NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT NO. NAS 7-918

TECHNICAL SUPPORT PACKAGE

On

FOLDED RESONANT HORNS FOR POWER ULTRASONIC APPLICATIONS

for 04/01/2003

NASA TECH BRIEF Vol. 27, No. 4

From

JPL NEW TECHNOLOGY REPORT NPO- 30489

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Folded Resonant Horns for Power Ultrasonic Applications

Ultrasonic actuators can be made shorter.

NASA's Jet Propulsion Laboratory, Pasadena, California

Folded horns have been conceived as alternatives to straight horns used as resonators and strain amplifiers in power ultrasonic systems. Such systems are used for cleaning, welding, soldering, cutting, and drilling in a variety of industries. In addition, several previous *NASA Tech Briefs* articles have described instrumented drilling, coring, and burrowing machines that utilize combinations of sonic and ultrasonic vibrational actuation. The main advantage of a folded horn, relative to a straight horn of the same resonance frequency, is that the folded horn can be made shorter (that is, its greatest linear dimension measured from the outside can be made smaller). Alternatively, for a given length, the resonance frequency can be reduced. Hence, the folded-horn concept affords an additional degree of design freedom for reducing the length of an ultrasonic power system that includes a horn.

Figure 1 depicts an ultrasonic actuator that includes a straight stepped horn, one that includes an inverted straight stepped horn of approximately the same resonance frequency, and one that includes a folded stepped horn of approximately the same resonance frequency. The main role of the straight stepped horn is to amplify longitudinal strain at its outermost end. In the folded version, one can exploit bending strain in addition to longitudinal strain, and by adjusting the thickness of the folds, one can increase or decrease the contributions of bending displacements to the overall displacement at the tip. In this case, the folded-horn concept not only yields a shorter horn, but by enabling utilization of bending displacements, it also affords an additional degree of design freedom. Figure 2 shows an experimental folded-horn actuator of 16-kHz resonance frequency alongside a straight-horn actuator of 20-kHz resonance frequency.

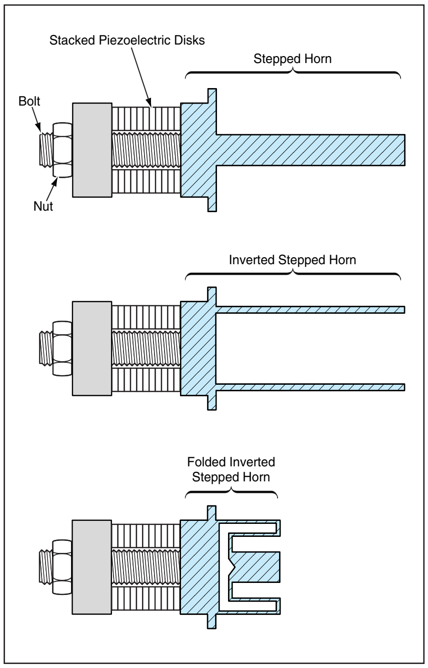

Figure 1. **Three Similar Power Ultrasonic Actuators** are depicted partly in cross sections to illustrate a progression of designs from a straight stepped horn to a folded inverted stepped horn.

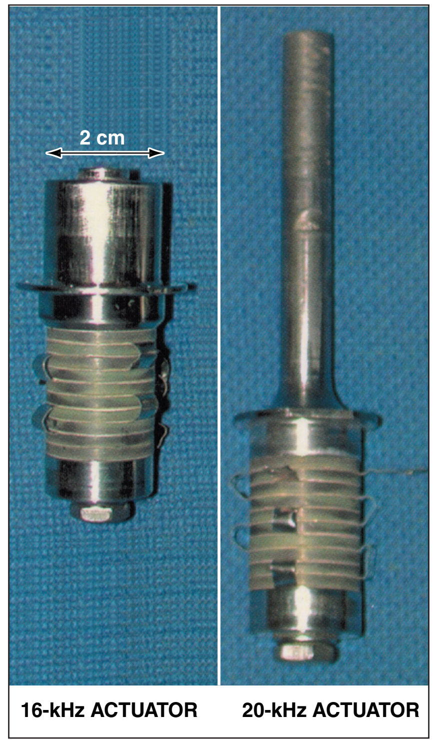

Figure 2. The **Overall Length of the 16-kHz Horn Is Shorter** than the 20-kHz horn by virtue of being folded. The distance the acoustic wave travels has been designed to be the same. The lower frequency in the folded horn is due to reduced clamping and bending at the folds.

