

FEA for a Focused-Ultrasound Transducer Prototype Intended for the Pulverization of Heart Calcification

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An Independent Investigation

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract

Despite trends in developed countries of decrease in the prevalence of degenerative mitral stenosis (DMS), which is frequently caused by mitral annular calcification (MAC), it is still a very important cause of mortality, especially in higher-risk populations. For this reason, surgical intervention is typically ruled out a priori and substituted instead for mild symptom management. These individuals then suffer a perpetually and increasingly diminished quality of life either until death or opting to roll the dice with surgery. Some novel therapeutic innovations have arisen, but with unimpressive success. We propose the use of high-intensity focused ultrasound (HIFU) to ablate the calcification via an endoscopic procedure. The therapy would be guided real-time by an imaging array of ultrasound transducers. This paper seeks to determine feasibility of such a proposed device via a FEA model, and to encourage the model's use for the optimization of this device prior to purchase of an expensive, custom-machined transducer for further testing.

Keywords: Degenerative mitral stenosis (DMS), mitral annular calcification (MAC), high-intensity focused ultrasound (HIFU), finite element analysis (FEA)

Introduction

Disease Background

Degenerative mitral stenosis (DMS), one form of mitral stenosis (MS) – the narrowing of the mitral valve resulting in obstruction of left ventricular inflow –, is often an indicator of developed mitral annular calcification (MAC). Symptoms include exertional dyspnea, fatigue, exercise intolerance, high blood-pressure, and irregular heartbeat. The prevalence of this disease has been steadily decreasing over the last decade, especially in developed countries, yet it remains an important cause of illness and death^{1,2}. MAC is “the most important risk factor for DMS,” as well it has been shown to be a predictor of all-cause and cardiovascular mortality, stroke, and other cardiac diseases². MAC prevalence is estimated at from 4.3% to 15%, increasing with age as well as other cardiovascular risk factors³. Interestingly, it was the first valvular disorder to be successfully corrected by surgery⁴. However, because of advanced age and multiple other comorbidities, the presence of mitral stenosis (MS) marks a high-risk cohort with limited treatment options. Standard care for DMS involves heart-rate management and diuretic medication; this can mildly relieve symptoms but, unfortunately, invasive treatment is required to address the problem more effectively².

Current Treatment Options

Currently, the main invasive therapeutic recourse consists of surgical intervention, such as mitral valve repair or replacement. However, as stated above, this is unideal because typically conditions that have a high comorbidity with DMS result in higher rates of inoperability due to excessive risk. Therefore, these patients have extremely

limited options outside of basic symptomatic management and surgical recourse as a last resort in late-stage decline, which presents an unmet clinical need. There are some emerging minimally invasive and transcatheter therapies, but none are at the stage of reliably addressing the disease. For example, mitral valve replacement using a balloon-expandable valve has been reported with a thirty-day and 1-year all-cause mortality of 25% and 53.7%, respectively⁵. This clearly represents a situation demanding improved solutions.

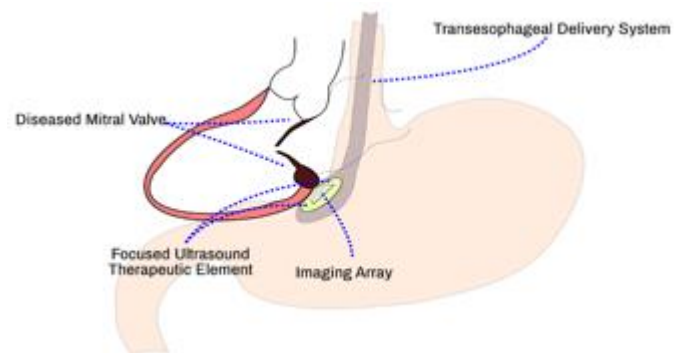


Figure 1. Proposal illustration. This illustration depicts the therapy being administered as described: the endoscope aperture is guided down the esophagus to be as proximal to the heart and otherwise unobstructed as possible so that the therapy can be maximally effective.

