Flat and Pulse Mode Filters

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Overview

Precision Filters' (PFI) signal conditioning products feature two proprietary low-pass filter designs. The "flat" mode and "pulse" mode filters provide complementary response characteristics that are optimized for different measurement criteria. In addition to programmable cutoff frequencies, the dual-mode setup allows the user to choose the best filter for the intended measurement application. This paper summarizes the key differences between PFI's low-pass flat and pulse mode filters in terms of their frequency and transient responses, along with comparisons to conventional filter types. Examples comparing the effect of each filter on simple test waveforms are also provided for further illustration.

Flat vs. Pulse Mode

Analog filter design requires a tradeoff between optimizing for a maximally flat amplitude response and optimizing for a linear phase response (which collectively define the filter's frequency response). In other words, passband flatness can be obtained at the expense of phase linearity and vice versa. To accommodate this tradeoff, PFI offers two filter modes in its product line: "flat" mode filters that are optimized for a maximally flat passband amplitude response, and "pulse" mode filters that are optimized for a linear phase response in the passband (i.e. a constant time delay).

Figure 1 compares the response characteristics for 8-pole versions of the low-pass flat (LP8F) and low-pass pulse (LP8P) filters. The amplitude response is shown in Figure 1A and 1B. While both filters provide 80 dB of stopband attenuation, the flat mode filter provides better amplitude preservation in the passband (i.e. $f \leq F_C$, where F_C is the cutoff frequency) and a sharper transition-band roll-off to the stopband (at $1.75F_C$ vs. $3.47F_C$ for the LP8P). The LP8F is effectively flat (no attenuation) over 80% of the passband while the LP8P rolls off gradually to the 3 dB attenuation level at F_C.