This work was done by Stewart Sherrit, Stephen Askins, Michael Gradziel, Xiaoqi Bao, Zensheu Chang, Benjamin Dolgin, and Yoseph Bar-Cohen of Caltech and Tom Peterson of Cybersonics Inc. for **NASA's Jet Propulsion Laboratory.**
NPO-30489

NEW TECHNOLOGY REPORT

Folded/Inverted Horns for Ultrasonic/Sonic Cleaning Welding, Soldering, Cutting and Drilling

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ABSTRACT

A variety of industrial applications exist where power ultrasonic elements such as the ultrasonic horn are used. These included the Automotive, Instruments, Foods, Medical, Textiles and Material Joining and Fabrication Industries. In many of these devices an ultrasonic horn is the key component of the actuation mechanism. It is estimated that the power ultrasonic industry utilizing products, which incorporate horns, is in excess of a hundred million dollars a year. The professional organization overseeing this industry is the Ultrasonic Industry Association[1]. The standard transducer used in these devices consists of three main parts, the backing, the piezoelectric elements and the horn (See FIGURE 1). A horn is used to amplify the induced strain and it is a solid of length L that is in contact with the piezoelectric material. Horns are generally configured as a tapered solid with a smaller diameter at the tip. The tapering of the area of the horn is used to amplify the limited displacement of the piezoelectric material. Standard horn designs have changed very little since their inception. There are four general designations of standard horns. They are; constant, linear, exponential and stepped, which refer to the degree to which the area changes from the base to the tip. A magnification in the strain occurs in the horn that in general is a function of the ratio of diameters. In addition the device is generally driven at resonance to further amplify the strain. The resonance amplification is determined by the mechanical Q (attenuation) of the horn material and radiation damping while the horn length primarily determines the resonance frequency. For a 22 kHz resonance frequency a stepped horn of titanium has a length of approximately 8 cm. Although these standard horns are found in many current industrial designs they suffer from some key limitations. In many applications it would be useful to reduce the resonance frequency necessitating the use of longer horns. Even though the horn can be of the order of fractions of meters long it can be critical to many applications where size is of premium. In addition, manufacturing a horn such as shown in Figure 1 requires the turning down of the stock titanium from the larger outer diameter to the horn tip diameter, which is both time consuming and wasteful. Additionally, the displacement of the horn tip is the result of the longitudinal strain in the material. In a folded horn as is shown in Figure 2 the tip displacement can be further adjusted by including bending displacements. By adjusting the fold thickness one can increase or decrease the bending contributions to the tip displacement. This gives the transducer designer another degree of freedom in the horn design. The increase in tip displacement and the reduction of length were demonstrated in our recent simulations and the details are described in this NTR. Schematics of these novel designs are

shown in Figures 2-4. The inverted horn is shown in Figure 2, doubly folded horn is shown in Figure 3 and a flipped horn is shown in Figure 4. The inverted horn is similar to the standard horn however the horn tip is a ring rather than a solid rod. In the doubly folded horn the horn starts out as an inverted horn with the same area ratio. (cross sectional area of the shell is the same as the cross sectional area of the horn tip of Figure 1.) At approximately 1/3 the length of the standard horn the shell is folded back towards the base and the thickness of this length of shell is adjusted to maintain the same area ratio. Finally as the horn approaches the base it is turned once again to form a solid tip. Since the horn is operated at its resonance frequency and the total length is less than a wavelength (actually $\lambda/2$) the folds to first approximation have no affect on the resonance frequency or magnification of the horn. The device shown in Figure 2 therefore allows for the manufacturing of horns of shorter length with the same performance.

