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DESIGNING ACTIVE FILTERS WITH THE DIAMOND TRANSISTOR OPA660 Part 1

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Signal frequency bandwidth limitation, fast pulse shaping, separation between telecommunications signals, and suppression of unwanted carrier and disturbance frequencies are among the most important jobs of filter circuits. While active filters with operational amplifiers and switched capacitor filters are used for lower frequency applications, passive filter versions dominate the application spectrum at frequencies above 5MHz. Now, however, a new active filter design has been developed that makes use of the open loop pole and delay time of an operational amplifier. The filter circuits consist of OPA660s, which provide the necessary bandwidth and allow access to the first open-loop pole and internal amplifier delay time. After presenting an overview of conventional filter circuits using 2nd, 3rd, and 5th order active filters with Tschebyscheff approximation, this Application Note will discuss the new filter structure in detail.

The filter circuits presented in Part One are optimized for the minimum possible number of components, while the filter circuits that will be analyzed in Part Two require more components, and board space, but are optimized for easy adjustment of the important filter parameters.

1.0 2ND ORDER LOW-PASS FILTER USING OPERATIONAL AMPLIFIERS

1.1 2nd Order Low-Pass Filter With An Ideal Op Amp

Figure 1 shows a classical example of an active 2nd order low-pass filter designed using an op amp. In this example, the op amp, IOPA, is assumed to be ideal.

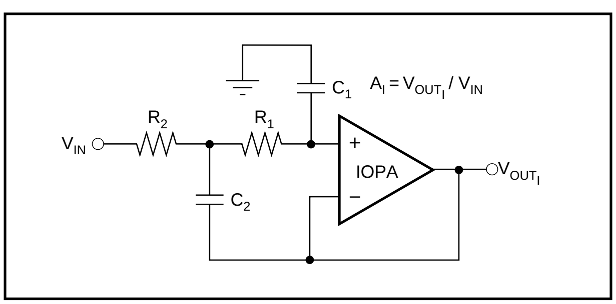

FIGURE 1. 2nd Order Low-Pass Filter Using an Ideal Op Amp.

Equation 1 can be derived from Figure 1 and describes the filter transfer function. In the following analyses, all parameters are assumed to be normalized to the –3dB frequency, ω_g, at which the amplitude $|A_I|$ is reduced to –3dB. When normalized to the –3dB frequency, Equation 1 becomes Equation 2. Technical literature about passive filters commonly uses the coefficients a_I and b_I (or a_1 or b_1). Equation 3 is the result of comparing these coefficients and shows their relation to the circuit parameters τ_1 and τ_2. The coefficients ω_{0i} (or ω_{01}) and Q_i (or Q_1) are easier to calculate and explain using circuit elements. Equation 4 shows these coefficients and those of a_I and b_I (or a_1 and b_1).

$$A_I = \left[1 + j\omega \bullet (2\tau_1) + (j\omega)^2 \bullet (\tau_1\tau_2)\right]^{-1} \quad (1)$$

$$A_I = \left[1 + j\frac{\omega}{\omega_g} \bullet (2\tau_1\omega_g) + \left(j\frac{\omega}{\omega_g}\right)^2 \bullet (\tau_1\tau_2\omega_g^2)\right]^{-1} \quad (2)$$

$$A_I = \left[1 + j\frac{\omega}{\omega_g} \bullet a_1 + \left(j\frac{\omega}{\omega_g}\right)^2 \bullet b_1\right]^{-1} \quad (3)$$

$$A_I = \left[1 + j\frac{\omega}{\omega_g} \bullet \frac{1}{Q_1(\omega_{01}/\omega_g)} + \left(j\frac{\omega}{\omega_g}\right)^2 \bullet \frac{1}{(\omega_{01}/\omega_g)^2}\right]^{-1} \quad (4)$$

These equations can be rearranged, resulting in:

$$a_1 = 2\tau_1\omega_g = \frac{1}{Q_1(\omega_{01}/\omega_g)}; b_1 = \tau_1\tau_2\omega_g{}^2 = \frac{1}{(\omega_{01}/\omega_g)^2} \quad (5)$$

Rearranging Equation 5 gives dimensioning rules for the active filter circuit shown in Figure 1:

$$\tau_1 = \frac{1}{2Q_1(\omega_{01}/\omega_g)\omega_g}; \tau_2 = \frac{2Q_1}{(\omega_{01}/\omega_g)\omega_g} \quad (6)$$

The values for Q_i and $\omega_{01}/\omega_g = f_{01}/f_g$ can be found in Tables I to V for the various passband ripple specs and for filter orders from 1 to 4.

STATUS		DESIGN				TEST AND ADJUST		
I	f_p/f_g	AI	BI	f_{oi}/f_g	Q_i	f_{gi}/f_g	f_{xi}/f_g	|HXI|
1	0.152620	1.000000	0.000000	1.000000	—	1.000000	—	—
1	0.509545	1.404882	1.162191	0.927601	0.767360	1.000000	0.360303	0.100000
1	0.719945	1.432831	0.000000	0.697919	—	0.697919	—	—
2	—	0.796864	1.141772	0.935859	1.340928	1.308626	0.795164	3.198263
1	0.821643	2.402002	2.377929	0.648486	0.618801	0.557823	—	—
2	—	0.483444	1.113711	0.947575	2.182931	1.417296	0.896485	7.014844
1	0.881276	2.105565	0.000000	0.474932	—	0.474932	—	—
2	—	1.555941	2.024763	0.702769	0.914522	0.854957	0.445671	0.766191
3	—	0.316283	1.077536	0.963350	3.282011	1.472181	0.940726	10.42479
1	0.913549	3.558215	4.549720	0.468822	0.599460	0.387303	—	—
2	—	0.985106	1.720656	0.762347	1.331570	1.064307	0.645976	3.147338
3	—	0.222328	1.060948	0.970852	4.632900	1.496039	0.959477	13.36794
1	0.936329	2.834566	0.000000	0.352788	—	0.352788	—	—
2	—	2.195827	3.454179	0.538056	0.846397	0.624395	0.295713	0.415494
3	—	0.666183	1.514331	0.812624	1.847213	1.196561	0.750728	5.660789
4	—	0.163930	1.044104	0.978652	6.233234	1.513678	0.972334	15.92230

TABLE I. Passband Ripple, P = 0.1dB.

STATUS		DESIGN				TEST AND ADJUST		
I	f_p/f_g	AI	BI	f_{oi}/f_g	Q_i	f_{gi}/f_g	f_{xi}/f_g	|HXI|
1	0.327091	1.000000	0.000000	1.000000	—	1.000000	—	—
1	0.586283	1.394652	1.234406	0.900059	0.796642	1.000000	0.414565	0.200000
1	0.779147	1.575499	0.000000	0.634720	—	0.634720	—	—
2	—	0.739619	1.165269	0.926375	1.459503	1.318092	0.810393	3.826278
1	0.859762	2.568461	2.752149	0.602787	0.645897	0.546179	—	—
2	—	0.436287	1.128618	0.941297	2.435013	1.418697	0.900734	7.917111
1	0.909791	2.382160	0.000000	0.419787	—	0.419787	—	—
2	—	1.469586	2.163607	0.679846	1.000908	0.865129	0.481160	1.254646
3	—	0.280509	1.081198	0.961717	3.706857	1.475016	0.944058	11.45986
1	0.933323	3.718489	5.417686	0.429629	0.625951	0.374863	—	—
2	—	0.894401	1.780075	0.749516	1.491718	1.070693	0.659959	3.991311
3	—	0.195864	1.065000	0.969003	5.268903	1.496012	0.960237	14.47369
1	0.952210	3.238203	0.000000	0.308813	—	0.308813	—	—
2	—	2.091516	3.758594	0.515807	0.926940	0.632143	0.333514	0.834338
3	—	0.592804	1.539416	0.805976	2.092989	1.201365	0.758586	6.670542
4	—	0.143584	1.044744	0.978352	7.118671	1.514831	0.973513	17.06946

TABLE II. Passband Ripple, P = 0.2dB.

