“Influence of Pulse Drive Shape and Tuning on the Broadband Response of a Transducer”

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Abstract:
The shape and symmetry of the pulser drive waveform and its interaction with the transducer and its tuning circuitry have a profound effect upon the pulse echo performance achievable from a medical transducer probe. Conventional wisdom has it that the shortest pulse obtainable, and subsequently the widest bandwidth achievable will come from the impulse response of the system. This study helps elucidate why an impulse generator may not always result in the shortest pulse and widest bandwidth. The pulse response is critically dependent upon the pulser drive symmetry, and its interaction with the reactance of the components making up the tuning topology. Unipolar pulses such as the spike impulse, or half wave square unipolar pulse drive, can create notches in the drive spectrum at the gold electrode that are deleterious, and significantly reduce available bandwidth. The transducer model used in this study is a 3.5 MHz 96 element sector phased array. In conjunction with a new innovativetransducer acoustic design and optimized tuning,experimental results producing bandwidths of over 90 % with clean, short pulse ringdown, have been achieved.

Introduction

In this study the following tuning topologies were studied; series only, shunt only , series inductors on both ends of the coax cable, series-series/shunt topology, and transformer tuning (see figure 1). As a test vehicle, the transducer studied was a single element of a 3.5 MHz sector phased array type of transducer diced on half wavelength pitch. The finite element code PZFLEX was used to analyze the results, and do the engineering trade studies. Pulser drive shapes included single cycle sine wave, single cycle square wave, unipolar pulses, and spike pulse excitation. To reduce system costs, or for systems requiring very large numbers of individual pulser channels, such as two dimensional arrays, many times the simpler circuitry of a one sided, unipolar (half wave) square pulse drive is chosen. The impedance matching tuning topology acts as a “filter” circuit. Pulser shapes that are markedly one sided, such as a spike impulse (Panametric), or unipolar square wave drive will create out of phase resonant energy in shunt inductance components that degrade the pulse length and resultant frequency bandwidth response of a transducer.

Tuning refers to the procedure where the reactance of a transducer device is canceled (approximately), by the addition of series or shunt inductor elements, and or auto transformers, in the electrical hookup circuit of the transducer. The objective is to present a mostly resistive (minimal reactive component), well matched load to the receiver pre-amp. The choice of tuning is a compromise between matching the source impedance’s on transmit versus receive. Typical system values for a pulser are 5 ohms (voltage source) , and between 100 to 500 ohms for the receiver input impedance. The values of the tuning components are typically chosen to represent a conjugate impedance match at the node of the circuit where they are placed. Simple series inductors are useful, since usually the elements of a piezoelectric transducer array are small in dimensions, and hence present a large electrical impedance. A series inductor has the beneficial effect of cutting the electrical impedance seen after the inductor almost in half (depends on the phase angle of the impedance of the element). Series tuning was observed to yield the cleanest, shortest pulse ringdown. Also a series inductor helps form a low pass filter that can filter out high frequency energy that might cause harmonic distortion in the Doppler signal processing chain. Some tuning schemes require shunt (parallel) inductors as tuning elements. More sophisticated schemes use a combination of series-series/shunt inductor components. The widest bandwidth response of the probe can be achieved with this topology. Use of a custom wound auto transformer is in principle a desirable but expensive tuning scheme, which conceptually helps achieve impedance matching over a broader frequency range.

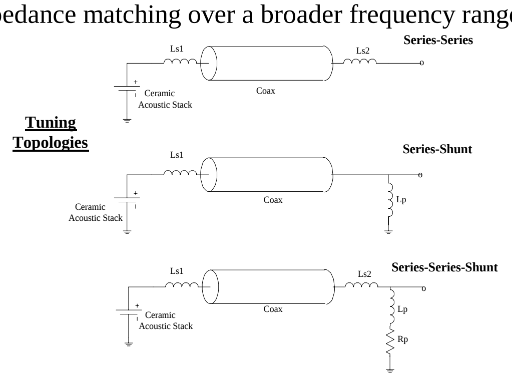


Figure 1. Various Tuning Circuit Topologies

Influence of Pulse Drive Shape

Figure 2 shows the response of a transducer, coax, plus tuning combination driven by unipolar spike excitation . The tuning consisted of a series inductor of value Ls= 15.0 uh at the transducer end of the coax, and Ls= 10.0 uh with a shunt value of Lp = 10.0 micro-henry , in the connector housing, at the end of the coax cable.