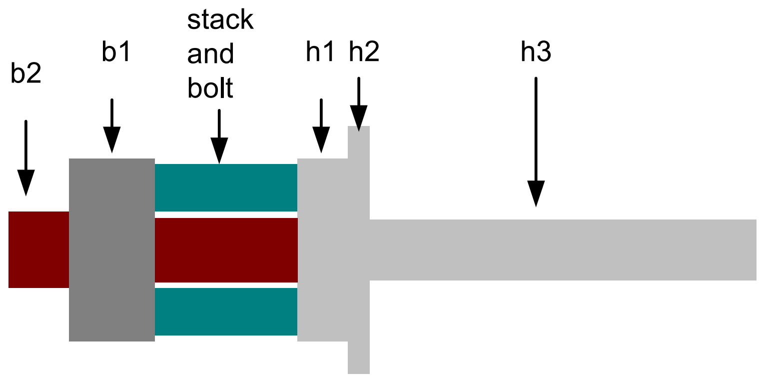


Figure 1. A standard stepped horn (three steps)

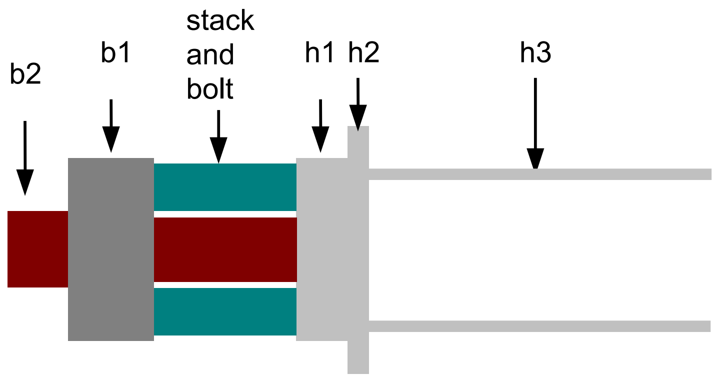


Figure 2. An inverted stepped horn (three steps)

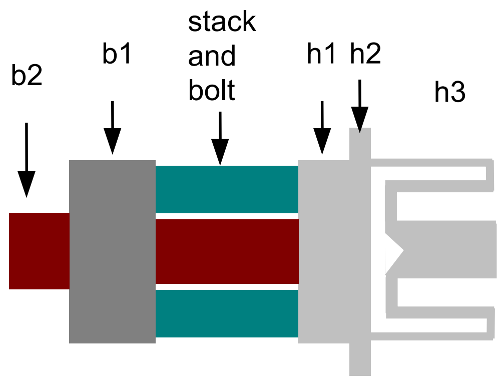


Figure 3. A schematic of a folded horn (2 folds)