STATUS		DESIGN				TEST AND ADJUST		
I	f_p/f_g	AI	BI	f_{oi}/f_g	Q_i	f_{gi}/f_g	f_{xi}/f_g	|HXI|
1	0.267431	1.000000	0.000000	1.000000	—	1.000000	—	—
1	0.632596	1.383913	1.291188	0.880046	0.821081	1.000000	0.447312	0.300000
1	0.813628	1.685318	0.000000	0.593360	—	0.593360	—	—
2	—	0.699249	1.178457	0.921177	1.552476	1.324872	0.820079	4.296095
1	0.880317	2.604074	3.023945	0.575060	0.667780	0.541312	—	—
2	—	0.405955	1.138083	0.937374	2.627901	1.418992	0.902803	8.552317
1	0.925452	2.590454	0.000000	0.386033	—	0.386033	—	—
2	—	1.403876	2.247589	0.667024	1.067898	0.871851	0.499850	1.645308
3	—	0.258290	1.082606	0.961092	4.028354	1.477015	0.946169	12.16998
1	0.943675	3.797733	6.042962	0.406794	0.647292	0.369527	—	—
2	—	0.834824	1.814592	0.742353	1.613595	1.074126	0.667278	4.594292
3	—	0.179775	1.067584	0.967830	5.747404	1.495732	0.960477	15.22243
1	0.960769	3.540230	0.000000	0.282468	—	0.282468	—	—
2	—	2.007356	3.943811	0.503549	0.989313	0.637414	0.352175	1.187620
3	—	0.546919	1.552727	0.802514	2.278372	1.204173	0.762886	7.366854
4	—	0.131337	1.044759	0.978345	7.782533	1.515687	0.974298	17.84038

TABLE III. Passband Ripple, P = 0.3dB.

STATUS		DESIGN				TEST AND ADJUST		
I	f_p/f_g	AI	BI	f_o/f_g	Q_i	f_{gi}/f_g	f_{xi}/f_g	|HXI|
1	0.310609	1.000000	0.000000	1.000000	—	1.000000	—	—
1	0.665456	1.372811	1.339700	0.863965	0.843127	1.000000	0.470548	0.400000
1	0.837887	1.779279	0.000000	0.562025	—	0.562025	—	—
2	—	0.667162	1.187067	0.917830	1.633076	1.330380	0.827331	4.687601
1	0.893939	2.621387	3.244945	0.555132	0.687183	0.539051	—	—
2	—	0.383191	1.145162	0.934473	2.792661	1.418897	0.904021	9.061859
1	0.936086	2.766593	0.000000	0.361455	—	0.361455	—	—
2	—	1.349474	2.307395	0.658323	1.125632	0.876917	0.512217	1.982446
3	—	0.241967	1.083152	0.960849	4.301189	1.478649	0.947776	12.73086
1	0.950419	3.841285	6.548634	0.390773	0.666191	0.366864	—	—
2	—	0.789577	1.838770	0.737456	1.717391	1.076372	0.672047	5.082044
3	—	0.168103	1.069542	0.966943	6.152101	1.495388	0.960535	15.80925
1	0.966515	3.794785	0.000000	0.263520	—	0.263520	—	—
2	—	1.935768	4.076623	0.495279	1.043030	0.641397	0.364090	1.499892
3	—	0.513081	1.561398	0.800282	2.435403	1.206176	0.765808	7.918443
4	—	0.122504	1.044564	0.978436	8.342904	1.516405	0.974915	18.44197

TABLE IV. Passband Ripple, P = 0.4dB.

STATUS		DESIGN				TEST AND ADJUST		
I	f_p/f_g	AI	BI	f_{oi}/f_g	Q_i	f_{gi}/f_g	f_{xi}/f_g	|HXI|
1	0.349311	1.000000	0.000000	1.000000	—	1.000000	—	—
1	0.690638	1.361436	1.382743	0.850412	0.863721	1.000000	0.488355	0.500000
1	0.856542	1.863635	0.000000	0.536586	—	0.536586	—	—
2	—	0.640186	1.193074	0.915517	1.706190	1.335117	0.833192	5.030512
1	0.903889	2.628161	3.434139	0.539624	0.705110	0.538096	—	—
2	—	0.364824	1.150866	0.932154	2.940553	1.418624	0.904802	9.495995
1	0.944056	2.923552	0.000000	0.342050	—	0.342050	—	—
2	—	1.302495	2.353418	0.651854	1.177805	0.880993	0.521307	2.284474
3	—	0.229001	1.083268	0.960798	4.544965	1.480065	0.949099	13.20349
1	0.955298	3.864492	6.979727	0.378513	0.683639	0.365535	—	—
2	—	0.752778	1.857255	0.733777	1.810376	1.077986	0.675491	5.499967
3	—	0.158910	1.071138	0.966223	6.512856	1.495030	0.960511	16.30110
1	0.970789	4.021119	0.000000	0.248687	—	0.248687	—	—
2	—	1.872914	4.179506	0.489145	1.091553	0.644589	0.372636	1.783643
3	—	0.486126	1.567604	0.798697	2.575546	1.207745	0.768006	8.384227
4	—	0.115575	1.044265	0.978576	8.841816	1.517046	0.975442	18.94474

TABLE V. Passband Ripple, P = 0.5dB.

The following equations are helpful when observing the effects of component deviations and temperature changes upon the filter transfer curve and phase behavior:

$$\omega_{01} = \frac{1}{\sqrt{\tau_1\tau_2}} = \frac{1}{\sqrt{R_1R_2C_1C_2}}; Q_1 = \frac{1}{2}\sqrt{\frac{\tau_2}{\tau_1}} = \frac{1}{2}\sqrt{\frac{C_2}{C_1}} \qquad (7)$$

The equation for the corner frequency, ω_{01}, describes the signal response over frequency, while Q_1 denotes the peaking of the frequency response in the passband.

Equations 8-10 give values for the frequency response expressed in the same variables used in Equations 2, 3, and 4.

$$|A_I| = \left[1 + 2\tau_1(2\tau_1 - \tau_2)\omega^2 + (\tau_1\tau_2)^2\omega^4\right]^{-\frac{1}{2}} \qquad (8)$$

$$|A_I| = \left[1 + (a_1 - 2b_1)\left(\frac{\omega}{\omega_g}\right)^2 + b_1^2\left(\frac{\omega}{\omega_g}\right)^4\right]^{-\frac{1}{2}} \qquad (9)$$

$$|A_I| = \left[1 + \left(\frac{1}{Q_1^2} - 2\right)\left(\frac{\omega/\omega_g}{\omega_{01}/\omega_g}\right)^2 + \left(\frac{\omega/\omega_g}{\omega_{01}/\omega_g}\right)^4\right]^{-\frac{1}{2}} \qquad (10)$$

Figure 2 shows the theoretical frequency response curve of the second order filter using an ideal op amp. The definitions given here will be used later on for comparison with and optimation of the filter response.

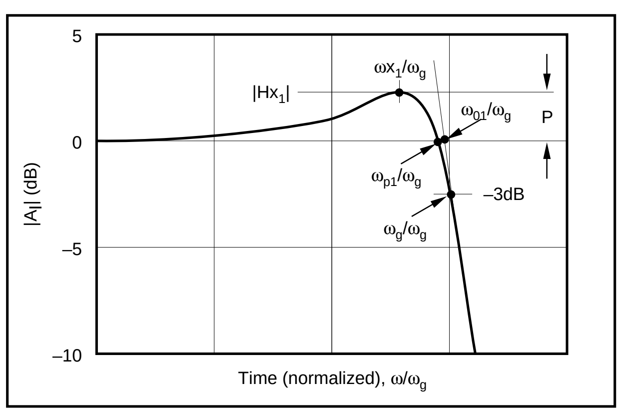

FIGURE 2. Definitions for a 2nd Order Low-Pass Filter.

Example Calculation
For a Low-Pass Filter

p = +0.1dB; f_g = 10MHz; $R_1 = R_2 = 300\Omega$

$Q_1 = 0.767360$

$f_{01}/f_g = 0.927601$

Q_1 and f_{01}/f_g are derived from the filter table.

$$\tau_1 = \frac{1}{2Q_1\left(f_{01}/f_g\right)\bullet 2\pi f_g}$$

$$= \frac{1}{2\bullet 0.767360\bullet 0.927601\bullet 2\pi\bullet 10\text{MHz}} = 11.18\text{ns}$$

$$\tau_2 = \frac{2Q_1}{\left(f_{01}/f_g\right)\bullet 2\pi f_g}$$

$$= \frac{2\bullet 0.767360}{0.927601\bullet 2\pi\bullet 10\text{MHz}} = 26.33\text{ns}$$

$$C_1 = \frac{\tau_1}{R_1} = \frac{11.8\text{ns}}{300} = 37.27\text{pF};$$

$$C_2 = \frac{\tau_2}{R_2} = \frac{26.33\text{ns}}{300} = 87.77\text{pF}$$

Figure 3 shows the frequency response $|A_I|$ of the filter circuit from Figure 1 using the filter component values calculated above.

