. Not shown is the piezoelectric actuator on the other side of the wall. The flexure fingers horn produced up to 70 RPM while the Kumada and the 4 bar stator were found to produce rotational speeds greater the 800 and 900 RPM respectively.

The three stator designs were bolted to a wall that is 0.375" thick which were used with the same piezoelectric stack actuator bolted to the other side. The electrical leads of the piezoelectric stack were connected to the output of and ENI 4100L power amplifier. The input signal to the amplifier was supplied by a function generator. The frequency was scanned and the preload was adjusted until rotary motion was seen. The frequency was then tuned to maximize the rotation speed. In each of the AMF designs the actuator was driven by a sinusoidal input voltage of 0.300 - 0.400 Volts on the input of the ENI amp. The rotor of the Kumada and 4 bar design was a thin disk (2 mm thick). The rotor was preloaded into the stator via a small thrust bearing and spring that was adjusted with a bolt. The rotor on the flexure finger horn was a 1.5" thick 2" diameter mass and was gravity preloaded. The speed of the 4 bar exceeded 900 RPM while the Kumada design produced speeds over 800 RPM. The rotation speed of the flexure finger horn was substantially less due to the increased mass of the rotor. We are currently investigating methods of increasing the torque for a given speed by adjusting the amplitude, frequency, preload force and surface treatments.

Note, the FEM modal simulations were used to quickly iterate on potential horn configurations, in order to investigate if the desired twisting motion was produced. Then, once a good horn designed was found through this process, it was passed to an ANSYS multi-physics analysis in order to determine the coupling coefficient and also better predict the driving frequency of the device. The multi-physics analysis well predicted the driving frequency of the as-built hardware. For example, the 4 bar horn had an optimal driving frequency of about 27 kHz, matching the predicted value from the multi-physics analysis.

CONCLUSIONS

In this paper we investigated the idea of building Acoustic Mechanical Feedthroughs. Like the Acoustic Electric Feedthrough, we use a piezoelectric transducer to generate a stress wave which travels across a structure. However, in the case of the AMF we do not use a piezoelectric to convert the stress back to an electrical signal. Using an ultrasonic piezoelectric actuator we create a stress waves on one side of a structure which drives a resonant mechanical structure that turns the stress wave into small extensional and twisting motions which can be used to drive a rotor. A variety of resonant structures were analyzed and 3 were found to produce appropriate motions and selected for fabrication. The three horns were assembled on a wall testbed with a piezoelectric stack on one side. All three designs were found to produce rotary motions. The 4-bar horn was found to produce speeds over 900 RPM. We are currently looking at ways to maximize the torque for these designs.

ACKNOWLEDGMENT

The research at the Jet Propulsion Laboratory (JPL), a division of the California Institute of Technology, was carried out under a contract with the National Aeronautics Space Agency (NASA). Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

[1] Y. Hu, X. Zhang, J. Yang, Q. Jiang, "Transmitting Electric Energy Through a Metal Wall by Acoustic Waves Using Piezoelectric Transducers", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, **50**, 7, pp. 773-781, 2003

[2] X. Bao, W. Biederman, S. Sherrit, M. Badescu, Y. Bar-Cohen, C. M. Jones, J. B. Aldrich, and Z. Chang, "High-power piezoelectric acoustic electric power feedthru for metal walls", Proceedings of the SPIE 15th International Symposium on Smart Structures and Materials, San Diego, CA, SPIE Vol. 6930-36, 9-13 March, 2008

[3] X. Bao, B. J. Doty, S. Sherrit, M. Badescu, Y. Bar-Cohen, J. Aldrich, and Z. Chang, "Wireless piezoelectric acoustic-electric power feedthru", Proceedings of the SPIE 14th International Symposium on Smart Structures and Materials, San Diego, CA, SPIE Vol. 6529-134, 18-22 March, 2007.

[4] S. Sherrit, B. Doty, M. Badescu, X. Bao, Y. Bar-Cohen, J. Aldrich, and Z. Chang, "Studies of acoustic-electric feed-throughs for power transmission through structures", Proc. SPIE 6171, 6171-02 (2006)

[5] S. Sherrit, L. Domm, X. Bao, Y. Bar-Cohen, Z. Chang, and M. Badescu, "Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill," Proceedings of the SPIE Smart Structures and Materials/NDE Symposium, held in San Diego, Vol 8345, CA, March 12-16, 2012.
[6] S. Sherrit, X. Bao, M. Badescu, and Y. Bar-Cohen, "Single Piezo-Actuator Rotary-Hammering Drill " NASA Tech Briefs, Vol. 35, No. 3, pp. 48, Mar 2011
[7] S. Sherrit, M. Badescu, X. Q. Bao, Y. Bar-Cohen, and Z. Chang, "Efficient electromechanical network model for wireless acoustic-electric feed-throughs," Proceeding of the Smart Sensor Technology and Measurement Systems Conference, SPIE Smart Structures and Materials Symposium, Paper #5758-44, San Diego, CA, March 7 - 10, 2005.
[8] S. Sherrit, S. P. Leary, B. P. Dolgin and Y. Bar-Cohen, "Comparison of the Mason and KLM Equivalent Circuits for Piezoelectric Resonators in the Thickness Mode", Proceedings of the IEEE Ultrasonics Symposium, Lake Tahoe, 1999, pp. 921-926
[9] D. A. Berlincourt, D.R. Curran, H. Jaffe, "Chapter 3- Piezoelectric and Piezomagnetic Material and their Function in Transducers, pp. 169-270, Physical Acoustics-*Principles and Methods,* Volume 1-Part A, ed. W.P. Mason Academic Press, New York, 1964
[10] M. Redwood, "Transient Performance of a Piezoelectric Transducer", Journal of the Acoustical Society of America, **33**, pp.527-536, 1961
[11] S. Saitoh, H Honda, N. Kaneko, M. Izumi, S. Suzuki, The Method of Determining k_t and Q_m for low Q piezoelectric materials" Proceedings of the IEEE Symposium on Ultrasonics, San Francisco, CA, pp. 620-623, 1985
[12] H.W. Katz (Ed.), Solid State Magnetic and Dielectric Devices, John Wiley and Sons, New York , 1959
[13] A. Kumada, "A Piezoelectric Ultrasonic Motor," Japanese Journal of Applied Physics, Vol. 24, Supplement 24-2, pp. 739-741, 1985
[14] T. Sashida, T, Kenjo , An Introduction to Ultrasonic Motors, Claredon Press , Oxford, 1993