CURRENT AND VOLTAGE SENSING IN ACT 'BLOCK NDS' TRANSVERSAL FILTERS

R. L. Miller and D. S. Bailey

Westinghouse Electric Corp.
Nursery & Winterson Roads
Linthicum, MD 21090

ABSTRACT

Fixed ACT transversal filters look like apodized SAW transducers, but because they capacitively sense charge packets directly below the surface, the individual lines can be smeared together into two plates separated by a wavy boundary. In the conventional "voltage sense" approach, the shape of the gap is made to be the desired impulse response, and each side is loaded by an RC network. We describe a "current sense" approach, in which the shape of the gap is the integral of the desired impulse response, and the current which must oscillate from one Non-Destructive Sense (NDS) plate to the other is taken to be the output. Unlike voltage sensing, current sensing does not have a "DC pedestal" in its impulse response to create an undesired passband at low frequencies.

INTRODUCTION

Figure 1 shows the Non-Destructive Sense (NDS) plate structure of a particular ACT bandpass filter. In the conventional "voltage sense" approach, for which this device was designed, the shape of the boundary between the two plates is made to be the shape of the desired impulse response, and each side is loaded by a parallel RC combination. Figure 2 shows the desired impulse response for the device shown in Figure 1, and Figure 3 shows its theoretical frequency response, after including the slow rolloff for the "element factor," which is due to the finite extent of the charge distribution induced on the NDS plates by a single charge packet.

For an impulse into the ACT channel, the voltage across each RC network is the desired impulse response superimposed on a DC pedestal. Moreover, the DC components of the signals on the two NDS blocks are the same, while the AC components are 180° out of phase. The corresponding frequency response at each NDS plate is the sum of the desired filter response and an undesired baseband response, the latter being the Fourier transform of the DC pedestal.

The baseband response can be quite large: the theoretical response shown in Figure 4 shows that the peak at DC can be substantially larger than the desired passband (by about 30 dB in this case), and the sidelobes of this objectionable baseband response are still large enough at the center frequency of the device to distort the passband. Single-ended measurements of this device and others like it do indeed display such characteristics. Smoothing the edges of the pedestal, by curving the ends of each NDS plate can reduce the spurious levels near the desired passband, but it does not remove the high peak at DC when a single-ended output is used.

Although the baseband response can in principle be cancelled by a differential amplifier, imperfect cancellation usually results, and large spurious sidelobes usually remain at low frequencies. The response shown in Figure 5 was measured by connecting each NDS block of the filter of Figure 1 to one of two matched source follower amplifiers, and subtracting the outputs of these with a 180° hybrid. The remains of a DC pedestal are clearly evident, and the spurious sidelobe levels at low frequencies are still as high as the desired passband. Figure 6 shows a theoretical response, in which 1/10th of the baseband pedestal remains uncancelled. Figures 5 and 6 show good general agreement.

CURRENT SENSING

In this paper we describe an alternative "current sense" approach, in which the shape of the gap is designed to be the *integral* of the desired impulse response. The output is then taken to be the current which must oscillate from one Non-Destructive Sense (NDS) plate to the other, as the image charge follows the charge packets below the surface. Unlike voltage sensing, current sensing does not have a "DC pedestal" in its impulse response to create an undesired passband at low frequencies. The current out of each NDS plate is the *derivative* of the shape of the boundary.

Figure 7 depicts the left end of the device, after a single charge packet has entered the NDS region. The positive image charges induced on each NDS plate are shown, and are assumed to have a uniform density Q/W (like the electron packet underneath does), and are travelling to the right at the acoustic velocity v. If the shape of the boundry is y(x), then at any instant the total charge on the bottom NDS plate is Qy/W, and the charge on the top plate is Q(W-y)/W. In time Δt, the charge packet travels $\Delta x = v\Delta t$, and causes a charge ΔQ to move from bottom plate to top plate in order to follow the electron packet underneath the plates. This results in a current out of the bottom plate