1.2

2ND ORDER LOW-PASS FILTER WITH AN OP AMP MODEL

Unlike the ideal op amp used for the analyses above, op amps used in real circuits do not always behave as one might wish. For this reason, the following analyses use the OPA660 in current-feedback configuration. Figure 4 shows the circuit schematic of the OPA660 using the PT_2 model to describe the AC behavior.

These components values produce the following results with an optimally flat frequency response adjustment:

f_g = 357MHz	$R_{OUT\ DC}$ = 45mΩ
$G_{OPEN\ LOOP\ DC}$ = 70dB	$R_{OUT\ 100MHz}$ = 2.9Ω

If the ideal op amp shown in Figure 1 is replaced by the OPA660 PT_2 model (MOPA660), the resulting circuit diagram looks like that shown in Figure 5.

Slight changes in the capacitors C_1 and C_2 are necessary to correct the frequency response to a –3dB frequency of 10MHz. At 100MHz and above, the modeled frequency

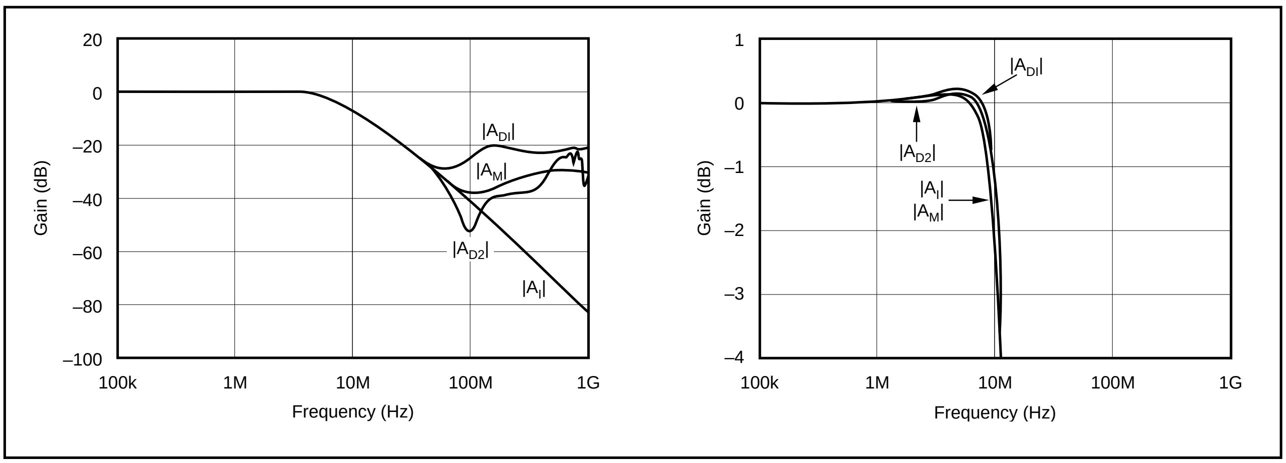

FIGURE 3. Frequency Response of the 2nd Order Low-Pass Filter from Figure 1 with Ideal Op Amp.

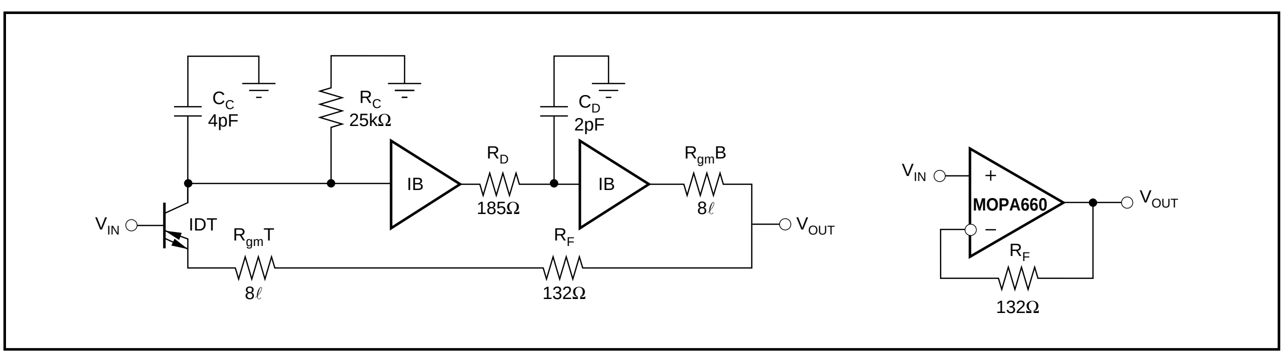

FIGURE 4. PT_2 Model Describing the OPA660 as Current-Feedback Amplifier.

response $V_{OUT\ M}$ begins to deviate from the ideal frequency response $V_{OUT\ I}$, since in practice the open-loop gain of the OPA660 decreases with increasing frequency. For this reason, the output impedance R_{OUT} rises from 45mΩ at DC to 2.9Ω at 100MHz.

1.3 TESTS WITH THE DEMO BOARD

As also shown in Figure 3, a demo board with the circuit shown in Figure 6 produces extremely poor stopband attenuation at the output $V_{OUT\ D1}$, primarily due to the package inductance in series to the resistor R_{gmB}. At 500MHz, for example, the package inductance of the output buffer (IB), which is about 10nH, causes R_{gmB} to increase by approximately 31Ω.

Poor stopband attenuation can be avoided by inserting the buffer, BUF600, and generating the output voltage at the capacitor, C_1. The BUF600 makes the original output $V_{OUT\ D1}$ superfluous. The rise in frequency response at 300MHz and above can be explained as a product of the direct crosstalk between input and output on the demo board.

2.0
2nd ORDER LOW-PASS FILTER USING THE FIRST AND SECOND OPEN-LOOP POLE OF WIDE-BAND AMPLIFIERS

2.1 Analyses Using The PT_2 Model

Wide-band op amps behave quite similarly to 2nd order low-pass filters. For this reason, their parameters can be determined by the equations used for the PT_2 model (see Figure 7).

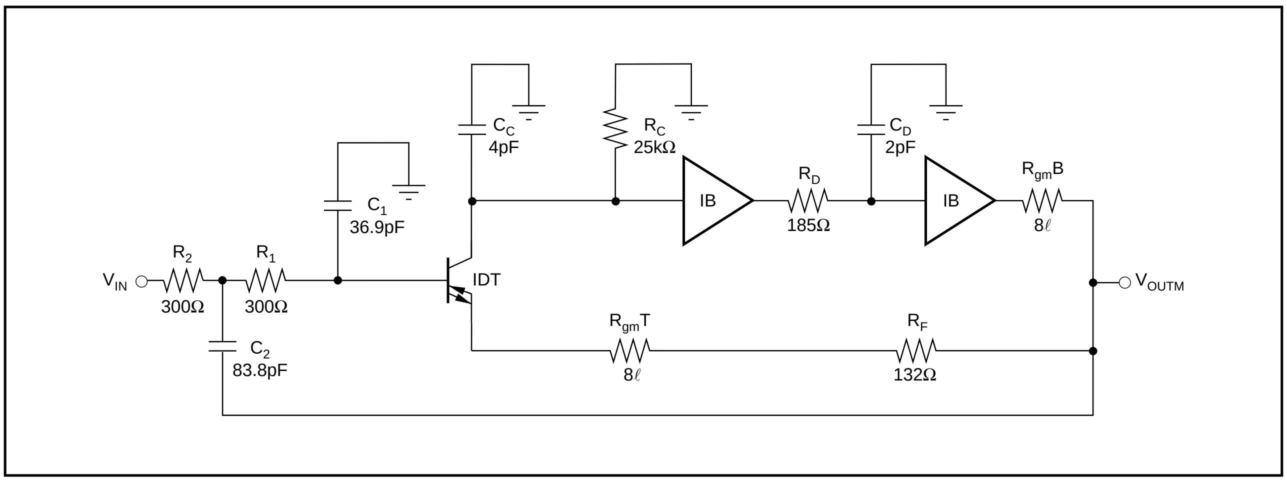

FIGURE 5. 2nd Order Low-Pass Filter Using the Modeled OPA660.