Therapeutic Proposal

Our proposal is to utilize the developing technology of focused ultrasound to externally soften and ideally pulverize the calcification in the heart via a relatively non-invasive measure that would be compatible with the historically high-risk cohort of DMS patients. As with traditional surgical interventions, this would help the valves

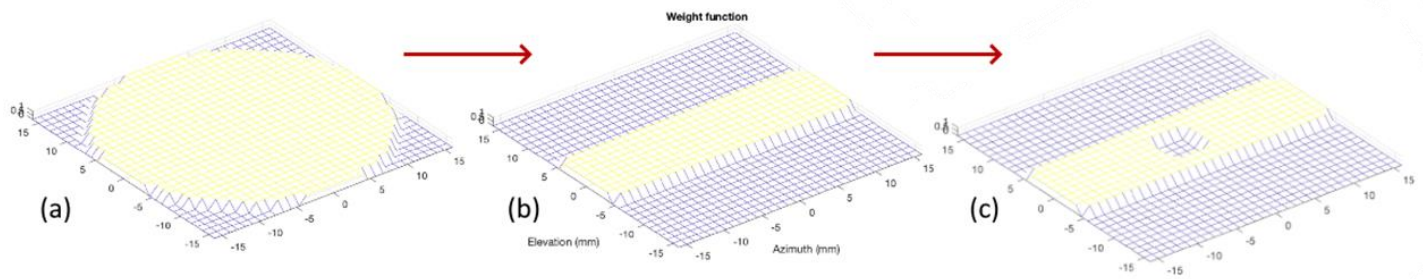


Figure 2. Transducer iterations. (a) represents the “unmodified” transducer – circular w/ 33 mm diameter; (b) represents the transducer after truncation, down to ~10x20 mm rectangular; (c) the final stage of obstruction by the ~5x5 mm imaging array in the center.

to loosen and be able to move more freely, resulting in clinical improvement. The high-powered transducer would be attached to the aperture of a transesophageal endoscope, guided down the esophagus to a strategic position to access the heart cavity. This method would avoid a cumbersome and very complex large aperture transthoracic approach, which would be problematic due to element blocking by the ribs and lungs. Mounted on the high-powered ultrasound transducer, which administers the therapeutic, pulverizing waves, there would be a smaller imaging array of traditional “diagnostic” ultrasound transducers; this would allow the physician to see real-time exactly where he or she is administering the therapy, resulting in more accurate treatment (see Figure 1).

Something revolutionary about this proposed treatment is that it could be used for patients at any stage of the disease, and it would be much more inclusive in terms of risk factors: it is the comparison between risky open-heart surgery and minorly sedated endoscopic procedure. This means that patients could even potentially have recourse to this as a first line of treatment before progression of the disease denies a substantial quality of life.

Focused Ultrasound

Ultrasound as such is any sound with frequencies greater than 20 kHz. This signal has the capability to propagate throughout human tissue, so for this reason it has been used in the medical field, among other applications, for diagnostic purposes and, somewhat more recently, in higher-powered implements, for “selective tissue necrosis in a very well defined volume, at a variable distance from the transducer, through heating or cavitation”⁶. The use of high-intensity focused ultrasound (HIFU) as a non-invasive surgical tool has been most studied in the context of treating prostatic disease, but recently there have been many other uses such as treatment of various tumors, correcting conduction defects in the heart, and the relief of chronic pain, among others⁶. “The ability to focus an ultrasound beam and its energy onto millimeter-size targets was a significant milestone in the development of therapeutic

applications of focused ultrasound,”⁷ which has led to these amazing innovations. In fact, it is now even possible to use traditional imaging techniques, such as MRI and ultrasound itself, in combination with HIFU in order to provide real-time image-based guidance to the therapy⁷.

Determining Feasibility of Prototype

The main goal of this investigation is to determine if the proposed device could be feasible. The reason computer simulation was chosen, rather than custom ordering and testing transducer prototypes on their own is because they can cost in the thousands per, and for a single-use that is unjustifiably wasteful. Feasibility having been established, the created model would also be useful in pursuing optimization of the prototype as regards dimensionality, material selection, and other specifications. In order to put the ultrasound transducer, which was used to establish baseline viability, on an endoscope, it would have to be shrunk and reshaped: going from a circular implement of 33 mm diameter to a rectangular one about 10x20 mm – in a word, truncated. Additionally, implementing the imaging array (~5x5 mm) would obstruct the high-powered transducer. Both modifications would result in a decrease in power, resolution, and focus. These “iterations” can be seen in Figure 2. The question that we are trying to answer is how much loss would result and would the therapy still be effective?