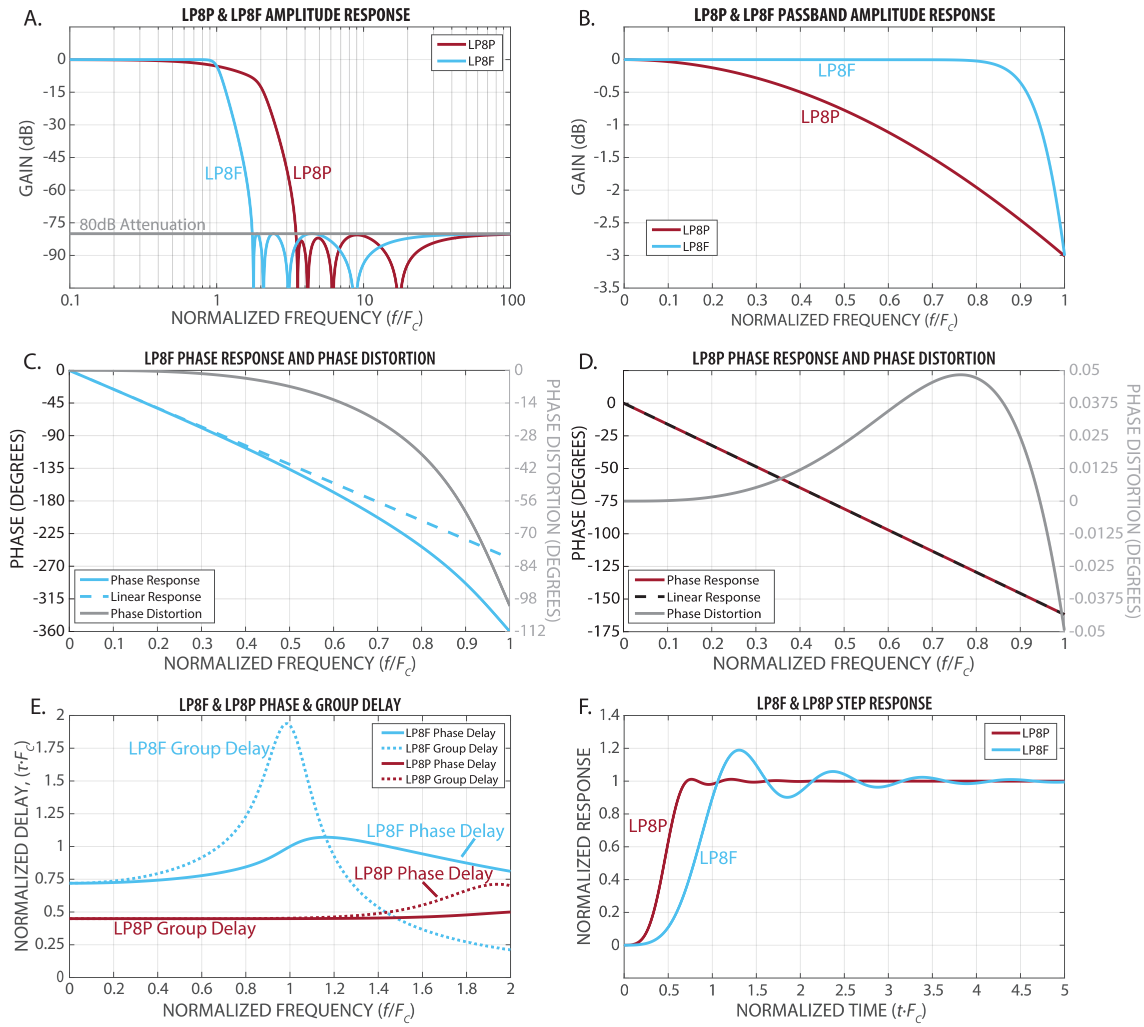

Figure 1. Amplitude (A and B), phase (C and D), time delays (E), and transient step response (F) of PFI's 8-pole flat (LP8F) and pulse (LP8P) mode filters.

The LP8F and LP8P passband phase responses are shown in Figure 1C and Figure 1D, respectively. In these plots, the phase distortion – so called because it quantifies how the filter will modify the shape of a spectrally rich, in-band periodic waveform – is defined as the deviation of the phase response from the idealized linear response shown by the dashed lines. The flat mode filter (Figure 1C) shows significant distortion across the passband, exceeding 100° at the cutoff frequency. In contrast, the pulse mode phase response (Figure 1D) is effectively linear across the entire passband: its phase distortion is negligible (< .05°). These differences can be further examined in terms of the phase and group time delays, as shown in Figure 1E. Over the passband, the LP8P shows constant (and equivalent) phase and group delays that are smaller in magnitude than the LP8F delays, which vary across the passband.

The difference between the flat and pulse mode responses can be illustrated by examining the output of each filter to a test waveform. As a first example, consider the steady-state input defined by the first two (odd) harmonics of a square wave:

$$s(t) = \sin\left(2\pi f_1 t\right) + \frac{1}{3}\sin\left(2\pi f_3 t\right),\ f_3 = 3 f_1 \tag{1}$$

The spectral components of the square wave (referred to here by their frequencies f_1 and f_3) are set to lie within the passband of the LP8F and LP8P by assigning $f_3 = .8F_C$. The two components, along with the composite square wave defined by (1), are shown in Figure 2A.