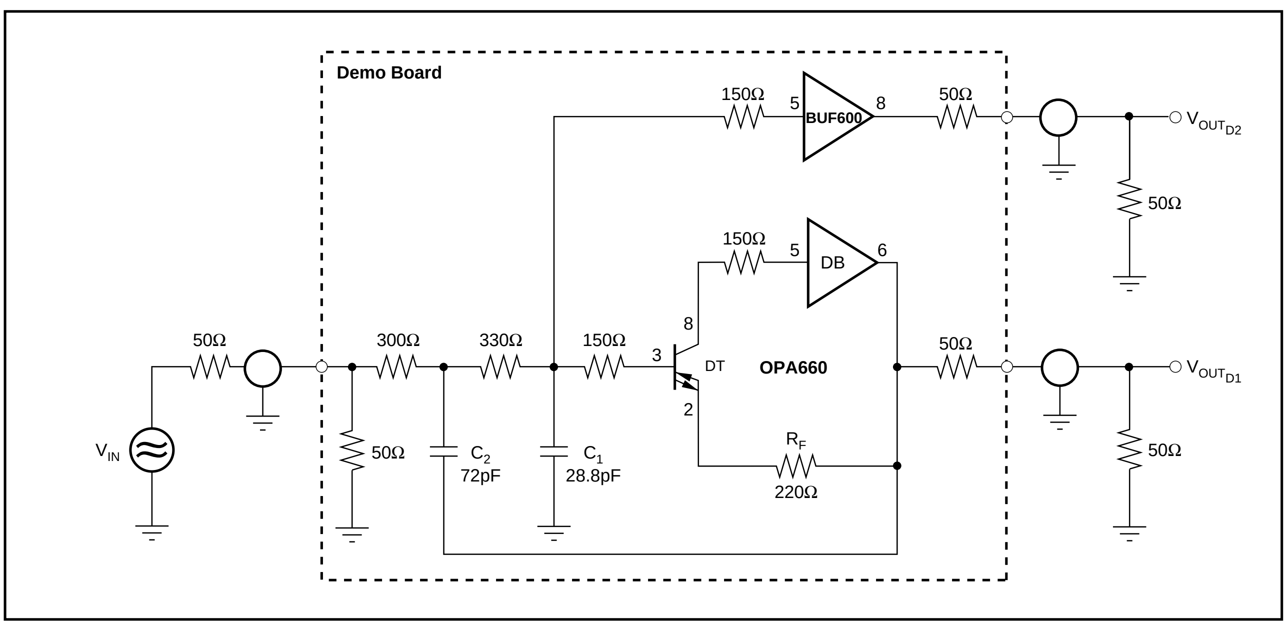

FIGURE 6. Demo Board Circuit Schematic for the 2nd Order Low-Pass Filter Using the OPA660.

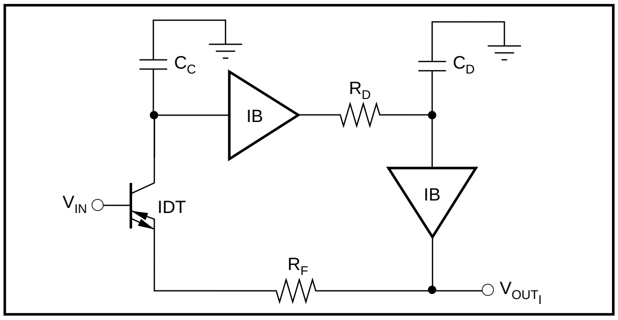

FIGURE 7. PT_2 Model for Wide-Band Op Amps.

The results are similar to the equations listed under point 1.1:

$$A_I = \left[1 + j\omega \bullet (\tau_C) + (j\omega)^2 \bullet (\tau_C \tau_D)\right]^{-1} \qquad (11)$$

$$a_1 = \tau_C \omega_g = \frac{1}{Q_1(\omega_{01}/\omega_g)}; \qquad b_1 = \tau_C \tau_D \omega_g{}^2 = \frac{1}{(\omega_{01}/\omega_g)^2} \qquad (12)$$

$$\tau_C = \frac{1}{Q_1(\omega_{01}/\omega_g)\omega_g}; \tau_D = \frac{Q_1}{(\omega_{01}/\omega_g)\omega_g} \qquad (13)$$

$$\omega_{01} = \frac{1}{\sqrt{\tau_D \tau_C}} = \frac{1}{\sqrt{R_D R_F C_C C_D}}; \qquad Q_1 = \sqrt{\frac{\tau_D}{\tau_C}} = \sqrt{\frac{R_D C_D}{R_F C_C}} \qquad (14)$$

$$|A_I| = \left[1 + \tau_C(\tau_C - 2\tau_D)\omega^2 + (\tau_C \tau_D)^2 \omega^4\right]^{-\frac{1}{2}} \qquad (15)$$

When the curves described in Equations 8 and 15 are compared to each other, the result is a transfer response as shown in Figure 2.

2.2 Modified PT_2 Model

The customary PT_2 model shown in Figure 7 can be modified to produce the circuit shown in Figure 8 without significantly changing the transfer response.

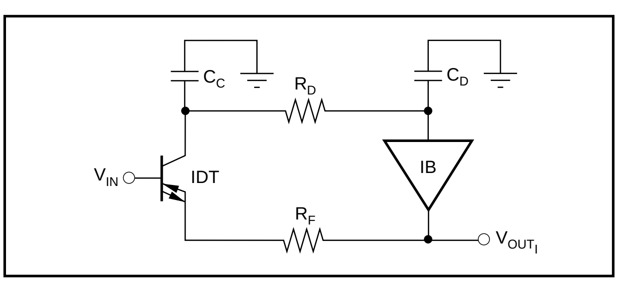

FIGURE 8. Modified PT_2 Model.

$$A_I = \left[1 + j\omega \bullet (\tau_C + \tau_D) + (j\omega)^2 \bullet (\tau_C \tau_D)\right]^{-1} \qquad (16)$$

$$a_1 = (\tau_C + \tau_{CD})\omega_g = \frac{1}{Q_1(\omega_{01}/\omega_g)}; \qquad b_1 = \tau_C \tau_D \omega_g{}^2 = \frac{1}{(\omega_{01}/\omega_g)^2} \qquad (17)$$

$$\tau_C = \tau_{CD} = \frac{1}{2Q_1(\omega_{01}/\omega_g)\omega_g}; \tau_D = \frac{2Q_1}{(\omega_{01}/\omega_g)\omega_g} \qquad (18)$$

$$\omega_{01} = \frac{1}{\sqrt{\tau_D \tau_D}} = \frac{1}{\sqrt{R_D R_F C_C C_D}}; \qquad Q_1 = \sqrt{\frac{R_D C_C C_D}{R_F (C_C + C_D)^2}} = \frac{1}{2}\sqrt{\frac{R_D}{R_F}} \qquad (19)$$

$$|A_I| = \left\{1 + \left[(\tau_C + \tau_{CD})^2 - 2\,\tau_C \tau_D\right]\omega^2 + (\tau_C \tau_D)^2 \omega^4\right\}^{-\frac{1}{2}} \qquad (20)$$

The modified version no longer requires a buffer, but the capacitor C_C must be equal to C_D. This condition is similar to Figure 1, in which R_1 must be equal to R_2.

Example Calculation
For a Low-Pass Filter

p = +0.1dB; f_g = 10MHz; $C_C = C_D$ = 30pF

Q_1 = 0.767360

f_{01}/f_g = 0.927601

a_1 and f_{01}/f_g can be derived from the filter table.

$$\tau_C = \tau_{CD} = \frac{1}{2Q_1(f_{01}/f_g) \bullet 2\pi f_g} = \frac{1}{2 \bullet 0.767360 \bullet 0.927601 \bullet 2\pi \bullet 10\text{MHz}} = 11.18\text{ns}$$

$$\tau_D = \frac{2Q_1}{(f_{01}/f_g) \bullet 2\pi f_g} = \frac{2 \bullet 0.767360}{0.927601 \bullet 2\pi \bullet 10\text{MHz}} = 26.33\text{ns}$$

$$R_F = \frac{\tau_C}{C_C} = \frac{11.18\text{ns}}{30\text{pF}} = 372.7\Omega;$$

$$R_D = \frac{\tau_D}{C_D} = \frac{26.33\text{ns}}{30\text{pF}} = 877.7\Omega$$

Figure 9 shows the frequency response $|A_I|$, which is identical to the frequency response shown in Figure 3.

2.3
2nd Order Low-Pass Filter Based On Adjusted Open-Loop Poles

The circuit shown in Figure 10 combines the ideal circuit from Figure 8 with the OPA660 model.

The resistors R_D and R_F are used to fine-tune the frequency response $|A_M|$, resulting in the curve shown in Figure 9. The conditions listed in section 1.2 for signals at 100MHz and above also apply here.