Results

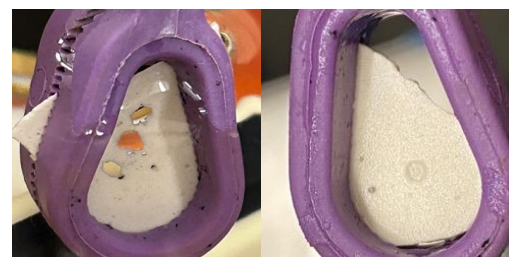


Figure 3. Perforated plaster. In these two images, you can see the outcomes of the preliminary laboratory testing. On the left you

see some large perforations, and on the right is a tightly bound 1 mm diameter erosion zone, showing good resolution.

Preliminary Laboratory Testing

In order to show that the application of HIFU for the pulverization of heart calcification is appropriate, we performed preliminary in-vitro testing using the aforementioned transducer (33 mm, circular) – this will be referred to as the “unmodified” transducer. These test showed promise: there was fine control over “calcium” (plaster) erosion using a variety of machine settings, with “remarkable dimensional control”⁸. The data for these experiments can be found below in Table 1.

Table 1.

Transducer lab results

Test #	Power (W)	Burst Duration (ms)	Period / PRF (Hz)	Treatment duration (# pulses)	Observations
1	64	10	100ms (10 Hz)	24s (240 bursts)	Perforation
2	64	5	100ms (10 Hz)	24s	Small perforation
3	64	5	25ms (40 Hz)	6s	Small perforation
4	32	5	25ms	6s	Plaster translucent
5	32	5	25ms	6s	Plaster translucent
6	64	5	25ms	6s	Plaster translucent
7	64	5	25ms	6s	Same location as #6: perforation
8	64	5	25ms	4s	Plaster translucent
9	64	5	25ms	2s	Plaster translucent
10	90	5	10ms	2s	Perforation (large)

Note. 140W equates to approximately 20 MPa.

This data is not meant to illustrate a trend, per se, though unsurprisingly some correlations present, such as higher power and larger perforations. Additionally, you can see some images of the resulting plaster models after treatment in Figure 3. Based on these results, we felt confident that HIFU would be an effective means to treating MAC caused DMC, so we decided to continue our investigation into how modifying the transducer would affect performance.

Linear Model

Using MATLAB, some linear simulations were performed to estimate the losses due to truncation and obstruction. The

results of this secondary testing suggest continuation as well, as they are in line with expectations: somewhat significant yet serviceable losses for truncation of the element and menial losses for obstruction by imaging-guidance array. The 3d charts and beam plots are provided below in Figure 4.

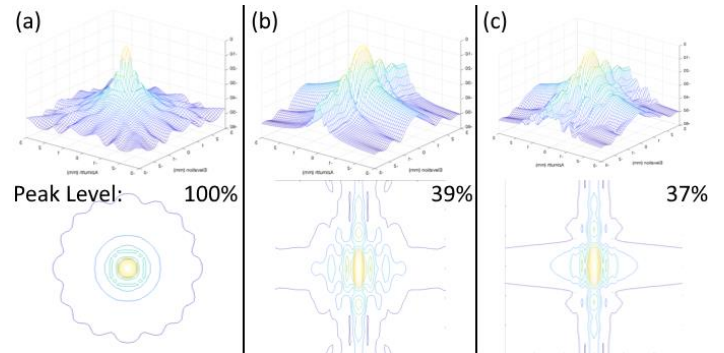


Figure 4. MATLAB results. These figures show the results of the linear testing performed using MATLAB. The parenthetical headings correspond to the steps referenced in Figure 2. The losses from truncation were large (61%), but they do not rule out treatment capabilities. The beam spread is also increased, but a central node persists. The losses from obstruction are minor (2%).

FEA Model

Our FEA model has not yet reached the definitive point of producing meaningful results for analysis and interpretation. Soon-to-come results would appear in the form of Figure 5. In lieu thereof, I will provide a walkthrough of the development process for the FEA model in Materials & Methods as well as a discussion of next steps in Discussion. The full code can be found in Appendix A.