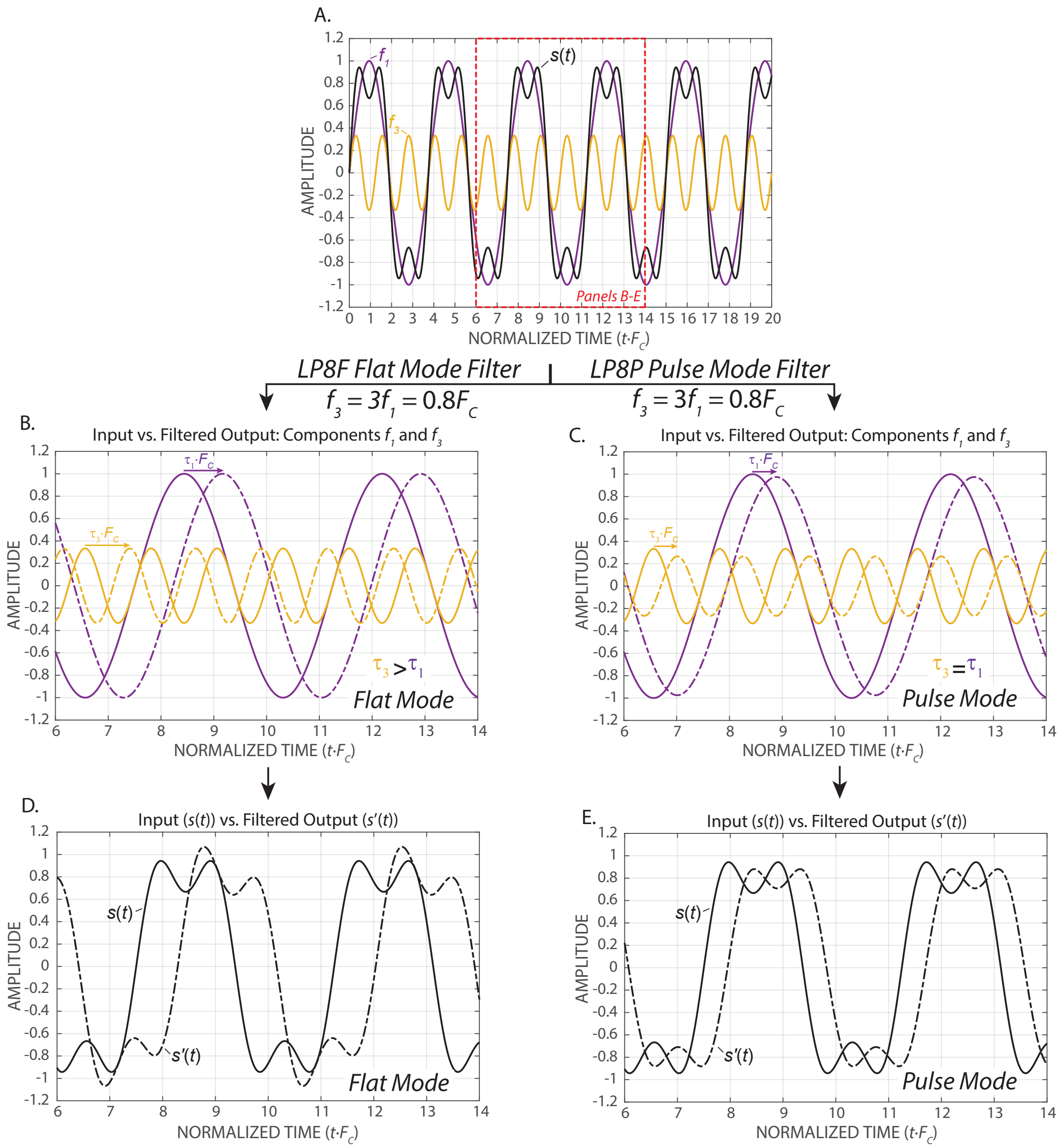

Figure 2. **(A)** Test square wave $s(t)$ (black) consisting of the first two odd harmonics (f_1 and f_3). Dashed red panel shows portion of the signal shown in (B)-(E). **(B)-(C)** Effects of the LP8F (B) and LP8P (C) on the spectral components f_1 and f_3 of the square wave, with phase delays highlighted. **(D)-(E)** Input square wave $s(t)$ vs filtered output $s'(t)$ from the LP8F (D) and LP8P (E).

Figure 2B and 2C show the effect of each filter on the components f_1 and f_3. Both filters impart time delays τ_1 and τ_3 to components f_1 and f_3, respectively. Notice, however, that the delays are equal for the pulse mode filter ($\tau_1 = \tau_3$) but differ for the flat mode filter ($\tau_1 < \tau_3$). The flat mode filter preserves the component amplitudes but the pulse mode filter does not: notice that the attenuation is higher for the higher frequency component (as can be seen from the passband response in Figure 1B).

These effects are apparent in the output waveforms $s'(t)$ shown in Figure 2D and 2E. The unequal phase delays of the flat mode filter generate an output waveform with a modified shape, despite the amplitude preservation of its spectral components. In contrast, the pulse mode filter preserves the shape of the waveform but attenuates its amplitude. This simple example highlights an important point: the pulse mode filter preserves wave shape, while the flat mode filter preserves spectral energy.

Another important performance measure is a filter's transient response. This is conventionally evaluated by examining the time domain output of the filter to an instantaneous unit step input at time $t = 0$. The flat and pulse mode transient responses are shown in Figure 1F. The LP8F has a slower rise time, greater overshoot, and more ringing than the LP8P. Put another way, the pulse mode filter is more responsive: it will introduce less distortion to pulses or other rapidly changing waveforms.

As a second illustrative example, consider a haversine transient pulse input, a waveform that is commonly used to model shock loads (i.e. acceleration) to mechanical systems. The haversine pulse is defined by

$$s(t) = \begin{matrix} \frac{A}{2}\left(1 - \cos\left(\frac{2\pi t}{T_P}\right)\right), & 0 \le t \le T_P \\ 0, & t > T_P \end{matrix} \qquad (2)$$

where T_P is pulse duration and A is the pulse amplitude. The haversine pulse has a nominal frequency $F_P = (T_P)^{-1}$, which defines the 6 dB-down upper bound on the frequency content of the pulse.