The 2nd order low-pass filter shown in Figure 5 contains 4 time constants: the dominating external time constants τ_1 and τ_2, which determine the actual filter curve, and the two parasitic internal time constants τ_C and τ_D. The 2nd order low-pass filter in Figure 10, however, contains only τ_C and τ_D. The unavoidable internal parasitic time constants $\tau_{C\ IN}$ and $\tau_{D\ IN}$ are included in the dominating external time constants $\tau_{C\ OUT}$ and $\tau_{D\ OUT}$.

2.4 Tests Using The Demo Board

The circuit shown in Figure 10 was used to construct the demo board shown in Figure 11. Figure 9 contains the frequency responses $|A_{D1}|$ and $|A_{D2}|$ measured at the outputs $V_{OUT\ D1}$ and $V_{OUT\ D2}$.

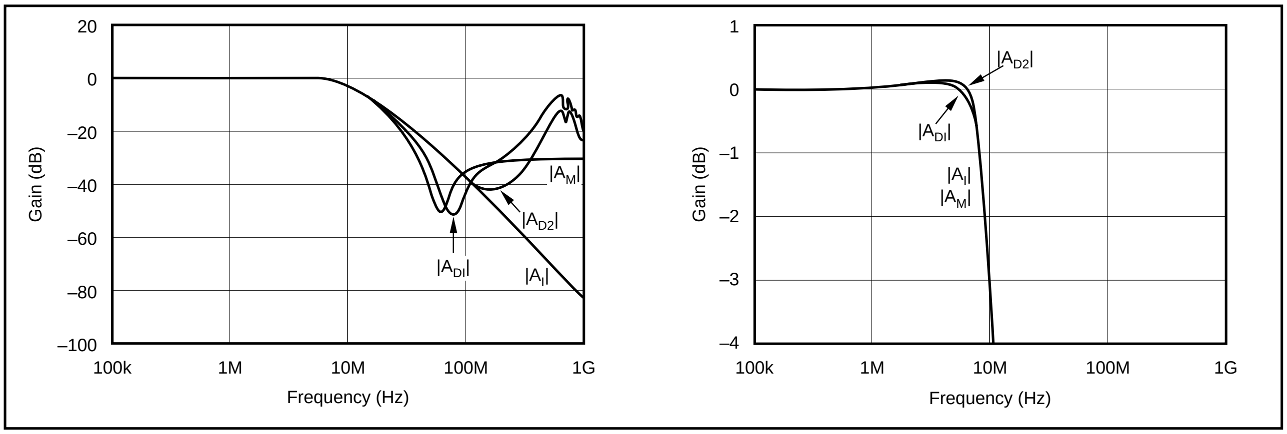

FIGURE 9. Frequency Responses of a 2nd Order Low-Pass Filter According to the Structure in Figure 8.

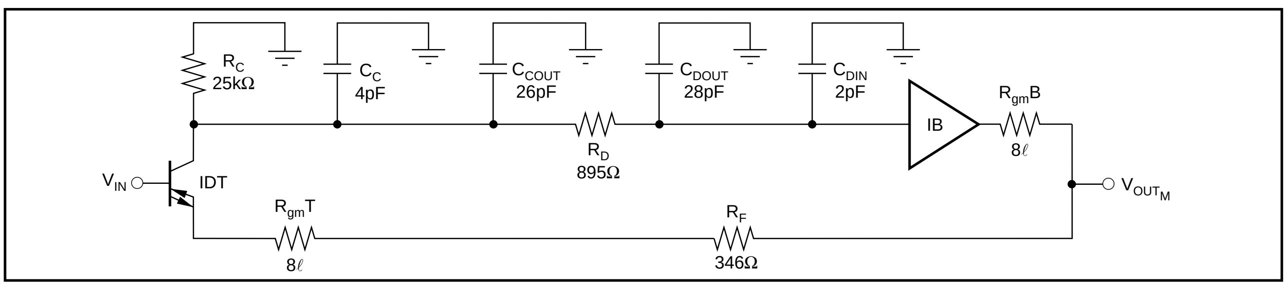

FIGURE 10. 2nd Order Low-Pass Filter Using the Modelled OPA660.

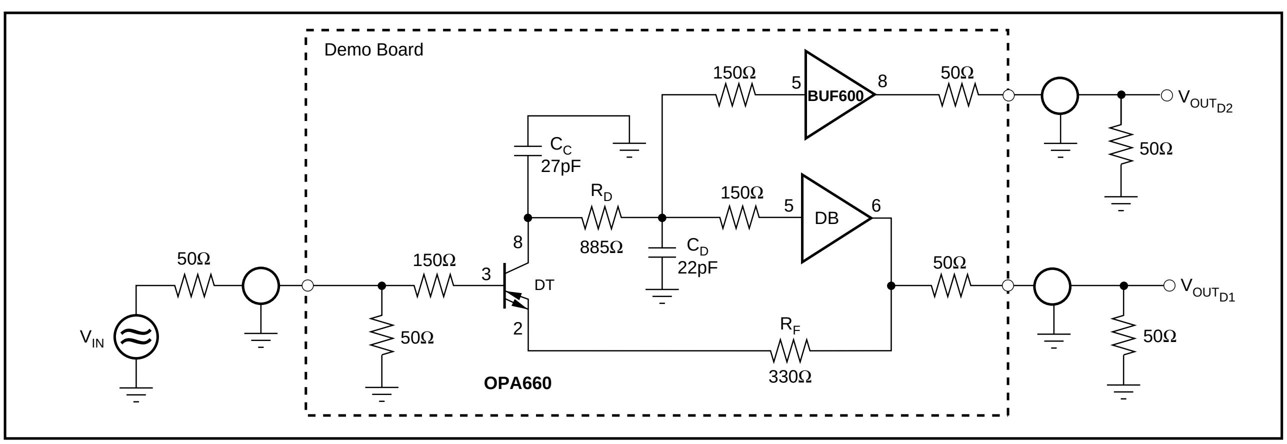

FIGURE 11. Demo Board with a 2nd Order Low-Pass Filter Using the OPA660.

As already explained in section 1.3, the output $V_{OUT\,D2}$ here also shows the improved frequency response $|A_{D2}|$.

3.0
3RD ORDER LOW-PASS FILTER BASED ON ADJUSTED OPEN-LOOP POLES

3.1
Modified PT_2 Model With Preceding Low-Pass Filter

The structure shown in Figure 8 does not contain a prefilter. Instead, the idealized Diamond Transistor IDT has to handle the full bandwidth of the input signal. In Figure 1, the low-pass filter in front of the op amp IOPA reduces the demands on its bandwidth. Consequently, the 2nd order filter structure in Figure 11 is extended by a passive RC filter at the input. This filter improves the overall filter performance, especially at frequencies above twice the –3dB frequency, where the increase in output impedance begins to degrade the filter curve.

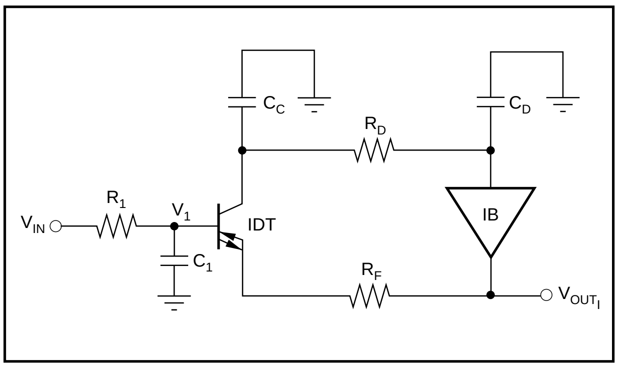

FIGURE 12. Modified PT_2 Model with Preceding Low-Pass Filter τ_1.