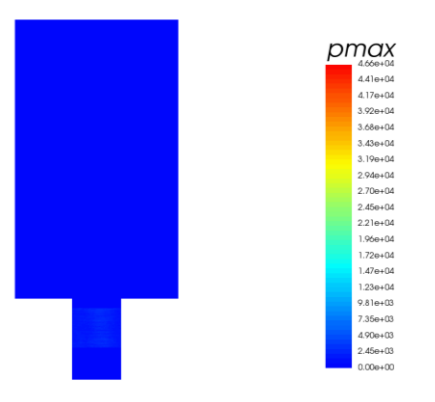


Figure 5. Simulation output sample. This is the format that the (primary) FEA output would be in. As you can see, the peak pressure levels would be shown according to color, and the color key spectrum is given on the right-hand side.

Discussion

Next Steps: Data Output and Analysis

Once the models are completed and the simulations are run, the next steps would be processing the data output and using that data to answer our guiding question: is the prototype a viable means of treating DMS, or would the losses from truncation and obstruction prove to be insurmountable? This would be done by comparing the peak levels to those of the laboratory tests of the unmodified transducer, as well as the linear model that correlated with our initial expectations. In reality, as long as the losses were not so low that treatment would either be impossible due to the weakness of the signal or take an unreasonable amount of time for the same reason, then the prototype could have enough justification to be custom ordered and tested on its own merits. If this were the case, the model could also be extremely useful in optimizing the prototype specifications: one could change the simulated transducer materials, size, and array dimensions, among other variables, to see how the peak levels are affected, then choose the most effective version.

Sources of Error

There are some potential flaws in the simulation as it is currently set up. These could be addressed prior to running the simulations or addressed in future studies. Using a proximate water load instead of a plaster- or even calcification-like material at a distance through some medium (human tissue), which would be true to the clinical conditions, could affect the data's fidelity and therefore its applicability. These effects may be negligible, but some standard should be pursued in verifying that. Additionally, using an array of transducers to simulate the single high powered focused ultrasound transducer rather than a single element could also cause deviation. This is probably not immensely significant, and it may be impossible to address, at least using OnScale, but it may be something to note for future investigations.

Materials and Methods

There were two steps performed which are prior to and outside the scope of this study, yet essential to its inception: the laboratory experiments using a HIFU to pulverize plaster, acting as a proof-of-concept, and the initial linear models. For this reason, they will both be briefly described, but not to an excruciating level of depth.

Laboratory Simulations

As one could imagine, actual calcified hearts are extremely difficult to obtain: you may get your hands on one per year – if you are lucky. Obviously, this is a far too slow rate of collection, and it may prove just as expensive as ordering the custom-machined transducers, especially if opportunity cost is factored in. Therefore, we decided to use plaster to simulate heart calcification. Despite potential functional differences between the two materials, plaster was deemed sufficient to prove the functionality of the focused ultrasound transducer to pulverize or at least soften calcium deposits in the heart. The transducer used was a model SU-102 from Sonic Concept (3.78MHz, 33mm diameter, 55mm focal length), Transducer #3. The treatment parameters can be found in Table 1.

Mathematical Methods

Physical experimentation, beyond testing of the unmodified transducer element to provide baseline data, would prove absurdly expensive: custom machined transducers cost thousands of dollars each. Given that our project would only have need of such implements for a single-use, this was immediately ruled out. Therefore, we turned to computer modeling technology. Since our problem is inherently non-linear – that is, as one variable is changed (iteration steps), the other (transducer performance) does not respond correlatively. Therefore, traditional linear mathematical methods such as MATLAB provided some insight (see Results, Linear Model), the conclusions that they can support would be limited. OnScale is a software specifically designed for simulating piezoelectric materials, and it possesses non-linear modeling capabilities, so it was selected to help estimate the losses in power and resolution at each stage from the unmodified transducer to our proposed prototype.