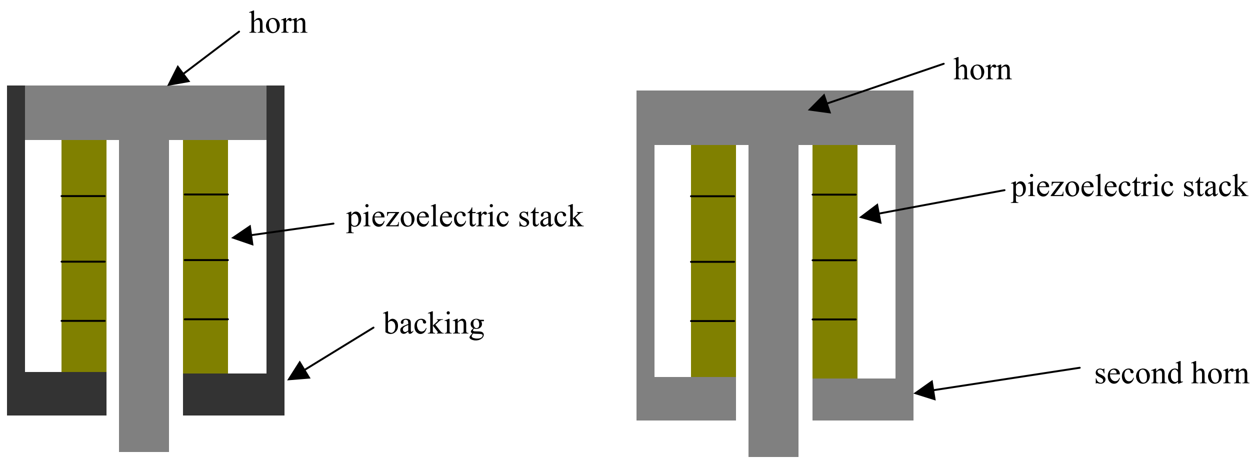
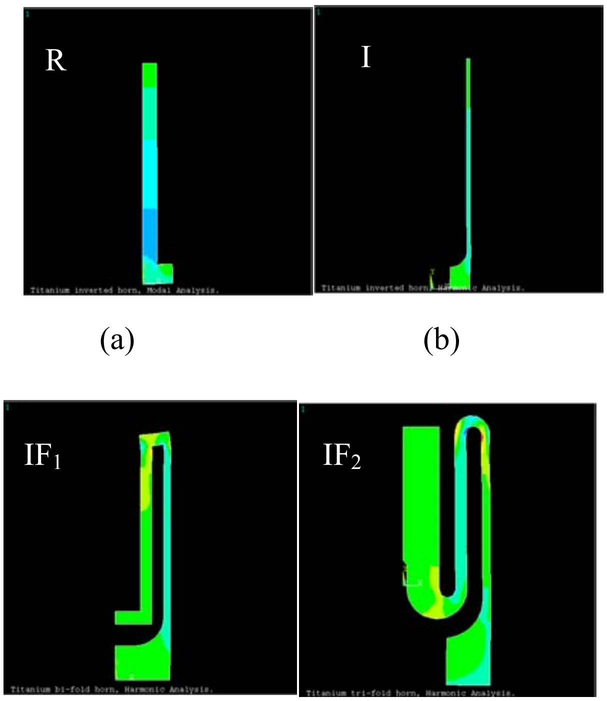


Figure 4. A schematic drawing of a flipped horn. The piezoelectric stack is concentric with the horn tip and generates a stress at the top surface of the horn base. The stress bolt is external and can be configured to be a backing material or horn material

THEORY

The theory for the standard horn as shown in Figure 1 has been known for over 4 decades[2]. Recently the one-dimensional model was extended to include the piezoelectric stack and the backing[3]. Excellent agreement between the full model and experimental results were reported. A variety of standard horns have been reported previously however for a given ratio of base diameter to tip diameter the stepped horn has the largest strain amplification[2] and can be shown to be proportional to $(D_1 / D_2)^2$ where D_1 is the base diameter and D_2 is the tip diameter. Since the wavelength of the ultrasound is twice as large as the length of the standard horn the extension to the folded horn is mathematically trivial since the wave does not to first order see the fold and the mathematical description remains the same. In order to confirm the one-dimensional model a series of FEM modal and harmonic simulations were perform on inverted, single and double folded horns. An axis-symmetric view of the models is shown in Figure 5. The inverted and folded horns are designed to keep the acoustic length and the cross sectional areas the same as those for the standard horn. The axis of rotation runs vertically on the left side of the devices shown.



(a) (b)

(c) (d)