$$A_I = \left\{\left[1 + j\omega \bullet (\tau_1)\right]\left[1 + j\omega \bullet (\tau_C + \tau_{CD}) + (j\omega)^2 \bullet (\tau_C \tau_D)\right]\right\}^{-1} \tag{21}$$

$$a_1 = \tau_1 \omega_g = \frac{1}{(\omega_{01} / \omega_g)}$$
$$a_2 = (\tau_C + \tau_{CD})\,\omega_g = \frac{1}{Q_2 (\omega_{02} / \omega_g)} \tag{22}$$

$$b_2 = \tau_C \tau_D \omega_g{}^2 = \frac{1}{(\omega_{01} / \omega_g)^2} \tag{23}$$

$$\tau_1 = \frac{1}{(\omega_{01} / \omega_g)\,\omega_g}; \tau_C = \tau_{CD} = \frac{1}{2Q_2 (\omega_{02} / \omega_g)\,\omega_g};$$
$$\tau_D = \frac{2Q_2}{(\omega_{02} / \omega_g)\,\omega_g} \tag{24}$$

$$\omega_{01} = \frac{1}{R_1 C_1}; \omega_{02} = \frac{1}{\sqrt{R_D R_F C_C C_D}};$$
$$Q_2 = \sqrt{\frac{R_D C_C C_D}{R_F (C_C + C_D)^2}} = \frac{1}{2}\sqrt{\frac{R_D}{R_F}} \tag{25}$$

$$|A_I| = \left[1 + A\omega^2 + B\omega^4 + C\omega^6\right]^{-\frac{1}{2}}$$
$$A = \tau_1{}^2 + (\tau_C + \tau_{CD})^2 - 2\tau_C \tau_D$$
$$B = \tau_1{}^2\left[(\tau_C + \tau_{CD})^2 - 2\tau_C \tau_D\right] + (\tau_C \tau_D)^2 \tag{26}$$
$$C = (\tau_1 \tau_C \tau_D)^2$$

Figure 14 shows the theoretical (ideal) frequency response curve of a 3rd order low-pass filter. The definitions in Figure 13 support the readings from the filter table.

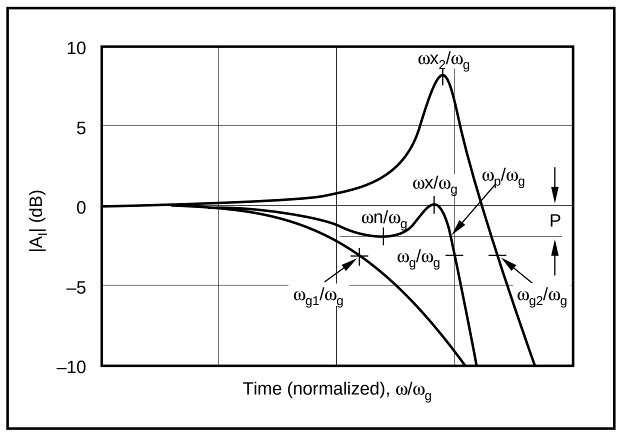

FIGURE 13. Definitions of a 3rd Order Low-Pass Filter.

Example Calculation
For a Low-Pass Filter

$p = +0.1\text{dB}$; $f_g = 10\text{MHz}$; $C_1 = C_C = C_D = 30\text{pF}$

$f_{01}/f_g = 0.697919$

$f_{02}/f_g = 0.935859$

$Q_2 = 1.340928$

Q_2 and f_{01}/f_g are derived from the filter table.

$$\tau_1 = \frac{1}{(f_{01}/f_g) \bullet 2\pi f_g} = \frac{1}{0.697919 \bullet 2\pi \bullet 10\text{MHz}} = 22.80\text{ns}$$

$$\tau_C = \tau_{CD} = \frac{1}{2Q_2 (f_{02}/f_g) \bullet 2\pi f_g}$$
$$= \frac{1}{2 \bullet 1.340928 \bullet 0.935859 \bullet 2\pi \bullet 10\text{MHz}} = 6.341\text{ns}$$

$$\tau_D = \frac{2Q_2}{\left(f_{02}/f_g\right)\bullet 2\pi f_g} = \frac{2\bullet 1.340928}{0.935859\bullet 2\pi\bullet 10\text{MHz}} = 45.61\text{ns}$$

$$R_1 = \frac{\tau_1}{C_1} = \frac{22.80\text{ns}}{30\text{pF}} = 760\Omega;\ R_F = \frac{\tau_C}{C_C} = \frac{6.341\text{ns}}{30\text{pF}} = 211.4\Omega$$

$$R_D = \frac{\tau_D}{C_D} = \frac{45.61\text{ns}}{30\text{pF}} = 1520\Omega$$

3.2 3rd Order Low-Pass Filter With A Modeled Op Amp

In Figure 15, the 3rd order low-pass filter circuit using an ideal op amp has been replaced by a modeled OPA660.

Figure 14 also shows how by inserting a passive prefilter, this 3rd order low-pass filter produces an improvement in stopband attenuation over a 2nd order filter while maintaining the same hardware in the active filter.

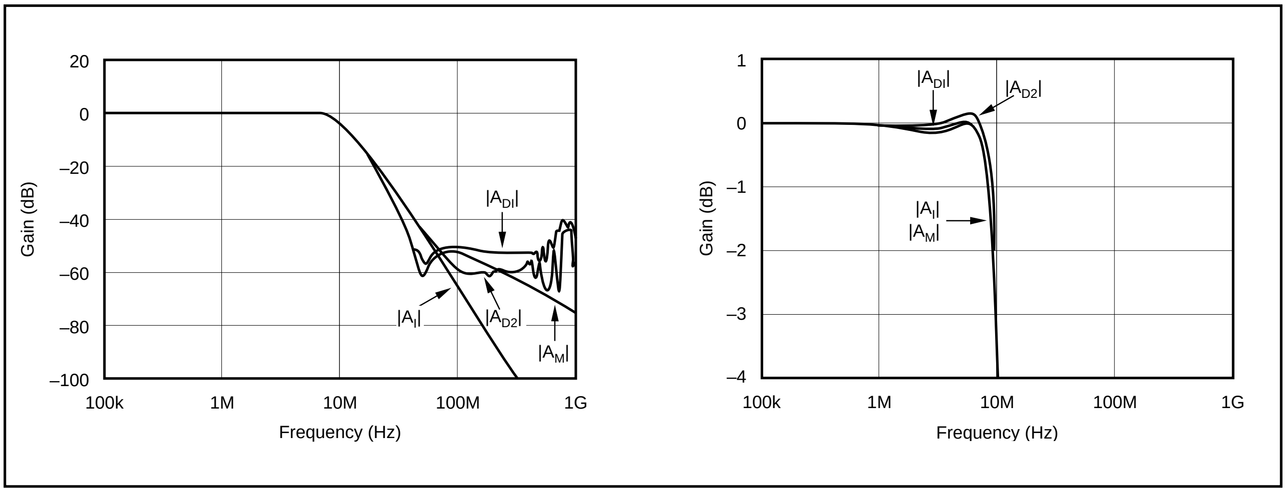

FIGURE 14. Ideal Frequency Responses of a 3rd Order Low-Pass Filter Based on Adjusted Open-Loop Poles.

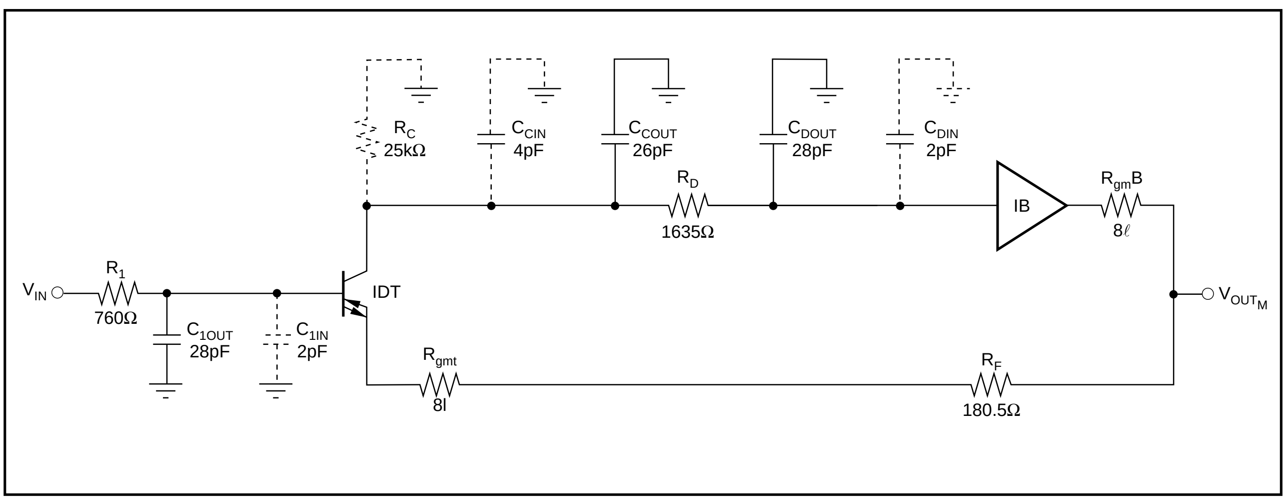

FIGURE 15. 3rd Order Low-Pass Filter with the Modeled OPA660.

3.3 Tests Using The Demo Board

Figure 14 shows frequency responses measured using the demo board illustrated in Figure 16. As with 2nd order low-pass filters, the best curve results when the frequency response $|A_{D2}|$ is decoupled separately by the BUF600 at V_{OUTD2}.

4.0
5TH ORDER LOW-PASS FILTER BASED ON ADJUSTED OPEN-LOOP POLES

4.1
5th Order Low-Pass Filter With Ideal Amplifiers

Figure 17 shows the 3rd order low-pass filter from Figure 12 in series with the 2nd order low-pass filter from Figure 8.

$\tau_1 = R_1C_1$	$\tau_{CD2} = R_{F2}C_{D2}$	$\tau_{C3} = R_{F3}C_{C3}$
$\tau_{C2} = R_{F2}C_{C2}$	$C_{C2} = C_{D2}$	$\tau_{D3} = R_{D3}C_{D3}$
$\tau_{D2} = R_{D2}C_{D2}$	$C_{C3} = C_{D3}$	$\tau_{CD3} = R_{F3}C_{D3}$

$$A_1 = \Big\{\left[1 + j\omega\left(\tau_1\right)\right]\left[1 + j\omega\left(\tau_{C2} + \tau_{CD2}\right) + \left(j\omega\right)^2\left(\tau_{C2}\tau_{D2}\right)\right]\left[1 + j\omega\left(\tau_{C3} + \tau_{CD3}\right) + \left(j\omega\right)^2\left(\tau_{C3}\tau_{D3}\right)\right]\Big\}^{-1} \tag{27}$$

$$a_1 = \tau_1\omega_g = \frac{1}{(\omega_{01} / \omega_g)};$$

$$a_2 = (\tau_{C2} + \tau_{CD2})\omega_g = \frac{1}{Q_2(\omega_{02} / \omega_g)}$$

$$b_2 = \tau_{C2}\tau_{D2}\omega_g^{\,2} = \frac{1}{\left(\omega_{02} / \omega_g\right)^2};$$

$$a_3 = \left(\tau_{C3} + \tau_{CD3}\right)\omega_g = \frac{1}{Q_3\left(\omega_{03} / \omega_g\right)}$$

$$b_3 = \tau_{C3}\tau_{D3}\omega_g^{\,2} = \frac{1}{\left(\omega_{03} / \omega_g\right)^2} \tag{28}$$

$$\tau_1 = \frac{1}{\left(\omega_{01} / \omega_g\right)\omega_g}; \tau_{C2} = \tau_{CD2} = \frac{1}{2Q_2\left(\omega_{02} / \omega_g\right)\omega_g};$$

$$\tau_{D2} = \frac{2Q_2}{\left(\omega_{02} / \omega_g\right)\omega_g}$$

$$\tau_{C3} = \tau_{CD3} = \frac{1}{2Q_3\left(\omega_{03} / \omega_g\right)\omega_g}; \tau_{D3} = \frac{2Q_3}{\left(\omega_{02} / \omega_g\right)\omega_g}$$

$$\omega_{01} = \frac{1}{R_1C_1}; \omega_{02} = \frac{1}{\sqrt{R_{D2}R_{F2}C_2C_{D2}}};$$

$$Q_2 = \sqrt{\frac{R_D\,C_{C2}C_{D2}}{R_{F2}\left(C_{C2} + C_{D2}\right)^2}} = \frac{1}{2}\sqrt{\frac{R_{D2}}{R_{F2}}} \tag{29}$$

$$\omega_{03} = \frac{1}{R_{D3}R_{F3}C_{C3}C_{D3}}; Q_3 = \sqrt{\frac{R_{D3}C_{C3}C_{D3}}{R_{F3}\left(C_{C3} + C_{D3}\right)^2}} = \frac{1}{2}\sqrt{\frac{R_{D3}}{R_{F3}}} \tag{30}$$

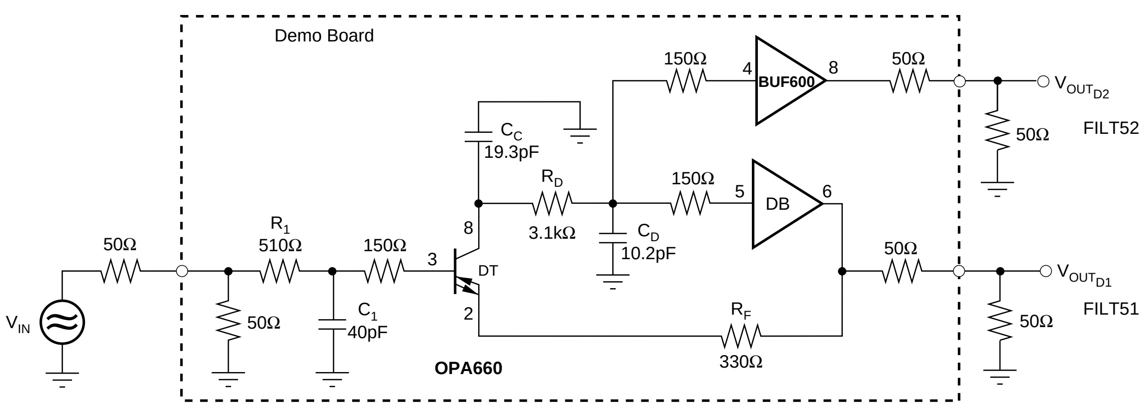

FIGURE 16. Demo Board with a 3rd Order Low-Pass Filter Using the OPA660.

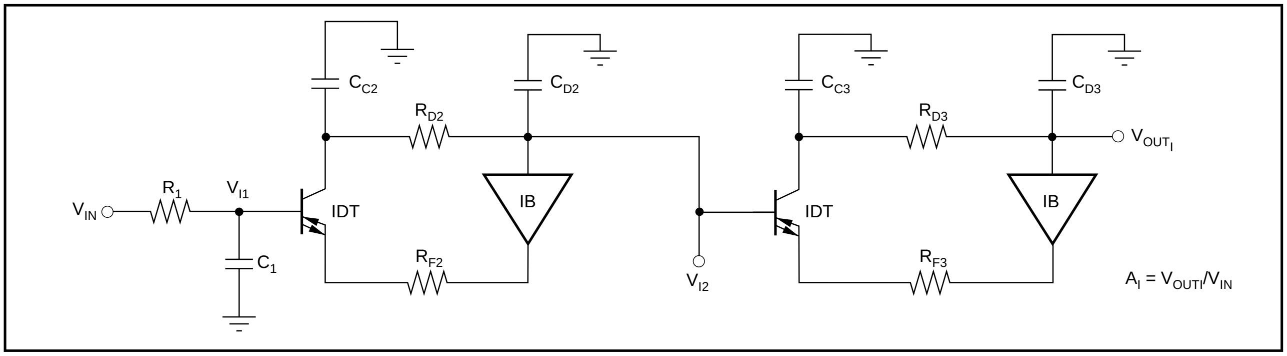

FIGURE 17. 5th Order Low-Pass Filter with Ideal Amplifiers.

Example Calculation
For A Low-Pass Filter

p = +0.2dB, f_g = 10MHz, C_1 = 70pF, $C_{C2} = C_{D2}$ = 30pF; $C_{C3} = C_{D3}$ = 9pF

f_{01}/f_g = 0.419787 Q_2 = 1.000908
f_{02}/f_g = 0.679846 Q_3 = 3.706857
f_{03}/f_g = 0.961717

f_{01}/f_g, f_{02}/f_g, f_{03}/f_g, Q_2 and Q_3 are derived from the filter table.