OnScale Environment

OnScale is an extremely powerful tool, and it allows a great deal of customization regarding model properties and simulation specifications. There are three different modes to work in: Designer, Analyst, and Post-Processor. Designer is a GUI-based design environment which allows the user to create models using interactive features such as buttons, data boxes, and a real-time rendering. Analyst is the original mode of development in OnScale, and it is completely code-based. The programming language that OnScale uses is based on FORTRAN, so it is a relatively lower-level, compiler-based language which is powerful for high-performance computing operations. We decided to utilize this environment for our simulations to have as much

control as possible over project variables. OnScale provides a number of very helpful models on their website which can serve either as learning tools or even as the basis for larger-scale projects. In fact, we decided to use one of the examples as a starting point for our model – “Phased 3d Array”. A large portion of my time spent on this project consisted in familiarizing myself with the OnScale environment and syntax, as well as working through the provided model to decipher the scripts line-by-line to be able to modify according to our purposes. The third working mode in OnScale is called Post-Processor. This is where one may view simulation results and interact with the data.

Phased 3d Array

The example model that we chose to use as a starting point for our simulations consisted of a 2d array of 3d transducers (See Figure 6). Although our prototype in reality is only composed of a single transducer, for the purposes of simulation we decided to use an array of transducers because it was the only way we were able to create the hole in the middle that simulates the obstruction caused by the imaging array; however, the array in our computer model does not correspond to the imaging array, it represents the single, high-powered transducer. In addition to the transducer elements and kerf (spacing between the elements), there are multiple components used as backing and absorptive surfaces, as well as a water load, which is what will actually be stimulated by the propagated signals. The full model as described is pictured below in Figure 7.

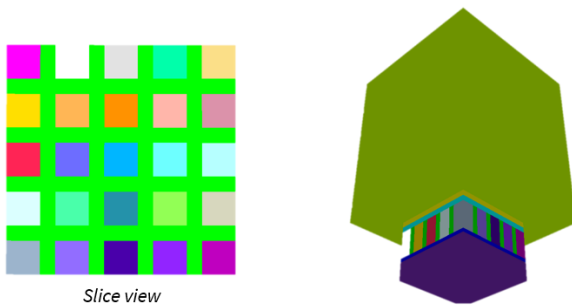


Figure 6. “Phased 3d Array” OnScale example model. This model, provided by OnScale, was modified to simulate our prototype (see Figure 7).

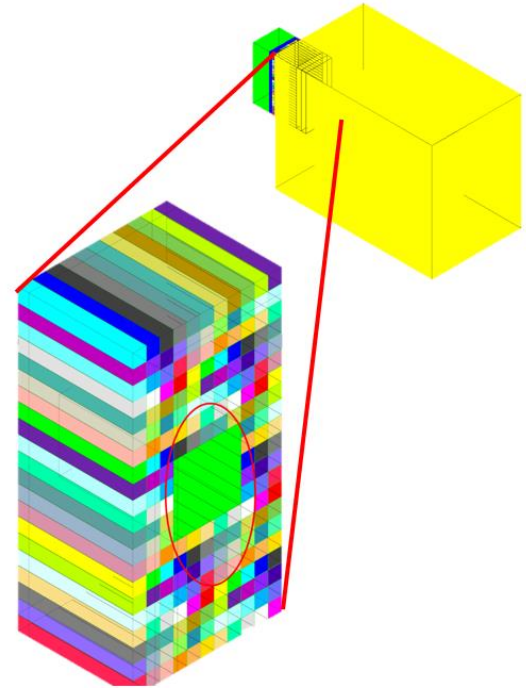


Figure 7. Final FEA model. This is the finished model we have created to simulate our prototype in OnScale. As you can see, the array dimensions have been modified and the “hole” implemented to most accurately reflect our proposed device.

Steps for Modification

In order to rework the Phased 3d Array model to become useful for the purposes of our simulation, multiple steps had to be performed, but these were all in pursuit of the single goal of changing the array size and dimensions to correspond to our prototype. First, the “hole” was made in the center of the array by reworking the for loop in the material assignment document to designate any transducers within the “hole” range as *void* material instead of *elementN*, which represents the piezoelectric material. Next, I changed the array dimensions and size. This was done by editing the scripts that determine the sizing, replacing certain variables with new formula-based ones to be able to edit it at will. Now, if one desires, it is possible to change the array size and dimension simply by changing the corresponding variables. Some of these edits, however, caused downstream problems, especially implementing the “hole.” OnScale requires the electrode assignment for the piezoelectric circuit to be done manually; when the hole was added, the original script kept trying to assign electrodes where there were no longer any transducers. Therefore, I had to add exceptions so that it ignored the “hole” and the model could run. Additionally, the scale of the project was changed from μm to mm (see Table 2), but the frequency of interest remained in approximately the same scale. OnScale

does its simulation meshing based on these two variables, and since the one was changed somewhat drastically while keeping the other static, it was trying to create an excessively fine mesh, which used far too much memory to be able to run. I fixed this by adding a variable “scalefact” which allows the user to manually adjust the meshing to a reasonable amount.