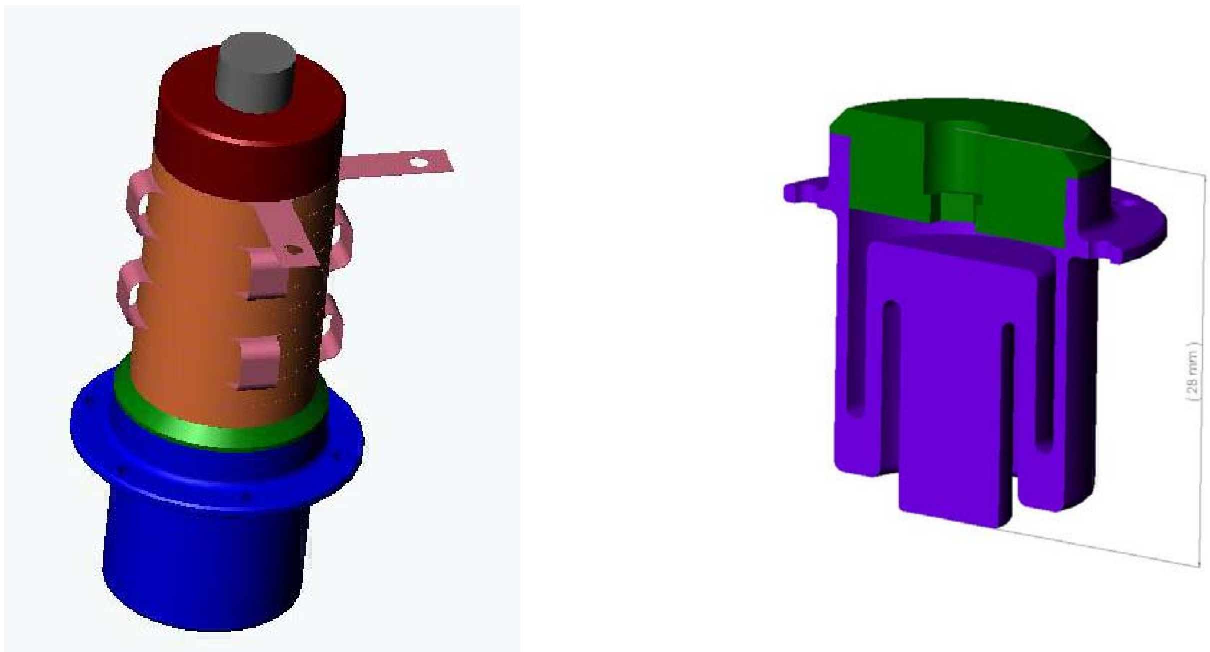
Figure 5. ANSYS axis-symmetric mesh of the a) regular stepped horn R, b) inverted stepped horn IF_0, c) inverted stepped horn with 1 fold IF_1 and d) the inverted stepped horn with 2 folds IF_2

It should be noted that we have shown only inverted folded horns however one can visualize regular folded horns (RF_0, RF_1, RF_2, etc.) and combinations of the two folded horn types connected mechanically in series. Table 1 lists the horn type and the 1st length extensional resonance frequency determined from the ANSYS modal analysis.

Table 1. List of the resonance frequencies for the various horn types. Acoustic length and cross sectional area is kept constant to first order. The frequency is also shown as a function of the thickness of the fold.

Horn Type	Resonance Frequency (kHz)
Regular R	18.3
Inverted no folds IF_0	18.3
Inverted one folds IF_1 (2 mm thick fold)	14.7
Inverted one folds IF_1 (4 mm thick fold)	16.0
Inverted one folds IF_1 (6 mm thick fold)	16.0
Inverted two folds IF_2(2 mm thick fold)	14.1
Inverted two folds IF_2(4 mm thick fold)	16.2
Inverted two folds IF_2(6mm thick fold)	16.4

In order to test the validity of the FEM results a folded horn was fabricated as shown in Figure 6 and 7.



(a) (b)

Figure 6. A Solidworks assembly drawing of the (a)folded horn, piezoelectric stack actuator, and backing. (b) Cross section of the folded horn.

Figure 7. Photograph of the folded horn (16 kHz) and a comparison of a straight horn with approximately the same frequency(20 kHz).

The impedance spectra of the two devices are shown in Figure 8. The standard horn designed for the Ultrasonic Rock Abrasion Tool URAT was determined to have a resonance frequency of approximately 20 kHz while the folded horn was found to resonate at approximately 16 kHz. Another noticeable difference was in the size of the resonance. The mechanical Q of the folded horn was a factor of ten below the standard straight horn. This had a detrimental effect on the displacement measured on the tip of the folded horn. It was also a factor of 10 roughly smaller (10 microns as compared to > 100) than the straight horn. Upon closer inspection of the new folded horn it was determined that the screw threads connecting the base plate of the horn to the outer walls of the horn were the source of the increased dissipation of energy and reduction of resonance. Another design without screw threads that can be manufactured quite easily is shown in Figure 9.