An example of a 1 ms haversine pulse with unit amplitude is shown in Figure 3A (black curve) along with its amplitude spectrum in Figure 3B. Filtering this pulse with the LP8F and LP8P set to a cutoff frequency of 2 kHz (i.e. $F_C = 2F_P$) results in the two output pulses shown in Figure 3A. Though both filters pass the pulse without significant modification of the waveform, the LP8P output shows a shorter delay and better shape preservation with some attenuation (0.4 dB) of the pulse peak. The LP8F shows a slight amplification of the peak (.06 dB) and amplitude ringing that extends beyond the duration of the input pulse.

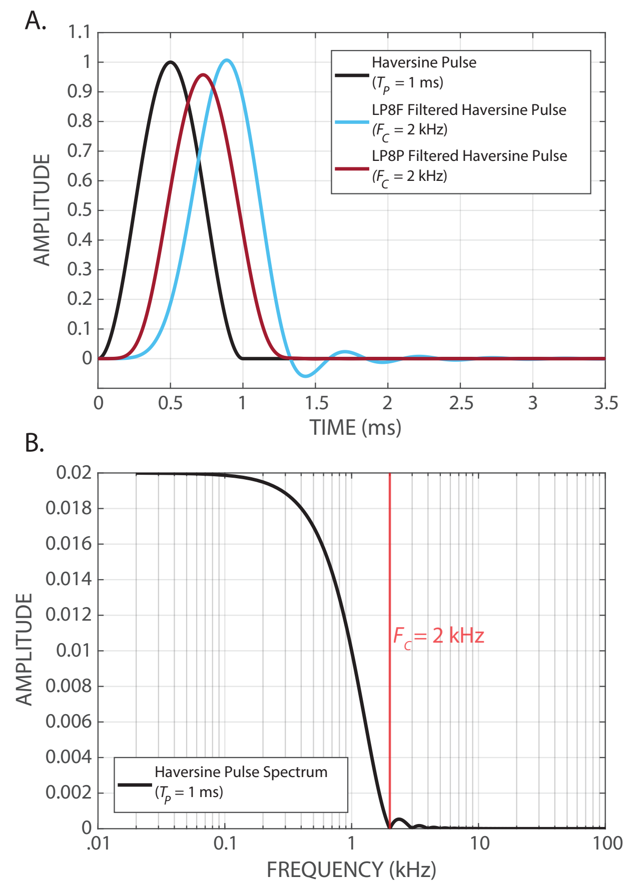

Figure 3. (A) Comparison of input haversine pulse with a 1 ms duration to filtered output pulses from the LP8F and LP8P. (B) Amplitude spectrum of the input haversine pulse. The cutoff frequency (2 kHz) of the LP8F and LP8P used in (A) is shown.

PFI Filters vs. Conventional Types

Among conventional filter types are designs optimized for either their amplitude response or phase response. The Butterworth filter has a maximally flat passband amplitude response but significant phase distortion. The Bessel filter has a linear phase response with constant time delay but its passband is not flat and its transition-band roll-off is more gradual. Hence the Butterworth and Bessel filters provide important benchmarks for assessing the performance of PFI's flat and pulse mode filters, respectively.

Figure 4 shows the LP8F and LP8P responses compared to 8-pole Butterworth and Bessel responses. Compared to the Butterworth response, the LP8F has a flatter passband (Figure 4B) and sharper transition-band roll-off (Figure 4A). The LP8P and Bessel filters show a nearly identical passband response (Figure 4B), but the LP8P has a sharper transition-band roll-off (Figure 4A).