Table 2.

Specifications for modification of OnScale provided model to proposed prototype.

	Array Dimensions	Real Dimensions
Original Model	5x5	48x48 μm
Prototype Specs.	11x21*	10x20 mm

Note. Odd so that a ~5x5 section may be removed from the center

Note for Future Implementations

Professor Hossack is provided with a document which details the function of the code, line-by-line; this should help any individuals who seek to use it for further investigation.

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8. Hossack Lab.

Appendix

Appendix A: Full Code

```

mem 2000 1000
c
*****
*****
*****
c
c
OnScale 3D Phased Array
c
c
*****
*****
*****
c
c DESIGNER           :           OnScale
c MODEL DESCRIPTION  :           3D Phased Array
c DATE CREATED       :           19/10/2017
c VERSION            :           1.0
c
c
*****
*****
c Initialisation
mp omp * *

titl 3D_Phased_Array  3D Phased Array

c
*****
*****
*****
c
MODEL PARAMETERS
c
*****
*****
*****
grph
type stnd

```

```

end

/* Ceramic
symb array_wdth_x = 10e-3
symb array_wdth_z = 20e-3
symb narray = 11 /* Increase Array
Size
symb narray_z = 21
symb ckerf = 15e-5 /* Kerf
symb cpitch_x = ( $array_wdth_x - $ckerf ) / $narray
/* Element Pitch x direction
symb cpitch_z = ( $array_wdth_z - $ckerf ) /
$narray_z /* Element Pitch z direction
symb pill_wdth = $cpitch_x - $ckerf
symb pill_wdth_z = $cpitch_z - $ckerf
symb pill_lgth = 1.016 /* Length of Element
symb pill_thk = 77e-4 /* Thickness of
Element
symb y_match1 = 15e-4
symb y_match2 = 15e-4
symb narrayt = $narray * $narray_z
symb void_wdth_x = 1
symb void_wdth_z = 2
symb void_start_x = 3 /* ( ( $narray - 1 ) / 2 - 1 ) * 2
symb void_end_x = 4 /* $void_start_x + ( $void_wdth -
2 ) * 3
symb void_start_z = 4 /* ( ( $narray_z - 1 ) / 2 - 1 ) * 2
symb void_end_z = 5 /* $void_start_z + ( $void_wdth -
2 ) * 3
symb void_inx = 6
symb y_back1 = 10e-4
symb y_back2 = 51e-4

c Loads Sizes
symb thk_load = 0.5e-1
symb side_load = 10e-3

/* Total wdths
symb total_wdth_x = $side_load * 2 + $array_wdth_x
symb total_wdth_z = $side_load * 2 + $array_wdth_z

/* Materials
symb piezo_mat = pzt4
symb filler_mat = ke16
symb match1 = hard
symb match2 = medm
symb back1 = back5
symb back2 = rtv

/* Frequency and mesh
symb freqint = 3.78e6
symb freqdamp = $freqint
symb vel = 1100
symb wavelength = $vel / $freqint
symb nelem = 15
symb scalefact = 1e1