$$i_B = \frac{\Delta Q}{\Delta t} = \frac{-Q}{W}\frac{dy}{dt} \tag{1}$$

and a voltage V_B across resistor R

$$V_B = \frac{-QR}{W}\frac{dy}{dt}. \quad (2)$$

Suppose our NDS plates are designed for voltage sensing. In this case, if we represent y as a function of time t = x/v,

$$y(t) = \frac{W}{2}\left[U(t) - U(t-T)\right] + \frac{W}{2}h(t) \quad (3)$$

where h(t) is the desired impulse response which has a maximum magnitude of ±1, and U(t-T) is a unit step function at time t = T = L/v, L being the length of the NDS plates. Using (2),

$$V_B = -\frac{RQ}{2}[\,\delta(t) - \delta(t-T) + \frac{d}{dt}h(t)] \quad (4)$$

while the voltage across the top resistor is

$$V_T = -\frac{RQ}{2}[\,\delta(t) - \delta(t-T) - \frac{d}{dt}h(t)] \quad (5)$$

The delta functions add a sinusoidal function to the single-ended frequency response:

$$V_{B,T} = -jRQ\,sin(\pi fT)e^{-j\pi fT} \pm \frac{j\omega RQ}{2}H(f) \quad (6)$$

A numerically calculated version of this single-ended response, with the element factor included, is shown in Figure 8. The first term of (6) is zero at DC and at multiples of 1/T (= 1.59 MHz for the device shown above), and maxima at multiples of 1/2T. As is clear from the figure, these maxima are small compared to the magnitude of the second term, which represents the desired passband of the device. Even with an imperfect differential amplifier or hybrid, the sinusoidal term will not be troublesome. The presence of the factor ω in front of the passband term means that if a device that was designed for voltage sensing is measured in current sensing mode, its frequency response will be distorted by an upward tilt. Figure 9 shows the device of Figure 1 measured in current sense mode with the same 180° hybrid. No baseband pedestal is evident, while the passband is clearly tilted upward.

The $j\omega$ factor makes sense: the impulse response of a device with a lower center frequency has a "carrier" which varies more slowly than that of a device with a higher center frequency. This means the derivative of the waveform is lower, so the current is smaller. (The envelope of the impulse is slowly varying, so it doesn't contribute much to the current.) This also means that, for a given width W, a higher frequency device measured in current sense mode will have lower insertion loss than a low frequency device.

If the device is designed for voltage sensing, this upward tilt is removed by integrating the signal in the time domain. This is usually done by placing a capacitor across each resistor in Figure 7. The frequency domain representation of this is a 1-pole rolloff of some sort, where the corner frequency $1/2\pi RC$ is chosen to be below the frequency range of interest (i.e. the desired passband H(f) of the device), so the impedance of the parallel RC is $Z \approx 1/j\omega C$. Following the same steps as above, but with Z substituted for R gives

$$V_{B,T} = -\frac{Q}{C}\frac{T}{2}\frac{sin(\pi fT)}{(\pi fT)}e^{-j\pi fT} \pm \frac{Q}{2C}H(F) \quad (7)$$

The first term in (7) again represents a spurious baseband response, but one which is much bigger than the desired response. (See Figure 4 above.)

Finally, we may design the device properly for current sensing by designing the boundary y(t) between NDS plates to be the integral of the desired impulse response. Specifically, in order to design the artwork for the device, we calculate the time integral of the desired impulse (usually numerically), and rescale the impulse integral to fit within the channel aperture $\pm W/2$. Figure 10 shows the result of such a numerical calculation. For purposes of analysis we can approximate this rescaling by

$$y(t) = \frac{W}{2}\left[U(t) - U(t-T)\right] + \frac{jW}{2}\omega_0\int_0^t h(t)dx \quad (8)$$

which makes use of the fact that h(t) is usually a slowly-varying envelope multiplied by a fast-moving "carrier" which is essentially a sinusoid at frequency ω_0. Integrating this h(t) is approximately equivalent to integrating just the sinusoid. Integrating a sine wave of frequency ω_0 results in a factor of $1/\omega_0$. This factor is removed by the rescaling operation, and is removed in (8) by the factor ω_0 in the second term.

