WCM00

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Electromagnetic beam position monitors usually have difference outputs (Δ) which are proportional to both displacement and beam intensity. To get an intensity-independent displacement signal, it is necessary to normalize against the sum signal (Σ) which is -conveniently- also usually available:

$$x \propto \frac{\Delta}{\Sigma} \tag{1}$$

In the case of WCM00, a high bandwidth device, both Δ and Σ channels depend on the instantaneous beam current. Unfortunately in the case of WCM00, the lower cut-off frequencies of these two signals are not the same, so that the simple normalization of (1) doesn't work.

In the monitor, the beam image current is forced to flow through a number of resistors that bridge a gap in the vacuum chamber. The voltage across these resistors is the output of the monitor. The whole monitor is enclosed inside a metallic box that diverts currents flowing on the outside of the vacuum chamber, which would otherwise be seen as interference. However, this box is also a short-circuit for the desired output signal. By inserting ferrite rings inside it, around the vacuum chamber, this short-circuit will actually look like a shunt inductor, so that the output signal acquires a high-pass characteristic.

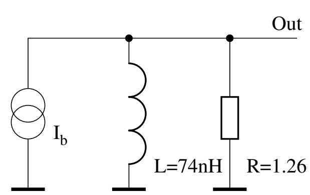

Figure 1: Low-frequency equivalent circuit of a wall current monitor

The value of the shunt inductor shown in Fig.1 is appropriate for the Σ output. For the Δ outputs, it's much less: about 21 nH. As a result, the lower cut-off frequencies are different. Fig.2 shows the asymptotic approximation of the frequency responses of the Σ and Δ outputs of the WCM. The actual curves would be smooth, of course.

This has its consequences in the time domain too. If we were to pass a beam with a Gaussian longitudinal profile through the monitor, say about 40 mm off-centre, the Σ signal would look like the green curve in Fig.3, while the Δ signal would be more like the red one. Note the greater undershoot of the Δ signal. Normally, the Σ and Δ signals would have been expected to be about equal for a 40 mm displacement.

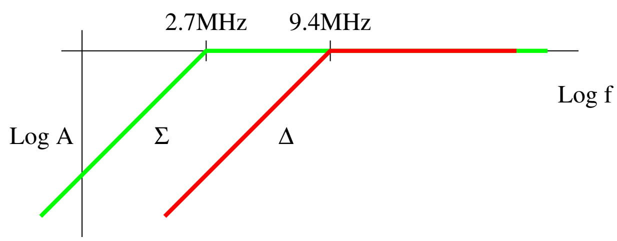

Figure 2: Frequency response of WCM Σ (green) and Δ (red) signals

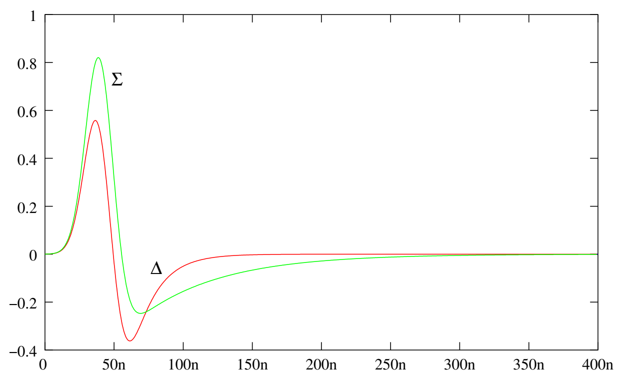

Figure 3: Time-domain response of WCM Σ (green) and Δ (red) signals with Gaussian stimulus

If we were to try to calculate the beam position by simple application of (1), we get the result of Fig.4 (red), which is not at all the desired result. In fact, in the timespan where the beam signal is non-zero, we would have wanted to see something like the green line. Outside this interval, the result would be undetermined.

Since we have the signals in digital form, acquired using a high-speed oscilloscope, we might try to apply some numerical filtering to make the frequency responses of the Σ and Δ signals match. The filter, applied to the Δ signal, would have a frequency response as depicted in Fig.5. On its logarithmic scale, this is just the difference between the green and red curves of Fig.2. Again, this is an asymptotic approximation.

Numerical filters can be very simple. We basically need a low-pass section at 2.7 MHz and a high-pass at 9.4 MHz. The general structures are depicted in Figs. 6 and 7. The blocks labelled z^{-1} are simply one-sample delays. This comes from digital signal processing math, where transfer functions are written in the z-domain. What remains to be done then is to find values for the coefficients a and b, such that the filter has the desired response, and to translate this into a little piece of program code.

Now I'll proceed in leaps and bounds, as going into much detail would turn this into a complete signal processing course. A low-pass filter with a corner frequency f =2.7 MHz would have a time-constant of $\tau = 1/2\pi f = 59$ ns. The step response of the filter would reach a fraction of $1 - e^{-t/\tau} = 1 - e^{-1} = 0.63$ of its final output at that time. The remaining error is thus $e^{-1} \approx 0.37$. For the numerical low-pass filter, this error amounts to a^n where n is the number

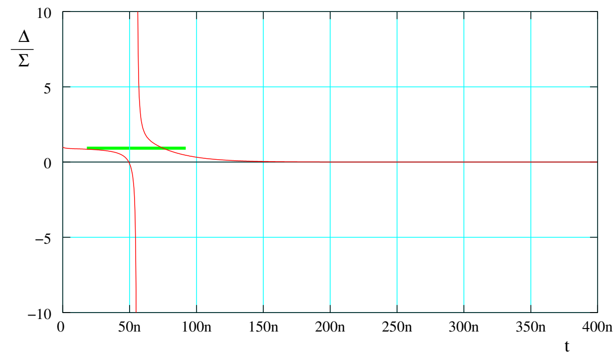

Figure 4: Time-domain position with uncorrected Δ signal (Gaussian stimulus)

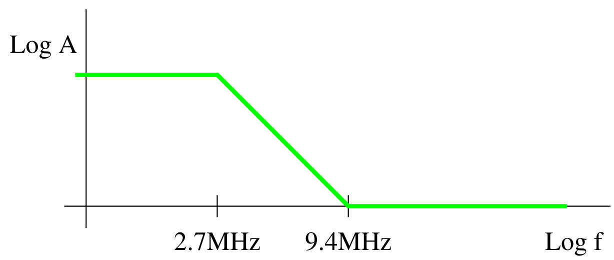

Figure 5: Filter curve for correction of Δ response

of iterations (samples) of the filter in time τ. So we want to find a such that $a^n = e^{-1}$. Solving this, we find $a \approx \sqrt[n]{0.37}$. In the sampled-data domain, with its 2.5 GS/s sampling rate, n is 147 samples, so $a = 0.99324$. Along the same lines, for a corner frequency f =9.4 MHz, we find $b = 0.97665$.

We can merge the two filters to eliminate one of the 1-sample delays, viz. Fig.8. From this figure, it's easy to write down a snippet of C-code to implement this:

```
#define a 0.99324
#define b 0.97665

double filter(double x)
{
    double y;
    static double e=0.0;

    y = x + (a-b)*e;
    e = x + a*e;
    return y;
}
```

Certainly a whole lot shorter than a pair of Fourier transforms!

The complete transfer function of this filter in the z-domain is then

$$\frac{y}{x} = \frac{1 - bz^{-1}}{1 - az^{-1}} \tag{2}$$

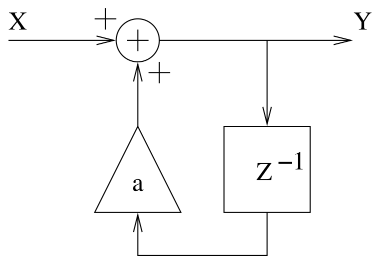

Figure 6: A low-pass filter

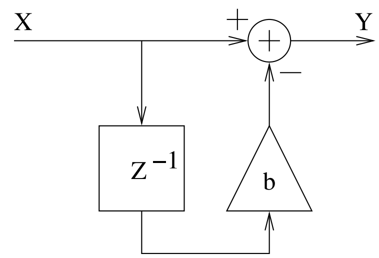

Figure 7: A high-pass filter

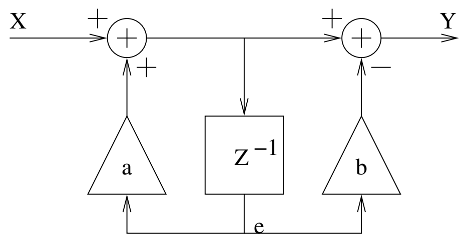

Figure 8: Numerical filter to correct Δ frequency response

And Fig.9 shows the actual Bode plot of the finished filter. Note also the phase response.

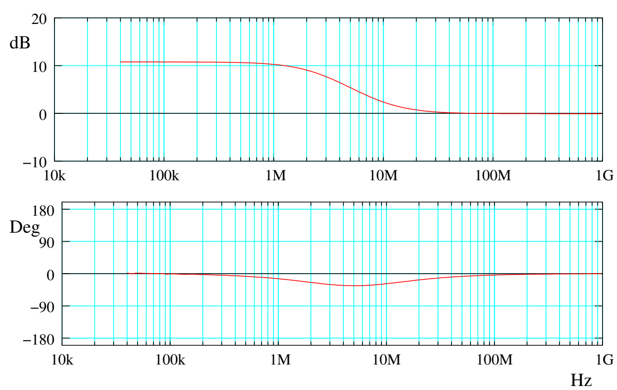

Figure 9: Bode plot of numerical filter to correct Δ frequency response

After correction, the position signal might look like Fig.10. There is still a small spike at the place where both Σ and Δ zip through zero. After all, we only corrected the Δ signal to be congruent with Σ, so both will still have an undershoot. You can't have perfection. I've thrown in some noise to demonstrate that the position is valid only where the beam signal is sufficiently large. Outside this range, the position is undetermined, which is nicely apparent by the fact that it jumps all over the place.

Now, how well this actually works with real signals remains to be seen. It depends on the possible presence of various other problems, such as offsets in time or amplitude, additional frequency dependencies, and noise and interfer-

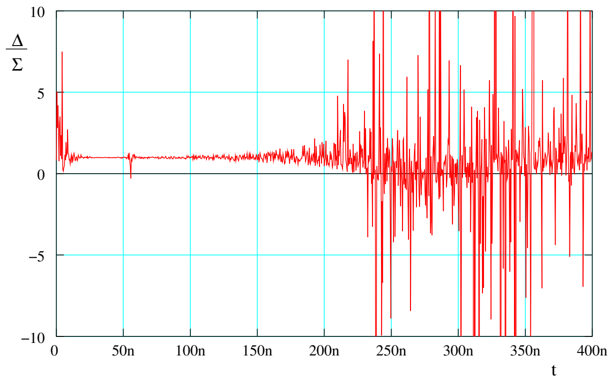

Figure 10: Time-domain position with corrected Δ signals (Gaussian stimulus)

ence levels. Reality is the final judge.