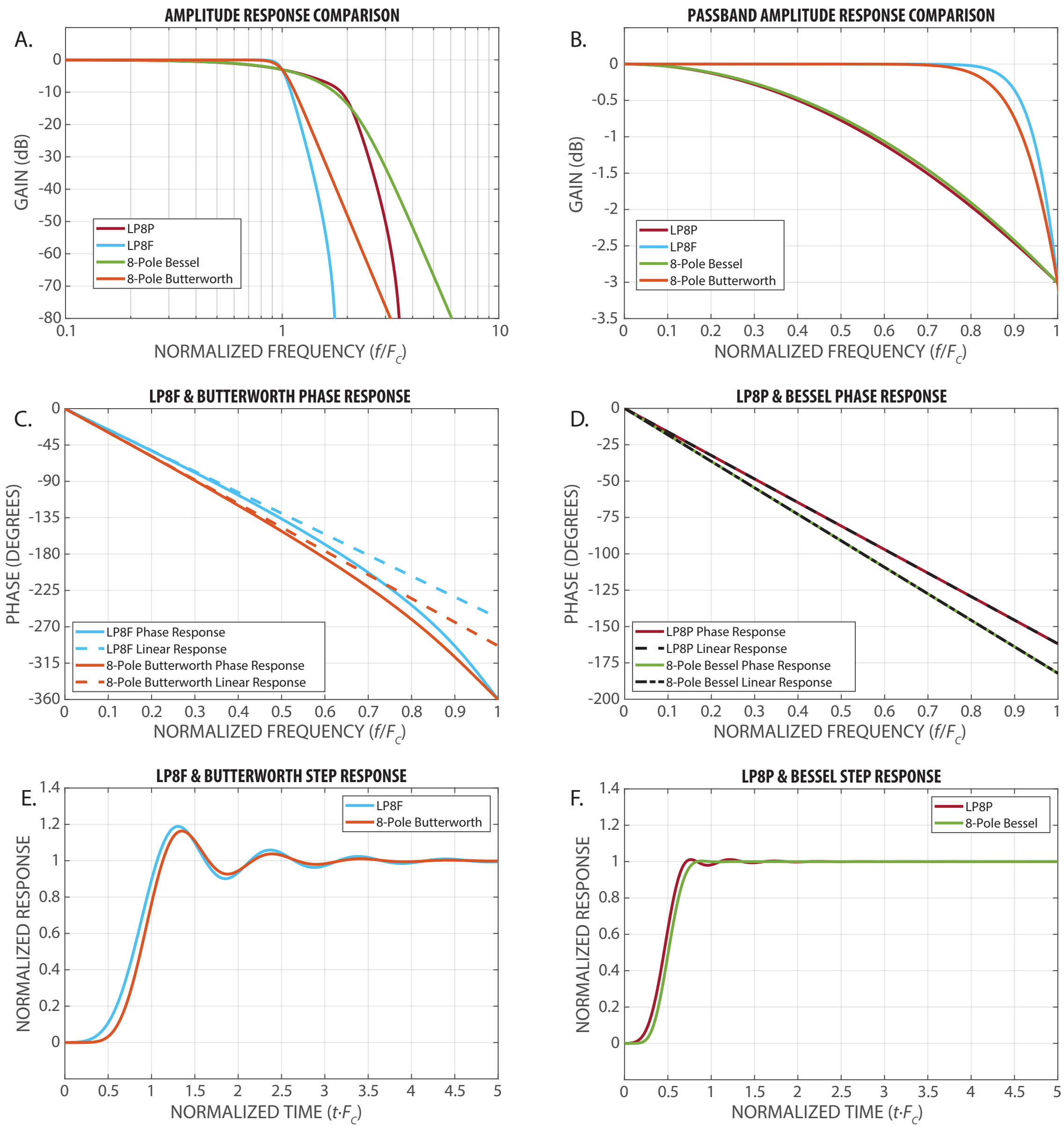

Figure 4. Amplitude (A and B), phase (C and D), and transient step response (E and F) of PFI's 8-pole flat (LP8F) and pulse (LP8P) mode filters compared with conventional 8-pole Butterworth and Bessel filters.

The phase responses of the four filter types are compared in Figure 4C and 4D. (In these plots the distortion curves are omitted for clarity.) Both the LP8F and 8-pole Butterworth have significant distortion over the passband: the Butterworth has a larger phase shift (which equates to larger phase delays) but lower distortion (66° at F_C) than the LP8F (101° at F_C). Both the LP8P and the 8-pole Bessel filters have a linear phase response over the passband, with the Bessel filter showing a larger phase shift.

The transient response of the four filter types are compared in Figure 4E and

4F. PFI's flat and pulse mode filters provide faster rise times in exchange for a small increase in the overshoot and amplitude of ringing.

Taken together, these comparisons suggest the following. For applications requiring an optimal amplitude response, PFI's flat mode filter provides a flatter passband response and sharper roll-off than a Butterworth filter of the same order. For applications requiring an optimal phase response, PFI's pulse mode filter provides a better amplitude response (i.e. comparable passband response with sharper roll-off) than a Bessel filter of the same order while preserving the required phase linearity.

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