The single-ended output from a device designed for and measured by current sensing is

$$V_{B,T} = -jRQ\,sin(\pi fT)e^{-j\pi fT} \pm \frac{j\omega_0 RQ}{2}H(f) \quad (9)$$

This is similar to equation (6) except that the second term is multiplied by ω_0, which is a constant, so the passband shape is no longer tilted. Like (6), the undesired term is small compared to the desired response term, so even imperfect differential cancellation will be acceptable.

Insertion Loss Comparison

The ACT channel by itself is inherently a high-impedance device. The input impedance of the device is quite high, which is equivalent to saying that the transconductance of the device is very low: about 20 μS at RF. The output equivalent circuit of an NDS plate essentially looks like a (small) current source shunted by the parasitic capacitance to ground of the metal plate, which can be substantial for some epi layer structures. The amount of signal that can be developed in an output load thus depends on whether we consider the signal to be the output current or the voltage this current can develop across the load impedance. This choice in turn depends on noise considerations for specific output amplifier scenarios.

If the output amplifier is to be a low noise current amplifier, then designing the device for current sense mode will make more sense for high-frequency bandpass devices, since the output current will be larger than for low-frequency devices. Baseband devices are not feasible with current sensing.

If the output amplifier is to be a low noise voltage amplifier, then Table I below compares the effective differential voltages that can be developed at the input impedance to the differential amplifier for the three cases analyzed above. This input impedance is assumed to be a parallel RC, where C is the sum of the NDS output capacitance, the amplifier input capacitance, plus any parasitic cpacitance. Current sensing occurs when the resistance is low enough that R dominates, and voltage sensing occurs when C dominates. In the table below, $X(\omega_0)$ represents the reactance of this capacitance at the design center frequency of the device.

Table I

Scenario	V_T-V_B
Designed for voltage sensing, tested by current sensing	$j\omega RQH(f)$
Designed for current sensing, tested by current sensing	$j\omega_0 RQH(f)$
Designed for voltage sensing, tested by voltage sensing	$\frac{Q}{C}H(f)$, or $j\omega_0 X(\omega_0)QH(f)$

Thus Q/C represents the maximum voltage that can be developed across the load. If the total capacitance C is dominated by the NDS plates, then two different devices having different center frequencies but the same absolute bandwidth will have the same maximum voltage. ACT channelizers, formed by dividing the NDS region into parallel channels each with different center frequencies but the same bandwidth in Hz will thus have the same voltage limit if dominated by the NDS capacitance: Q goes down for each subchannel, but so does C.

Conclusion

A method has been shown and analyzed for the design of fixed ACT filters using current sensing. This approach has the advantage of having no "baseband pedestal" in the response, and can supply a large output signal for high-frequency devices if the output amplifier is a current amplifier. For baseband devices or scenarios involving a high-impedance amplifer, voltage sensing is preferable.

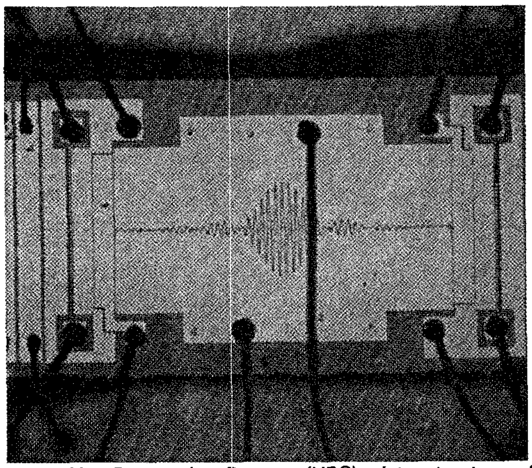

Figure 1: Non-Destructive Sense (NDS) plate structure of ACT transversal filter.