```

```

symb box = $wavelength * $scalefact /
$nelem
symb tfact = 0.95

/* Electrical
symb rdamp = 50

/* Runtime
symb nloops = 10
symb ncycles = 50

/* Calculations
symb ckerf2 = $ckerf / 2
symb pill_wdth2 = $pill_wdth / 2

c
*****
*****
***
c
X-Y-Z CO-ORDINATE SYSTEM
c
*****
*****
***
symb #keycord x 1 0. $side_load $pill_wdth
symb #keycopy x 2 3 $narray-1
symb #get { icend } rootmax x
symb #keycord x $icend $x$icend $side_load
symb #get { idx } rootmax x

symb #keycord y 1 0. $y_back2 $y_back1 $pill_thk $y_match1
$y_match2 $thk_load
symb #get { jdx } rootmax y

symb #keycord z 1 0. $side_load $pill_wdth_z
symb #keycopy z 2 3 $narray_z-1
symb #get { kcent } rootmax z
symb #keycord z $kcent $z$kcent $side_load
symb #get { kdx } rootmax z
c
*****
*****
***
c
I-J-K CO-ORDINATE SYSTEM
c
*****
*****
***
c *** Grid in I direction, using approximately element size of
'box' ***
symb #keyindx i 1 $idx 1 $box 1
symb indgrd = $i$idx

```



```
symb #keyindx j 1 $jdx 1 $box 1
symb jndgrd = $j$jdx
```

```
symb #keyindx k 1 $kdx 1 $box 1
symb kndgrd = $k$kdx
```

```
c *** list the creation of all the key points in XYZ and IJK ***
symb #list
```

```
c
*****
*****
*****
```

GRID DEFINITION

```
c
*****
*****
*****
```

```
c Define grid
grid $indgrd $jndgrd $kndgrd
```

```
c
*****
*****
*****
```

GEOM DEFINITION

```
c
*****
*****
*****
```

```
c Read build geometry
geom
    keypnt $idx $jdx $kdx
end
```

```
c
*****
*****
*****
```

MATERIAL PROPERTIES

```
c
*****
*****
*****
```

```
c Read
symb #read 'materials.prjmat'
```

```
c
*****
```

```
*****
**
```

MATERIAL SITE DEFINITION

```
c
*****
*****
**
```

```
c Locate materials
site
```

```
    regn void
```

```
    /* Generic Epoxy - Switch out for filler material
    regn $filler_mat $i2 $i$icend $j3 $j4 $k2 $k$kcend
    symb ib = 2
    symb ie = 3
    symb kb = 2
    symb ke = 3
```

```
    symb icounter = 1
```

```
    do loopK K 1 $narray_z 1
        do loopI I 1 $narray 1
            regn elem$icounter $i$ib $i$ie $j3 $j4 $k$kb
```

```
$k$ke
```

```
    c        symb #msg 2
    c            elem$icounter
    c            i $i$ib $i$ie k $k$kb $k$ke
    symb ib = $ib + 1
    symb ie = $ie + 1
    symb icounter = $icounter + 1
```

```
end$ loopI
    symb ib = 2
    symb ie = 3
    symb kb = $kb + 1
    symb ke = $ke + 1
```

```
end$ loopK
```

```
    regn void $void_start_x $void_end_x $j3 $j4
    $void_start_z $void_end_z
```

```
    regn $match1 $i2 $i$icend $j4 $j5 $k2 $k$kcend
    regn $match2 $i2 $i$icend $j5 $j6 $k2 $k$kcend
    regn $back1 $i2 $i$icend $j2 $j3 $k2 $k$kcend
    regn $back2 $i2 $i$icend $j1 $j2 $k2 $k$kcend
```

```
    /* Water Load
    regn watr $i1 $indgrd $j6 $j7 $k1 $kndgrd
```

```
end
```

```

c
*****
*****
**
c
                BOUNDARY CONDITIONS
c
*****
*****
**
boun
    side xmin absr
    side xmax absr
    side ymin free
    side ymax absr
end

c
*****
*****
c
                DRIVING FUNCTION
c
*****
*****
func wvlt $freqint 1. * *

c
*****
*****
c c
                ELECTRICAL FIELD APPLICATION
c
*****
*****
*
circ
    defn dmp
    elem rest sers $rdamp
end

c Focal Point Co-ordinates
symb focalx = $total_wdth_x / 2
symb focaly = 55e-3
symb focalz = $total_wdth_z / 2

c Find closest node and element to focal point
symb #get { ifocn jfocn kfocn } clsnod $focalx $focaly $focalz
symb #get { ifoce jfoce kfoce } clselem $focalx $focaly $focalz

c Plot model
grph