BW	Fc	PL20	PL30	Sensitivity
72.0 %	3.75	1.19 us	2.76	0.0052 v

where BW is the -6 dB two way bandwidth, Fc the center frequency in MHz, PL20 is the -20 dB round trip pulse length, and PL30 the -30 dB pulse length.

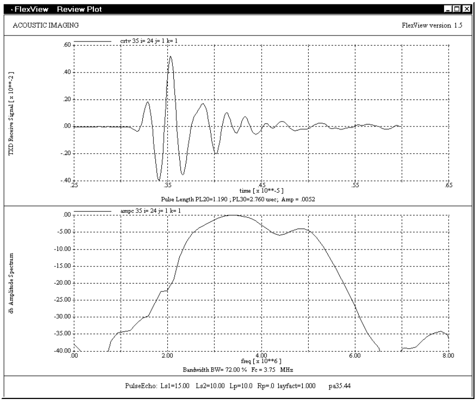


Figure 2: Pulse/Echo response with a
Unipolar Spike (Impulse)

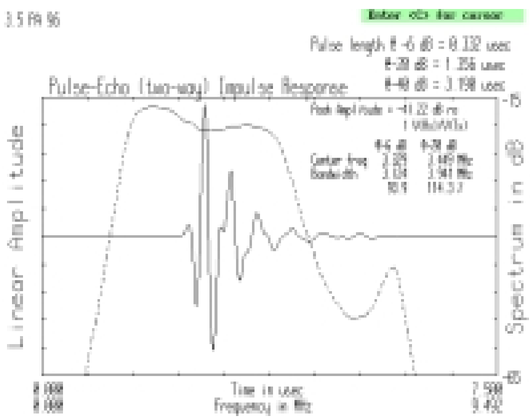


Figure 3: Response predicted by KLM model (Piezocad) for impulse response.

The impulse response predicted by the KLM model as illustrated in figure 3, is a much more optimistic 93 %. The KLM model works in the frequency domain, and predicts the time domain response via an inverse FFT.

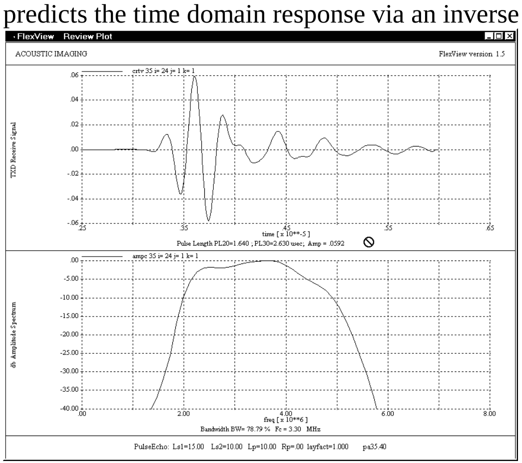


Figure 4: Pulse Echo with single cycle Square wave.

Figure 4 shows the same transducer driven with a single cycle square wave.Surprisingly, for the square wave drive (figure 4), a bandwidth of 78.8 % was achieved, more than with the spike impulse drive !? Conventional wisdom says that the ultimate bandwidth can be extracted from a transducer/cable assembly, by pulsing with a spike pulser drive, to generate the "impulse response" of the system. Any other response can be predicted by convolving the pulse drive shape of any desired pulser drive, with the impulse response of the transducer. Hence, typically the shortest pulse length will always be achieved with the spike pulse shape, and the widest bandwidth frequency response as well. Commonly the Panametrics 5250 pulser/receiver is used in the laboratory to create the impulse response test data for a probe. However, enigmatically, the results for the probe above being driven by the Panametrics spike pulse shape are even worse: (see figure 5)

results:

BW	Fc	PL20	PL30	Sensitivity
49.3%	3.45	1.11 us	2.80 us	0.010 v

These results are with a pulse shape that emulates the Panametrics 5250 which is not a true spike, but has a slow decaying tail after the peak spike voltage.

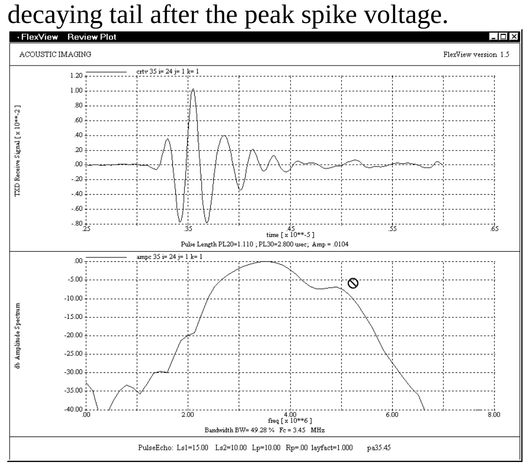


Figure 5. Results with Panametrics 5250 spike pulse
with slow recovery tail.

One reason the impulse response here is not as broadband as the sine wave drive or square wave drive, is that the spike pulse shape is non-symmetrical, and dumps a significant amount of energy at low frequencies approaching DC. There also is an inductive kickback effect in the shunt inductor that causes the transducer/coax/tuning system to ring. This is particularly illuminating if one looks at the shape of the pulse drive that actually arrives at the ceramic electrode, after passing down the tuning components and coax cable. This is illustrated with the aid of figures 6 and 7. The plot shows the pulse drive after passing through the transmission line and tuning components, as it drives the actual gold electrode on the ceramic. Figure 6 is for a case of simple series inductor tuning, drive with a unipolar quarter wave, negative going pulse. The inductive kickback from the inductor goes positive, and makes the pulse drive behave almost like a bipolar drive. The bottom half of the figure shows the frequency content of the drive at the electrode.

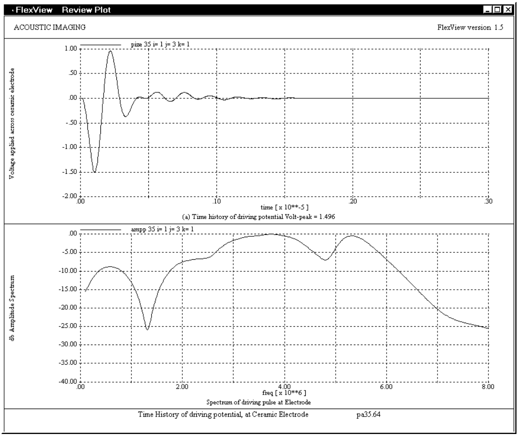


Figure 6: Inductive kickback seen with simple series tuning, and Quarter wave unipolar pulse drive.

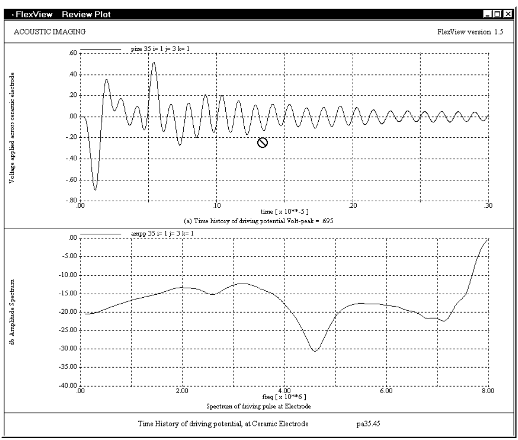


Figure 7: Behavior of Panametrics Drive Pulse at Ceramic

Figure 7 shows the pulse excitation driving the gold electrode, corresponding to figure 5. With the more complicated tuning topology of series-series-shunt, the ringing of the excitation voltage is apparent, as well as delayed spike voltages that activate the transducer out of phase. The reason the probe response is not very broadband is apparent by taking the FFT of the actual driving waveform at the electrode. It is seen that the notch creating a low shoulder on the right side of the transducer passband response is not a defect in the acoustic stack design, but a net result of the drive waveform having notch in its spectrum in the vicinity of 4.5 MHz.

A solution to the poor performance with shunt tuning elements can be provided by considering the transducer/coax/inductor system to be a resonant circuit, and adding a resistive element to dampen the circuit "Q", or ringing factor. Thus, the undesirable results seen in figure 5, can be corrected by introducing a resistive element shunt to ground, in the leg with the shunt inductor. This basically helps set the Q or resonance factor of the equivalent circuit of the probe to a more desirable range of Q equal approximately 2, for broadband performance.

The thermal noise voltage generated by such a damping resistor is given by:

$$Vn = \sqrt{4kTR \cdot \Delta f} \qquad \text{Equation(1)}$$

where k is Boltzmann's constant, T is temperature in degrees Kelvin, R is the resistance in ohms, and Δf is the frequency bandwidth.

For a 47 ohm resistor, and a 100 % bandwidth of 3.5 MHz, the thermally generated Johnson noise is only 1.7 micro-volt. Any thermal electronic noise generated by the physical resistor is attenuated from being injected into the pre-amp directly by placing it on the ground side of the inductor, thus forming a voltage divider. The results from adding a R=47 ohm tuning component in the shunt tuning leg are: (as driven by the Panametrics like pulse shape)

BW	Fc	PL20	PL30	Sensitivity
75.7%	3.70	1.13 us	1.70 us	0.0093 v

The results show that the delayed, pronounced positive going pulse lobe from inductive kickback has been squelched by adding the damping resistor Rp. This results in much better pulse echo performance. The remaining oscillations seen in the main bang are primarily high frequency, and do not effect the passband of interest significantly.

For a symmetrical pulse drive shape, such as a full single cycle of a square wave, it is not so critical to have the resistive damping component in the tuning network.For example: -with 47 ohm resistor in the tuning (full wave square drive):

BW	Fc	PL20	PL30	Sensitivity
66.7%	3.45	1.61 us	2.58 us	0.055 v

-with no resistor in tuning:

BW	Fc	PL20	PL30	Sensitivity
70.6%	3.40	1.64 us	2.63 us	0.059 v

Influence of Pulse Width:

Rather than use a more complex bipolar, push/pull pulser drive, systems with hundreds of channels sometimes take a less costly approach of implementing a pulser that only a creates a unipolar, half wave, negative going square drive shape. However, much better broadband performance can be obtained from a probe driven with a unipolar pulse drive, if the width of the pulse duration is set to a quarter of a wave period (at the center frequency), rather than a half wave duration. The quarter wave drive basically emulates the broad band performance of a spike pulser, but with significantly more energy coupled into the transducer, for much better pulse echo signal to noise strength. It is also more consistent to achieve repeatable results. The rise time of a Panametrics type spike pulser varies considerably from unit to unit. The concept of the quarter wave drive is somewhat analogous to pushing the girl in a swing in the opposite direction, one forth of a period after she is released, resulting in damping of the oscillation of the swing/pendulum.

The results with a quarter wave unipolar pulse and resistance (Rp=47 ohm) added to the tuning circuit shunt leg are seen in figure 8:

BW	Fc	PL20	PL30	Sensitivity
81.7%	3.55	1.61 us	2.50 us	0.0198 v

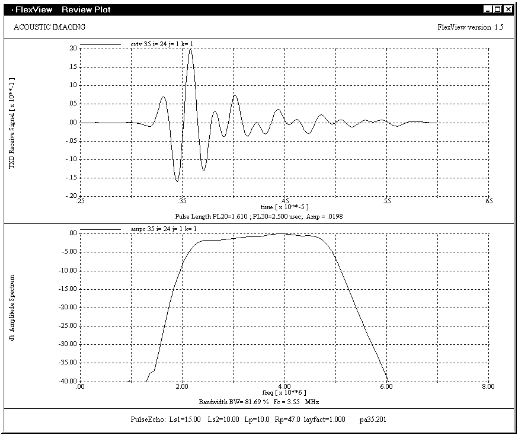


Figure 8: Pulse Echo performance with Quarter wave unipolar excitation.

Main Bang Pulse Behavior

It is interesting to observe the distortions and changes in the applied pulse drive shape as it travels through the tuning components, down the transmission line, and arrives at the gold electrode to excite the piezoelectric ceramic element. Figure 9 shows the reaction of a single cycle square wave pulse drive at the actual ceramic gold electrode, after passing down the transmission line, along with its frequency content. The ringing is predominantly at higher frequencies, outside of the passband of interest for pulse/echo response.

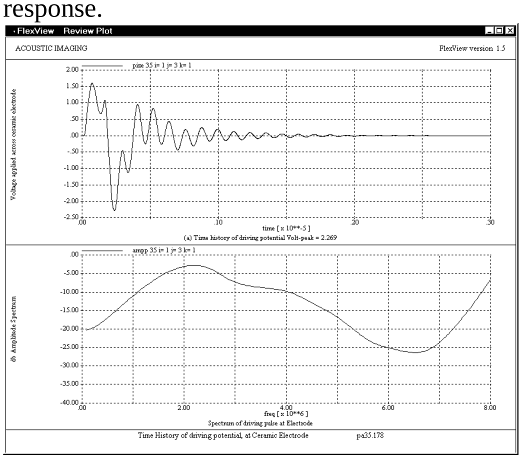


Figure 9: Main bang behavior (and its frequency content) of square wave drive at the ceramic gold electrode.

Performance of Various Tuning Topologies:

Electrical Impedance Transformation

Table I lists the electrical impedance and phase angle of the probe, as measured at 3.5 MHz, for various tuning topologies:

Table I:

Tuning	Impedance - Z	Phase Angle
Coax only	283.7 ohms	-72.9 degs
Transformer(2:1)	183.9	+44.4
Series-Series	172.2	-5.62
Series-Shunt	406.7	-33.1
Series-Series/Shunt	163.9	+11.5

The electrical impedance and phase angle looking at the connector end of the transducer/tuning/cable assembly is plotted in figures 10 - 11 for various tuning topologies. Figure 10 is for the case of no tuning (coax only); and figure 11 for Series-Series/Shunt tuning. It is seen that with series-series/shunt tuning, an impedance across the passband that is very flat and uniform is achieved. Also, the phase is linear and well behaved.

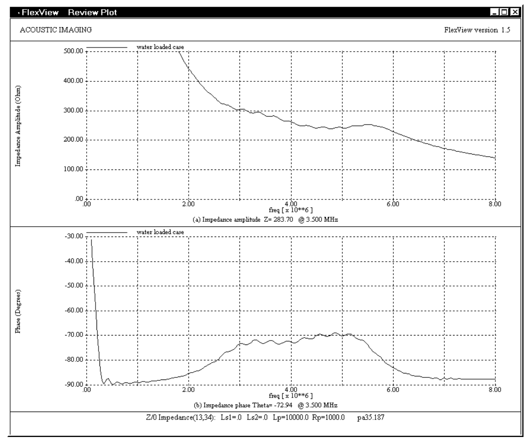


Figure 10: Electrical Impedance/Phase angle with no tuning (coax cable only).

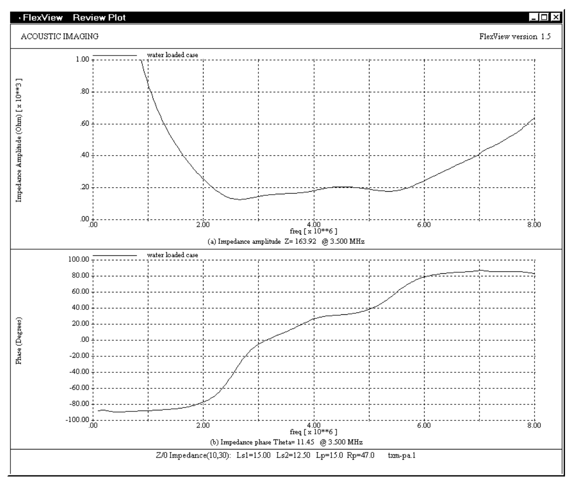


Figure 11: Electrical Impedance/Phase angle with Series-Series/Shunt Tuning.

Pulse/Echo Response:

Transformer Tuning:

In principle, matching the high impedance ceramic element with a transformer of the proper turns ratio before it drives the coax cable would be the technically superior way to tune a transducer, since it matches over a broadband of frequencies. However, this tuning scheme can be more expensive and occupy more space, making the probe handle size larger. With transformer tuning, for a single cycle sine pulser drive the results would be:

BW	Fc	PL20	PL30	Sensitivity
70.3%	3.70	1.22 us	1.91 us	0.038 v

However, used with a non-symmetrical unipolar, quarter wave, square pulse drive shape, the results with transformer tuning degraded to:

BW	Fc	PL20	PL30	Sensitivity
40.0%	3.75	1.45 us	2.42 us	0.019 v

Since a transformer intrinsically consists of significant inductance in a shunt topology, it suffers the same degradation of other shunt inductor tuning schemes, when used in conjunction with non-symmetrical unipolar pulse drive shapes!

When achieving the utmost bandwidth is not a concern, many times the best choice of tuning is a combination of series-series inductor elements. With a unipolar quarter wave drive this yields the results:(figure 12)

BW	Fc	PL20	PL30	Sensitivity
72.0%	3.75	0.830 us	1.040	0.087 v

This tuning generates a very short, clean pulse ringdown.

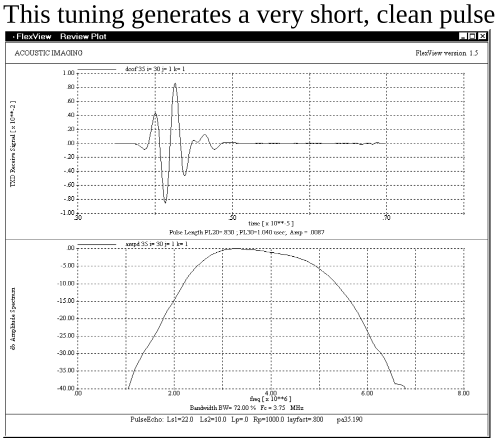


Figure 12: Pulse Echo response with Series-Series Tuning.

With Series/Shunt tuning, bandwidths of 90 % can be achieved (see figure 13).

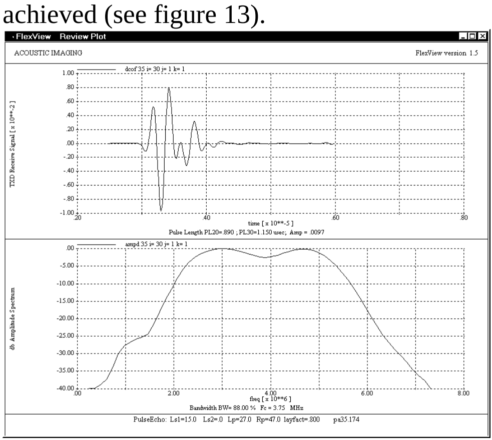
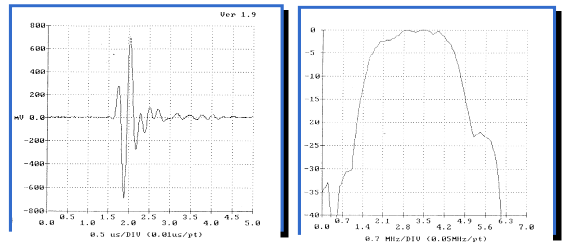


Figure 13: Pulse Echo response with Series /Shunt Tuning.

Experimental Results:

The experimental results for an innovative new construction technique for phased array transducers, combined with optimized tuning are illustrated in figure 14. For the first time, bandwidths in a phased array probe of 90% combined with clean pulse ringdown, are achievable.



PL20 = 1.04 usec BW = 95.2 %

Figure 14: Experimental results of new transducer architecture for phased array construction, with series-shunt tuning. Bandwith BW = 95.2 % ; -20 dB pulse length PL20 = 1.04 microsecond.

Discussion:

The electromotive voltage generated by the inductive kickback of inductor tuning components, can have a significant effect on pulse performance. Thus the choice of tuning topology and pulse drive shape are critically interdependent. It is important to note that these interesting observations would not be predicted or observed in transducer computer models that do their base analysis in the frequency domain, such as KLM , Piezocad, or finite element analysis (FEA) codes such as Ansys or Algor, which use algorithms setup in the frequency domain. Here we have utilized a very fast FEA code (PZFLEX) which computes all results in the time domain and is ideally suited for transient analysis. Linear system theory says:

$$y(t) = \quad g(t,r)\, u(r)\, dr$$

where u is the input, y is the output, and g is the impulse response, or Green's function. The implication of this convolution integral is that one can freely go between the time domain and the frequency domain via use of the FFT or inverse FFT.

The reason these significant results are missed by the other computer models, is that the tuning network circuit is not a linear system. This is because of the electromotive kick back effect found in inductive elements, that creates an opposing self voltage, internal in the inductor element proportional to $V = L\,(di / dt)$. This introduces a feedback element in the circuit and subsequently makes the system non-linear.Other reasons for system non-linearity's include: 2) the switch over of T/R impedance's after the main bang of the pulser. Typical transmitter source impedance's are 5 ohms, whereas typical receiver loads are from 100 to 500 ohms, 3) polarization hysteresis in ceramic, 4) non-linearity's of the propagation medium (water).