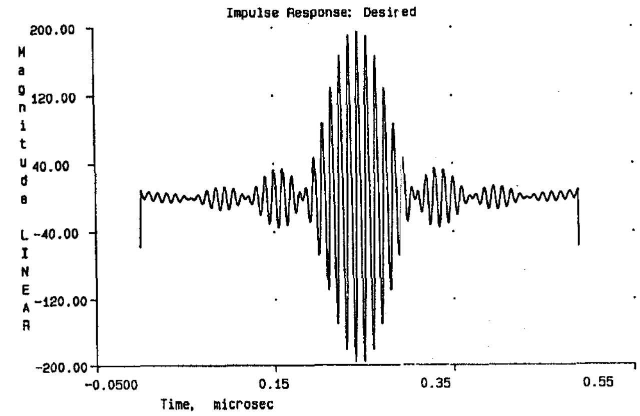

Figure 2: Desired impulse response of device shown in Figure 1 has same shape as boundry between NDS plates.

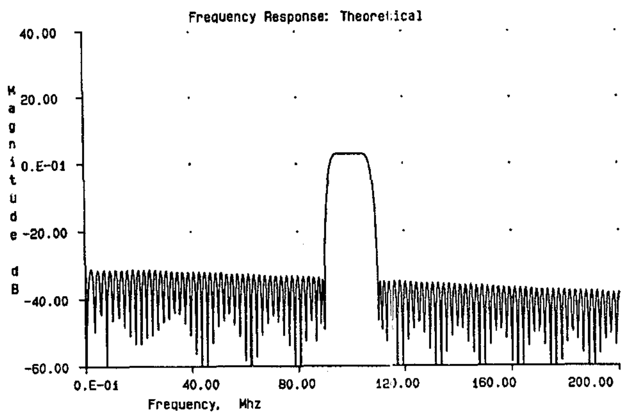

Figure 3: Design frequency response of device shown in Figure 1.

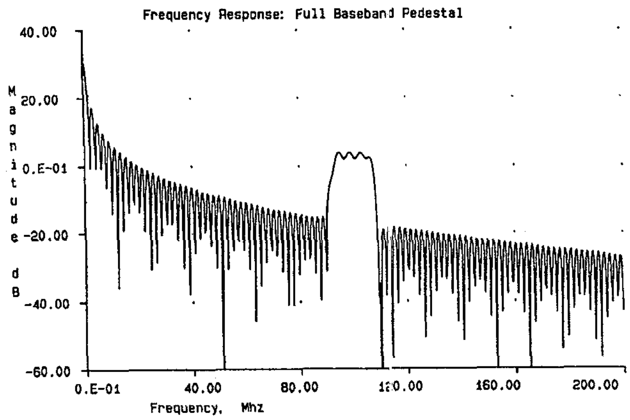

Figure 4: Calculated output of one NDS block of device of Figure 1, showing results of full baseband pedestal. Note large spurious passband at DC, which is typical of voltage sensing.

Figure 5: *Device of Figure 1 measured in differential voltage sense mode. Substantial spurious peak at DC still remains, due to imperfect cancellation.*

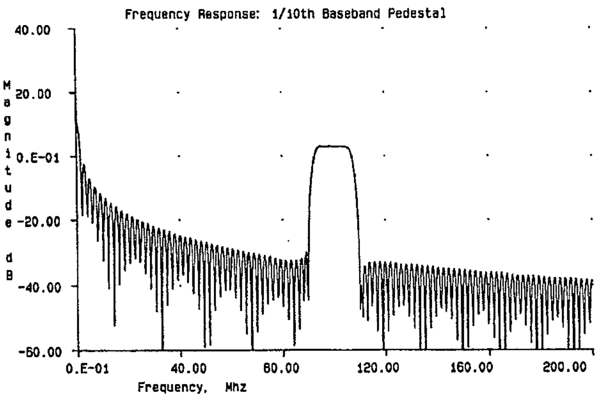

Figure 6: *Calculated response with 1/10th of full basband pedestal shows good agreement with Fig. 5.*