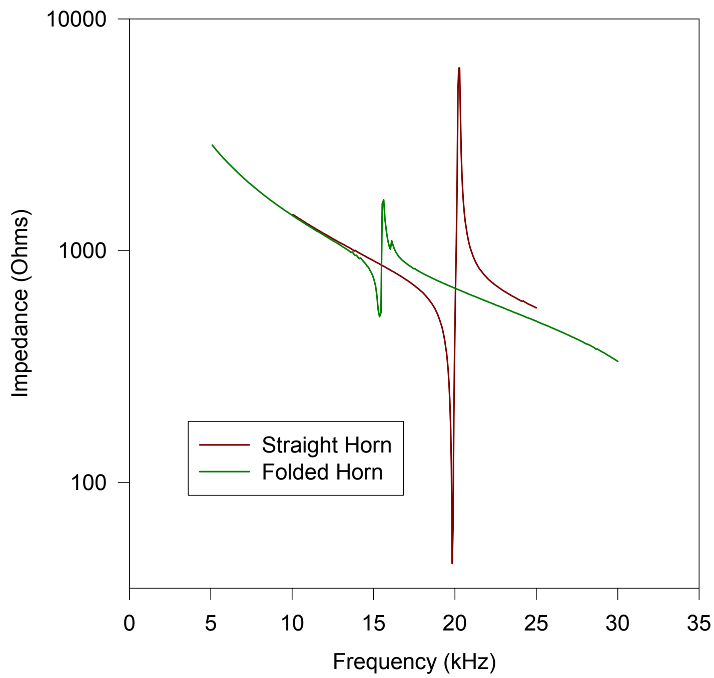


Figure 8. The impedance spectra of the folded and straight horns. The reduced resonance amplitude in the impedance values for the folded horn is the result of the lower Q of the device caused by poor energy transfer across the screw threads in the base.

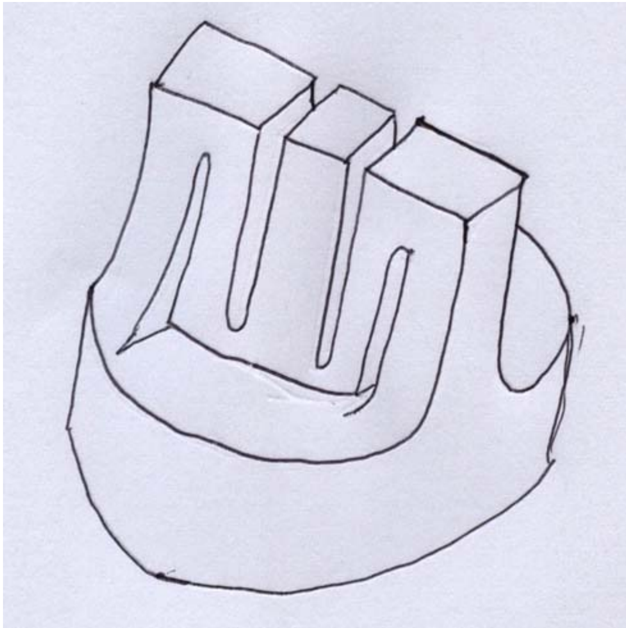


Figure 9. A schematic drawing of a folded horn design, which is easily manufactured and does not require screw threads in the acoustic path.

*REFERENCES

[1] Ultrasonic Industry Association., 1111 North Dunlop Avenue, Savoy, IL., 61874, (217) 356-3182, http://www.ultrasonics.org

[2] J. F. Belford, "the Stepped Horn", Proceeding of the National Electronics Conference, 16, Chicago, pp. 814-822, 1960

[3] S. Sherrit, B.P. Dolgin, Y. Bar-Cohen, D. Pal, J.Kroh, T.Peterson, "Modeling of Horns for Ultrasonic/Sonic Applications" Proceedings of the IEEE International Ultrasonics Symposium, pp. 647-651, 1999

*Please obtain references from sources listed.

"The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration."