AUTOMATIC TUNING OF HIGH FREQUENCY, HIGH Q, MULTIPLE LOOP FEEDBACK BANDPASS FILTERS

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ABSTRACT

Off-line tuning of leapfrog multiple loop feedback bandpass filters is demonstrated using a modification of Dishal's method. The proposed method is suitable for high frequency, high Q bandpass filters, and has advantages including simplified tuning circuits and algorithms, minimal additional circuit parasitics and suitability for high frequency applications.

1. PROBLEMS OF BANDPASS FILTER TUNING

The drive to achieve the analogue signal processing "system on a chip" has led to major efforts by designers to integrate filter functions as part of the IC design. High frequency, high Q bandpass filters are important in many signal processing applications; traditionally these have been implemented using specialised passive components which are not readily fabricated in current IC technologies. However, high Q active bandpass filters operating up to the gigahertz range are possible.

High Q bandpass filters are particularly sensitive to changes in their pole frequencies. The bandwidth of the filter is small compared to the pole frequencies, so small fractional changes of pole frequency lead to severe distortions of the frequency response. Due to the high accuracy required, and to the wide tolerances of values of integrated components caused by process variations, environmental effects and parasitics, on-chip tuning is generally required.

A filter structure with low component sensitivity reduces the accuracy and resolution required from the tuning scheme. Leapfrog (LF) multiple loop feedback (MLF) active filters have lower sensitivity than other filter types [1]. Unfortunately, the multiple feedback paths that are responsible for low sensitivity also make these filters difficult to tune, since the positions of the poles are interdependent. The cascade of biquads architecture is easier to tune, since each conjugate pair of poles is created by a separate, independently tuned biquad. However, this structure has relatively high sensitivity.

The difficulties in tuning LF filters also apply to the LC ladder prototypes from which they are derived. One approach to tuning LC bandpass filters is to isolate the signal paths between individual resonators and tune these separately; the LF bandpass filter may similarly be divided into separate biquads for tuning, as in [2]. Another method of tuning LC bandpass filters was devised by Dishal [3]. It can be shown that this method is also applicable to LF active filters [4].

2. LC AND LF FILTER TUNING USING DISHAL'S METHOD

Dishal's method can be illustrated using the LC ladder bandpass filter shown in figure 1:

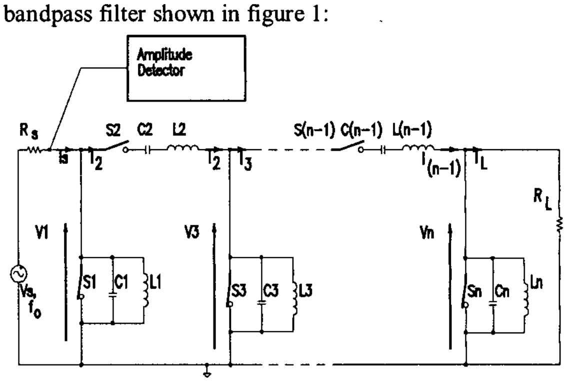


Fig. 1 LC Bandpass Tuning using Dishal's Method

Synthesis of this ladder filter with centre frequency ω_0 results in the inductor and capacitor values in each branch of the ladder having the same resonant frequency, $1/L_iC_i = \omega_0^2$. To tune the filter, initially all switches in the series arms are open, and all those in the shunt arms are closed. A signal is applied to the input at frequency ω_0, and V_1 is monitored by the amplitude detector. S_1 is opened, and C_1/L_1 are tuned to parallel resonance, i.e. maximum amplitude of V_1. Since S_2 is open, the resonator C_1/L_1 is isolated from the rest of the circuit, which therefore does not alter the resonant frequency. Next, S_2 is closed, and C_2/L_2 are tuned to series resonance and minimum V_1. Since S_3 is closed, C_2/L_2 are also isolated from succeeding stages of the filter. Each successive branch is then adjusted in turn, the shunt branches for maximum V_1 and the series branches for minimum V_1, with the associated switch being opened or closed. Since all preceding branches are already resonant, the reactive component of their net series or shunt impedance is zero, and they are "transparent" at frequency ω_0. When L_n/C_n have been adjusted, the tuning process is complete.

In tuning schemes for second order cascade filters, it is normally necessary to provide Q-tuning capability. This is not done when tuning using Dishal's method as described, and so the tuning process does not completely define the transfer function of the filter. The bandwidth and ripple in the response are defined by ratios between component values in different branches of the circuit, whilst the method described above only tunes the inductor and capacitor in each individual branch in isolation However, because all branches are resonant at ω_0, the passband is symmetrical, insertion loss is minimised, and gross distortion of the frequency response does not occur.

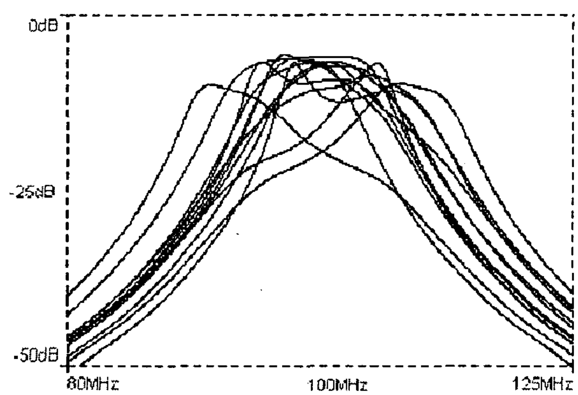


Fig. 2 Monte Carlo Simulation of Untuned Filter

Figure 2 shows a Monte Carlo simulation using PSpice of the amplitude response of a 3rd order Butterworth LC ladder bandpass filter, with centre frequency 100MHz and bandwidth 10MHz, and having a tolerance of 10% on all inductor, capacitor, and terminating resistor values. Considerable distortion of the amplitude response is evident. In figure 3, the same filter has been tuned using Dishal's method, by making each capacitor resonate with the corresponding inductor at 100MHz. Errors in component ratios are still present, but cause relatively minor effects, such as slight changes in bandwidth and passband ripple. In integrated filter designs, quite accurate matching of component ratios can be achieved, so it can be expected that tuning using Dishal's method will achieve sufficiently accurate results for many applications.

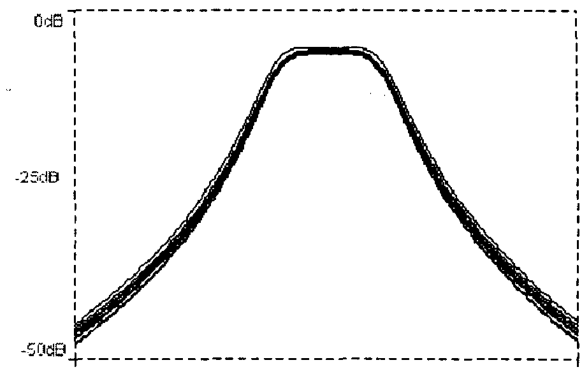


Fig. 3 Filter response after tuning by Dishal's method

Dishal's tuning method can readily be modified for use with LF active filters. Figure 4 shows the block diagram of a LF bandpass filter in which the outputs of active integrators simulate the capacitor voltages and inductor currents of the LC filter of figure 1. Thus, in both circuits the capacitor voltages and inductor currents, or the integrator outputs are of the form:

$$V = \frac{1}{sC_i}\left(I_{(i-1)} - I_i - I_{(i+1)}\right), \quad I_i = \frac{1}{sL_i}V_i,$$

$$I_{(i+1)} = \frac{1}{sL_{(i+1)}}\left(V_i - V_{(i+1)} - V_{(i+2)}\right),$$

$$V_{(i+1)} = \frac{1}{sC_{(i+1)}}I_{(i+1)}. \qquad (1)$$

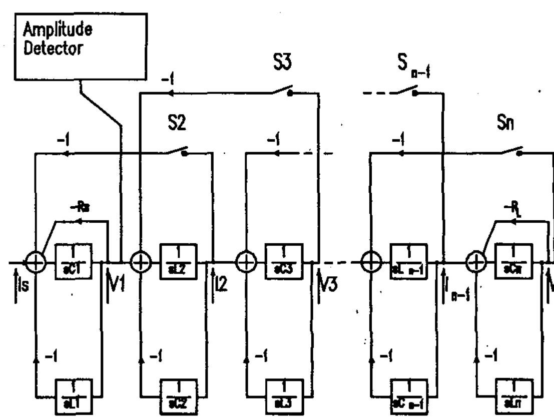


Fig. 4 LF Simulation of LC Bandpass Filter

Each LC resonator in the prototype is replaced by a two integrator loop biquad with the same ω_0. In the LC filter, coupling between resonators occurs because they are connected together; in the LF filter, this coupling occurs via the feedback paths. Therefore, the switches in figures 1 and 4 perform an equivalent function.

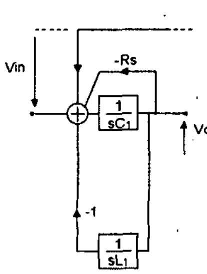
As in the LC prototype, it is only necessary to monitor the test signal amplitude at one point in the LF circuit, the output of the first integrator, V_1. Tuning of pole frequencies is performed by electronically varying the integrator gains.

3. IMPLEMENTATION

A single biquad making up part of the filter in figure 4 is shown in figure 5a. As an example, this could be implemented as the OTA-C circuit of figure 5b (the input current of the original LC network here becomes a numerically equal voltage). The transfer function of figure 5a is:

$$H(s) = \frac{s\frac{1}{C_1}}{s^2 + s\frac{R_s}{C_1} + \frac{1}{L_1 C_1}}; \qquad (2)$$

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}}, \quad \frac{\omega_0}{Q} = \frac{R_s}{C_1}, \quad K_{BP} = 1/R_s$$



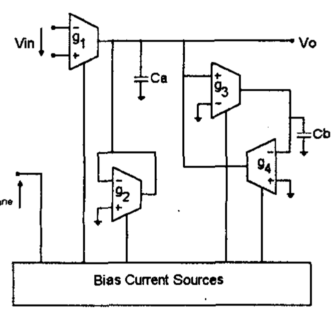


Fig. 5a Biquad *Fig. 5b OTA-C Realisation*

And that for figure 5b:

$$H(s) = \frac{s\frac{g_1}{C_a}}{s^2 + s\frac{g_2}{C_a} + \frac{g_3 g_4}{C_a C_b}}; \qquad (3)$$

$$\omega_0 = \sqrt{\frac{g_3 g_4}{C_a C_b}}, \quad \frac{\omega_0}{Q} = \frac{g_2}{C_a}, \quad K_{BP} = g_1/g_2$$

By equating coefficients in (2) and (3), the circuit of figure 5b can be used to generate the transfer function of figure 5a. The complete LF filter can be implemented by cascading a number of these biquads, and providing the feedback path connections. Only the first and final biquads have finite Q (corresponding to the terminating resistors of the prototype ladder network), so transconductor g_2 is only required for these stages. Suitable gain and impedance scaling will yield practical component values.

In order to implement Dishal's tuning method, $g_1 \ldots g_4$ and the bias current sources are dimensioned so that the ratio between the transconductances remains constant as V_{tune} is varied. Similarly, the ratio of C_a/C_b will be preserved with variations in absolute capacitance. Suppose process variations change all transconductances by a factor k_g, and all capacitances by a factor k_c. The transfer function of figure 5b then becomes:

$$H'(s) = \frac{s\frac{k_g g_1}{k_c C_a}}{s^2 + s\frac{k_g g_2}{k_c C_a} + \frac{k_g^2 g_3 g_4}{k_c^2 C_a C_b}}; \quad \omega_0' = \frac{k_g}{k_c}\sqrt{\frac{g_3 g_4}{C_a C_b}} \qquad (4)$$

ω_0' is altered from ω_0 by a factor of k_g/k_c. The effect of tuning the circuit to resonance using Dishal's method is to force ω_0' to the design value ω_0 by changing V_{tune}, and hence $k_g g_1 \ldots k_g g_4$. This is achieved when $k_g = k_c$. Substituting $k_g = k_c$ into (4) gives the original transfer function. Thus, tuning only the pole frequencies of the biquad also restores Q to the original value.

An on-chip tuning system which tunes the pole frequency of a single biquad by detecting the peak of its amplitude response is described in detail in [5]. This system is shown in elementary form in figure 6. A test signal at ω_0 is applied to the biquad input, and V_o is rectified. The rectified signal V_{env} is applied to a peak detector. In the first tuning phase, V_{tune} is swept through its range by a ramp generator. At the point where the pole frequency of the biquad is equal to ω_0, V_{env} is a maximum, and this value is stored by the peak detector output V_{pk}. In the second tuning phase, V_{tune} is swept again, and V_{env} is compared with V_{pk}. At the point where both are equal, the control logic opens the switch, causing the current value of tuning voltage to be stored on C_{hold}, which is again the peak of the amplitude response. Reference [5] describes a more sophisticated implementation in which the effects of delays and offsets are cancelled.

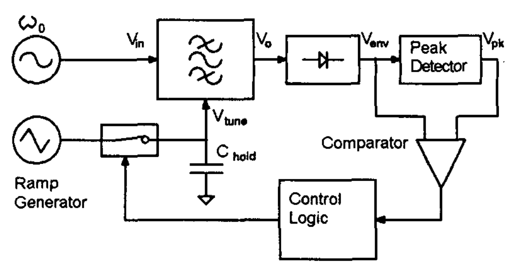


Fig. 6 Simplified Peak Tuning Scheme

This scheme may be extended as in figure 7 to sequentially tune a number of biquads making up the bandpass LF filter. Initially, V_{tune1} is adjusted for peak output at V_1. To isolate the first biquad from the rest of the filter, $V_{tune2} \ldots V_{tuneN}$ are initialised to zero, debiasing the other biquads. After V_{tune1} has been adjusted, Vt_{une2} is tuned for minimum V_1. The minimum detector is a peak detector with inverted polarity. The process is repeated with $V_{tune3} \ldots V_{tuneN}$ until all biquads have been tuned.

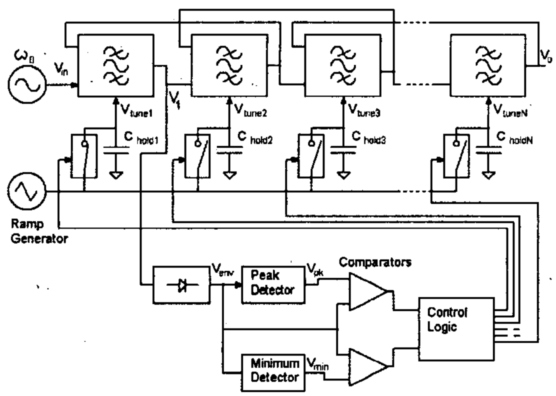


Fig. 7 Tuning Scheme Extended to LF bandpass Filter

4. EXPERIMENTAL EVALUATION

To demonstrate the tuning method, a discrete component filter was built. A 5th order active-RC LF bandpass filter was designed to have a 1dB ripple Chebychev response with f_0 = 3kHz and bandwidth 300Hz. The circuit was designed using the techniques of [6], and used National Semiconductor LM6134 op-amps. Tuning of integrator gain was provided by digital potentiometer ICs (Dallas DS1804). A 3kHz signal was applied to the input, and the amplitude at point V_1 measured using an oscilloscope. The integrators were then tuned using Dishal's method.

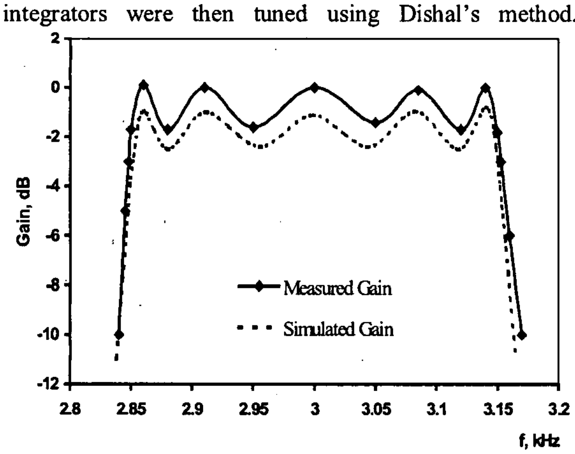


Fig. 8. Frequency Response of Test Filter

Figure 8 shows a comparison of the measured passband response of the filter after tuning with the response simulated using PSpice and accurate component values. The simulated curve is offset by 1dB to ease comparison. The measured and simulated responses of the aligned filter are in close agreement.

5. CONCLUSIONS

We have shown that Dishal's method can be applied to off-line tuning of LF bandpass filters. Dishal's method could equally be applied to other filter architectures based on LC ladder prototypes, such as those using inductor substitution techniques. Although we have illustrated this method using OTA-C and active-RC examples, the method can clearly be applied to any implementation using electronically tunable integrators.

Dishal's method tunes only the resonant frequencies of the biquads making up the bandpass filter, and relies upon the low sensitivity of LF bandpass filters to changes in ratios of component values to obtain a response which is a close approximation to the theoretical ideal. Compared to cascade filter tuning techniques, this method has the advantages that:

- All biquads are tuned to the centre frequency of the filter; a test signal is only required at the centre frequency. In a signal processing system, this signal is often already available as a carrier or clock frequency.
- The test signal is applied to the filter input during the whole of the tuning procedure, and the only feedback data required by the tuning algorithm is the signal amplitude at the output of the first stage. No additional signal routing is required. This reduces complexity and minimises parasitic loading effects on critical signal paths of the filter circuit at high frequencies.
- Only relative amplitude information is required by the tuning algorithm; this is an advantage at high frequencies, since parasitic phase shifts in the detector are not important.

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