Conceptually transformer tuning can yield the best impedance match over the widest frequency. However, really broad band pulses could not be achieved from transformer tuning, when using non-symmetrical transmitter pulse shapes, such as unipolar pulse drives. Moreover, the best tuning topology found in this case study of a phased array, was the combination series -series/shunt with judicious choice of component values . When an additional resistive element is included in the shunt leg, to control the circuit Q (or damping) factor, this tuning topology is well behaved under all drive conditions, including spike and asymmetrical pulses. Thus it was found to be the best and most ubiquitous tuning topology for all conceivable pulse shapes. With this modification, series/shunt tuning combinations can result in clean pulse shape, and broader band performance than transformer tuning, or series inductor element tuning. Series inductor tuning is a simple scheme to implement that stays well behaved, even with unipolar, asymmetric pulse shapes. It gives the shortest, cleanest pulse ringdown, and will yield about 72 % bandwidth. When using a unipolar pulse drive, a quarter wavelength pulse width gives the best combination of short pulse, broadband response with good signal output strength .

By optimizing a series/shunt tuning circuit component values with statistical design of experiments methodology (DOE), experimental bandwidths for a phased array element of 90 % were achieved with clean pulse lengths of 1.00 micro-second. It is not unusual to achieve 80 % bandwidth in a linear or convex array, but this is very difficult to achieve in a sector phased array for cardiology. This is because, to create wide angular sensitivity, the elements must remain significantly isolated from each other acoustically, without coupling to spurious modes. Here, a major new design architecture was combined with new acoustic materials to achieve state of the art performance, for a cardiac phased array probe. Significantly, with the optimal tuning network, not only is bandwidth maximized, but also round trip sensitivity is increased by 6 to 9 dB over the untuned case (coax only). This can result in up to two centimeters more useable penetration depth in the image, and enhanced sensitivity for Doppler blood flow studies .

Conclusions:

In summary, the following conclusions can be made.

1. Pragmatically a true spike pulse for testing the impulse of a transducer is difficult to obtain, and be consistent from instrument to instrument; **2**. An excellent choice for the generation of a very broadband pulse with good signal to noise ratio, is the unipolar Quarter wave pulse drive. a) it should be used with judicious choice of a damping resistor; **3**. One can optimize the tuning network component values with a statistically designed experiment (DOE) methodology. a) best values for broadband performance are usually "skewed" from a nominal conjugate impedance match.; **4**. The most universal tuning topology is the series-series-shunt configuration. a) works better than even transformer tuning b) achieves very broadband performance c) gives a very flat electrical impedance for the probe, across the passband, coupled with linear phase response; **5.** Using proper tuning configurations and component values, can increase the round trip pulse echo sensitivity by 6-9 dB ! a) this is significant! ; **6**. For the shortest pulse ringdown response, use Series-Series tuning. (also yields slightly higher center frequency); **7.** Add a shunt resistive component to control damping (Q) of circuit network for best Broadband performance. a) very helpful when shunt inductor components are used b) is especially needed when one has to use a Unipolar pulse drive shape (as opposed to a more symmetrical bipolar pulse drive) c) the added thermal noise is less than 2 micro-volts, and is negligible; **8**. Remember the TIPIT principle when qualifying performance specifications for new transducer design: "Test It the way you Plan to use IT ! "a) this avoids surprises between translating water test tank data to expected clinical image quality. b) prevents misunderstandings and disappointments between suppliers and clients.

9. Computer Modeling Issues:

- use a Time Domain analysis code (PZFLEX), for more accurate predictions. b) no surprises comparing to experimental results c) no lost opportunities d) modeling programs that do the analysis primarily in the frequency domain first, (such as the KLM model) cannot accurately predict the behavior of certain tuning networks, with the attendant feedback effect due to the electromotive kickback created with inductive components;

10. Experimental broadband performance of 90% bandwidth has been achieved with significant improvements in sensitivity and excellent pulse ringdown resolution for a 3.5 MHz sector phased array probe used for cardiology imaging.

- includes major new acoustic design innovations
- with optimized tuning

11. Benefits of new optimized phased array architecture :

- Broad band HARMONIC Imaging
  - contrast agent studies
  - native tissue echoes
  - clutter reduction in Cardiac images
- Signal Processing and Speckle reduction schemes
- Excellent sensitivity
- Clean pulse ringdown resolution
- Wide angular sensitivity for wide angle (+/- 45 degs) beam steering

Acknowledgments:

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