```

```

plot matr
end
term

c RETURN 1st Distance between focal point and element
symb dist_min = 1.0
symb dist_max = 0.0

c DETERMINE Min and Max Wave Paths Distances and store them
do loopK K 1 $narray_z 1
symb kb = 2 + (( $K - 1 ) * 2 )
symb ke = 3 + (( $K - 1 ) * 2 )
if ( $kb ne 9 and $ke ne 9 ) then
    if ( $kb ne 11 and $ke ne 11 ) then
        symb kelem = ( $k$ke + $k$kb ) / 2
        do loop I 1 $narray 1
            symb ib = 2 + (( $I - 1 ) *
2 )
            symb ie = 3 + (( $I - 1 ) *
2 )
            if ( $ib ne 7 and $ie ne 7 )
then
                symb ielem = (
$i$ie + $i$ib ) / 2
                symb #get {
cur_dist } distnode $ielem $ifocn $j4 $jfocn $kelem $kfocn
                if ( $cur_dist lt
dist_min ) then
                    symb
dist_min = $cur_dist
                endif
                if ( $cur_dist gt
dist_max ) then
                    symb
dist_max = $cur_dist
                endif
            endif
        end$ loop
    endif
endif
end$ loopK

symb icounter = 1

c Time = Distance Difference / Speed
do loopK K 1 $narray_z 1
symb kb = 2 + (( $K - 1 ) * 2 )
symb ke = 3 + (( $K - 1 ) * 2 )
if ( $kb ne 9 and $ke ne 9 ) then
    if ( $kb ne 11 and $ke ne 11 ) then
        symb kelem = ( $k$ke + $k$kb ) / 2
        do loop I 1 $narray 1
            symb ib = 2 + (( $I - 1 ) *
2 )

```

```

2 )
then
  $i$ib ) / 2
  cur_dist } distnode $ielem $ifocn $j4 $jfocn $kelem $kfocn
  $dist_max - $cur_dist ) / $vel
  1
  endif
endif
end$ loopK

/* Apply electrodes to ceramic
piez
  wndo auto piez
  symb nb = ( $narrayt / 2 )
  symb ne = ( $narrayt / 2 ) + 1

  do loopP K 1 $narrayt 1

  if ( $nb ne 1 and $ne ne 14 ) then
    /* Top Electrodes
    defn top$K $pill_lgth
    nod2 elem$K $match1 ** $j4-1 $j4+1 **

    /* Bottom Electrodes
    defn bot$K $pill_lgth
    nod2 $back1 elem$K ** $j3-1 $j3+1 **

    /* Connections
    conn top$K dmp volt func 1 $delay$K
    bc bot$K grnd

    symb nb = $nb - 1
    symb ne = $ne + 1

  endif

end$ loopP

end

extr
  defn kirc
  ref out $focalx $y1
  node $i1 $indgrd $j6+2 $j6+2
  end

```

```

c
*****
*****
*
c
      CHOOSE TIME HISTORIES TO STORE
c
*****
*****
*
calc
  pres acoustic
  disp
  max aprs none pmax
  end

c
*****
*****
*
c
      PROCESS MODEL
c
*****
*****
*
c Timestep
time ** $fact

prcs                               /* run process step

c
*****
*****
*
c
      RUN THE MODEL
c
*****
*****
*
/* Calculate simulation time
symb #get { step } timestep
symb simtime = $ncycles * ( 1 / $freqint )
symb nexec = $simtime / $step
symb nexec2 = $nexec / $nloops

grph
  nview 2
  arrow off
  line off
  type runtime
  set imag avi
  end

proc plot save

```

```

exec $nexec2

symb imid = ${id} / 2
grph
    pset sttl 1 'Wave Propagation in a Water Load'
    plot aprs i $i1 $imid rang 0 1e4

    pset sttl 2 'Maximum Acoustic Pressure'
    plot pmax j $j1 $jfocn rang 0 5e4

    imag
end

end$ proc
/* *****

symb #get { timenow } datetime
symb #msg 2
time start = $timenow

/* Run model
proc plot $nloops

symb #get { timenow } datetime
symb #msg 2
time end = $timenow

c
*****
*****
c
symbol variables to file for later use
c
*****
*****

data
    out pmax
end

symb #get { labl } jobname
/* find name of run
symb #save symb.$labl
/* save in symb file

stop
/* return to command prompt

```