$$\tau_1 = \frac{1}{(f_{01}/f_g) \bullet 2\pi f_g} = \frac{1}{0.419787 \bullet 2\pi \bullet 10\text{MHz}} = 37.91\text{ns}$$

$$\tau_{C2} = \tau_{CD2} = \frac{1}{2Q_2(f_{01}/f_g) \bullet 2\pi f_g}$$

$$= \frac{1}{2 \bullet 1.000908 \bullet 0.679846 \bullet 2\pi \bullet 10\text{MHz}} = 11.69\text{ns}$$

$$\tau_{D2} \frac{2Q_2}{(f_{02}/f_g) \bullet 2\pi f_g} = \frac{2 \bullet 1.000908}{0.679846 \bullet 2\pi \bullet 10\text{MHz}} = 46.86\text{ns}$$

$$\tau_{C3} = \tau_{CD3} = \frac{1}{2Q_3(f_{03}/f_g) \bullet 2\pi f_g}$$

$$= \frac{0.1}{2 \bullet 3.706857 \bullet 0.961717 \bullet 2\pi \bullet 10\text{MHz}} = 2.2322\text{ns}$$

$$\tau_{D3} = \frac{2Q_3}{(f_{03}/f_g) \bullet 2\pi f_g} = \frac{2 \bullet 3.706857}{0.961717 \bullet 2\pi \bullet 10\text{MHz}} = 122.69\text{ns}$$

$$R_1 = \frac{\tau_1}{C_1} = \frac{37.91\text{ns}}{70\text{pF}} = 541.6\Omega$$

$$R_{F2} = \frac{\tau_{C2}}{C_{C2}} = \frac{11.69\text{ns}}{30\text{pF}} = 389.8\Omega$$

$$R_{D2} = \frac{\tau_{D2}}{C_{D2}} = \frac{46.86\text{ns}}{30\text{pF}} = 1562\Omega$$

$$R_{F3} = \frac{\tau_{C3}}{C_{C3}} = \frac{2.2322\text{ns}}{9\text{pF}} = 248.0\Omega$$

$$R_{D3} = \frac{\tau_{D3}}{C_{D3}} = \frac{122.69\text{ns}}{9\text{pF}} = 13.632\text{k}\Omega$$

Figure 18 shows the ideal frequency response $|A_I|$ of a 5th order low-pass filter.

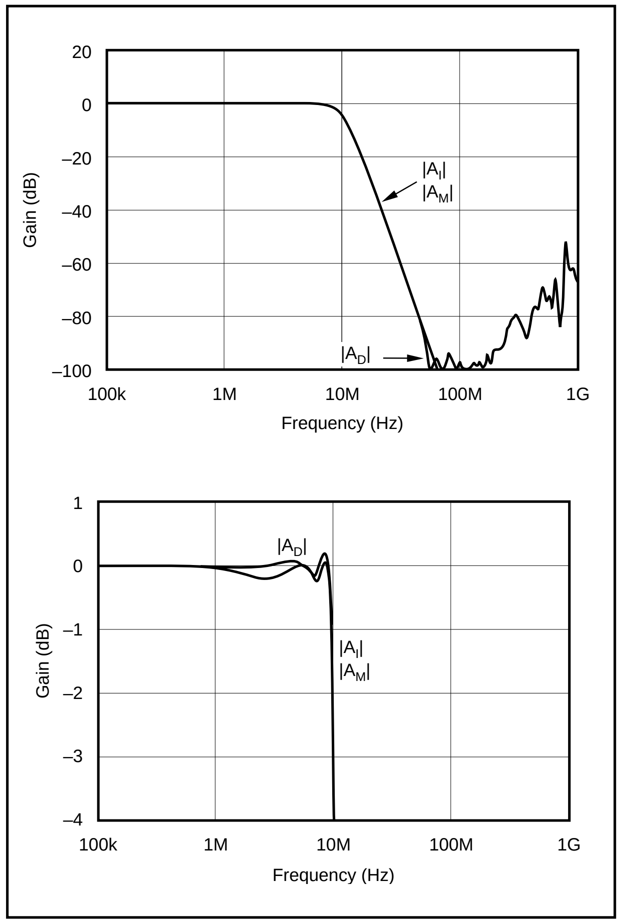

FIGURE 18. Frequency Responses of a 5th Order Low-Pass Filter Based on Adjusted Open-Loop Poles.

4.2
5th Order Low-Pass Filter With A Modeled Op Amp

By adjusting the resistors R_{FX} and R_{DX}, it is possible to include the effects of the parasitic resistors R_{CX} and capacitors $C_{XX\ IN}$ in the frequency response curve while changing the curve only slightly. This process is comparable to changing $|A_I|$ to $|A_M|$ as shown in Figure 18. The output impedance R_{CX} produces more and more disturbances with increasingly higher order filters. The size of the filter capacitors C_{CX} and C_{DX} also increases with higher order filters and –3dB frequencies. Experiments are currently in progress to develop filter circuits using the OPA660 that are much less susceptible to filter quality and capacitance; we will present the results in Part Two.

4.3 Tests Using The Demo Boards

Figure 18 shows the frequency response $|A_D|$ measured using the demo board in Figure 20.

Further application notes about the OPA660:

AN-179 "Current or Voltage Feedback? That's the Question Here."

AN-180 "Quasi-Ideal Current Source"

AN-181 "Circuit Technology with the Diamond Transistor OPA660"

AN-183 "New Ultra High-Speed Circuit Techniques with Analog ICs"

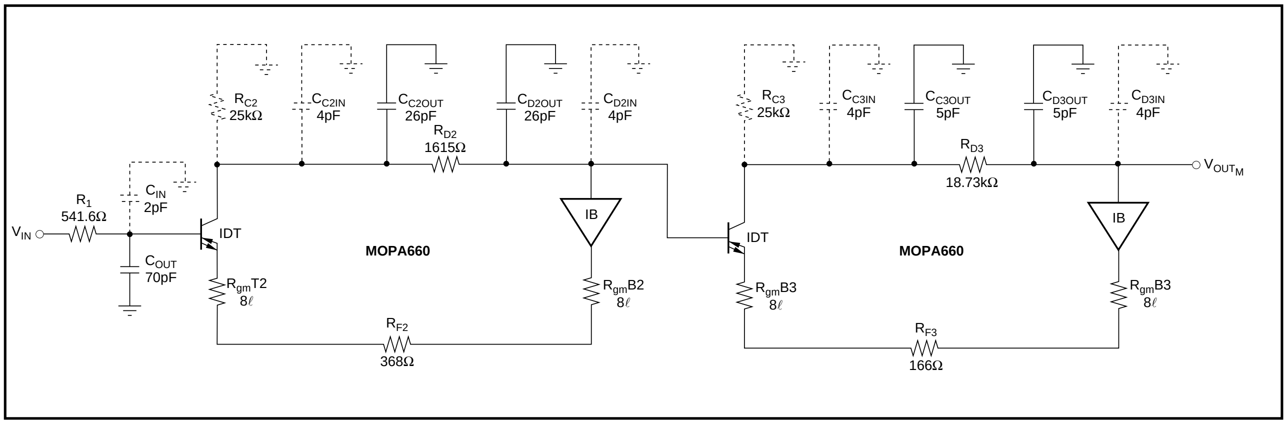

FIGURE 19. 5th Order Low-Pass Filter with the Modeled OPA660.

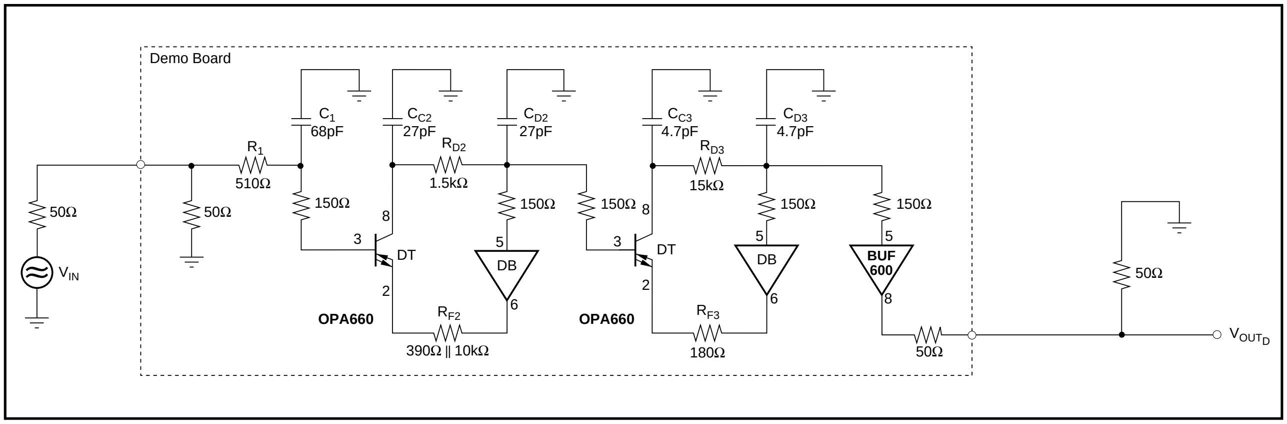

FIGURE 20. Demo Board with a 5th Order Low-Pass Filter Using the OPA660.

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