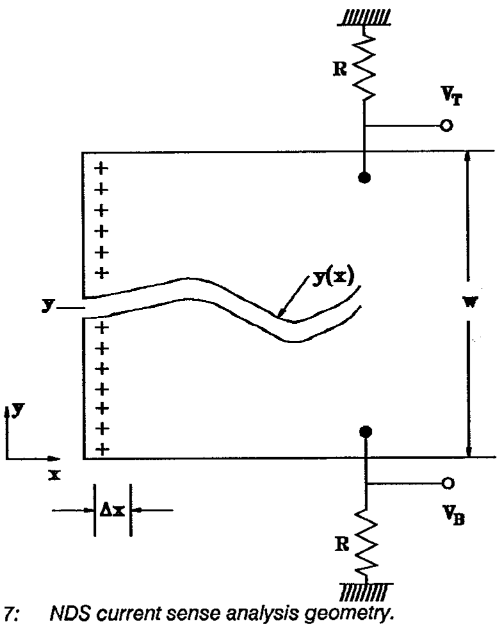

Figure 7: *NDS current sense analysis geometry.*

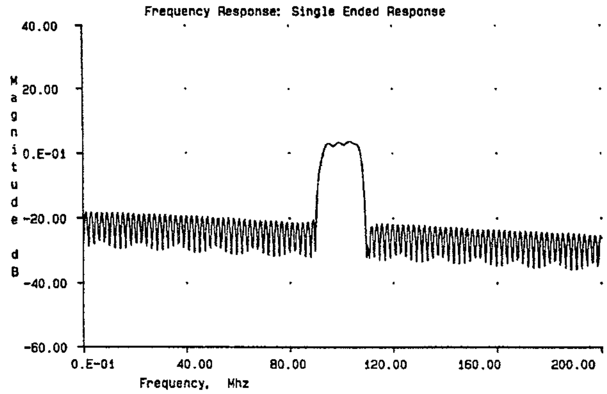

Figure 8: *Calculated single-ended response of ACT filter designed for voltage sensing but tested by current sensing. Upward tilt is present in passband, but does not appear as pronounced as in Fig. 9 due to different horizontal and vertical scales in this figure.*

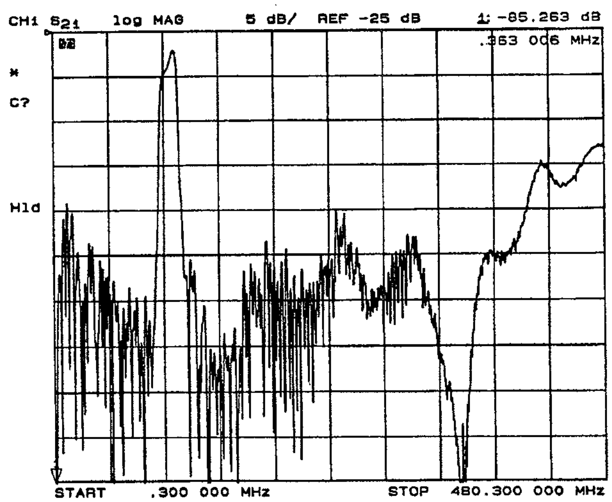

Figure 9: *Measured response of Fig. 1 device, designed for voltage sensing but tested by differential current sensing. Note upward tilt in passband, as predicted.*

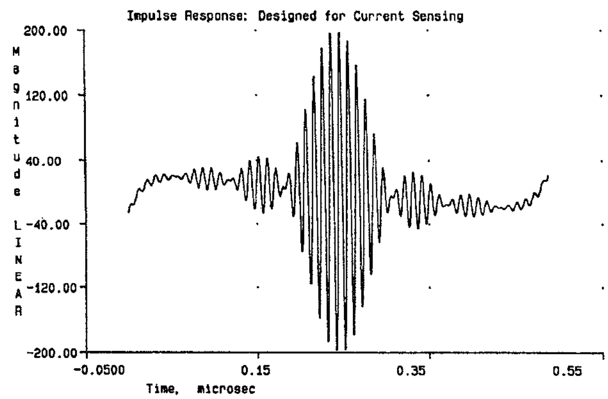

Figure 10: *NDS plate boundary designed for current sense operation is the integral of shape shown in Figs 1 and 2, rescaled to fit within 400 micron ACT channel aperture.*