Analog Engineer's Circuit

Decompensated Amplifier Stabilization Circuit

Design Goals

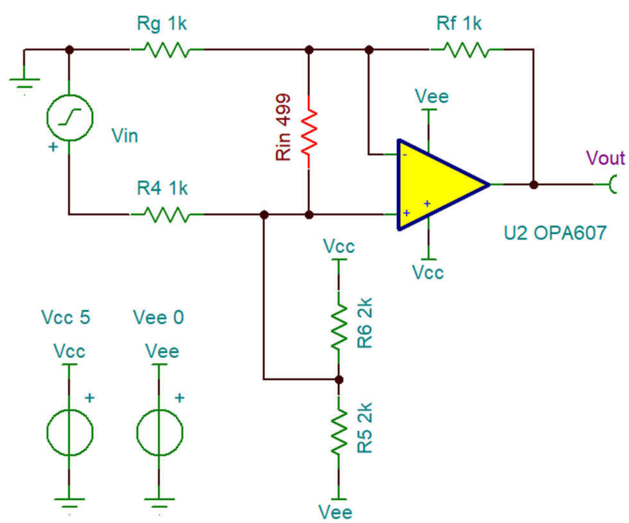
Input	Output	Supply		
		V_{cc}	V_{ee}	V_{ref}
2 V_{PP}, 500 kHz Square wave	Gain = 1 V/V	5 V	0 V	2.5 V

Design Description

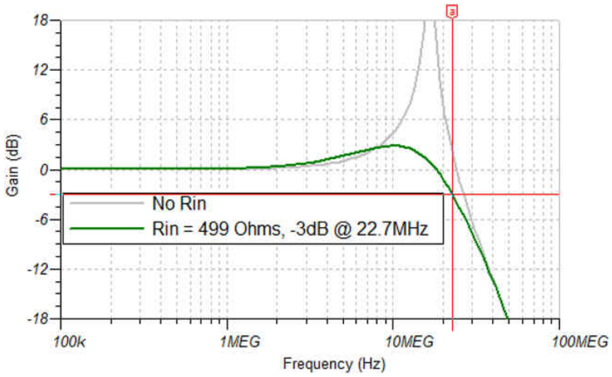
A decompensated amplifier is defined as an amplifier that is not inherently stable below a minimum specified gain, but offers a higher gain bandwidth product (GBWP) and sometimes lower noise versus its unity-gain stable counterpart (see OPA858 versus OPA859). This circuit document presents three different external compensation methods for making these amplifiers unity-gain stable. Each circuit increases low gain stability at the expense of bandwidth. The first two circuits modify the amount-of-feedback (β) to increase the noise-gain (1/ β). The third circuit uses the output impedance of the amplifier in conjunction with an output load to attenuate the effective open-loop gain (A_{OL}).

These examples stabilize the OPA607, a ≥ 6 V/V decompensated amplifier, in a unity-gain difference amplifier circuit.

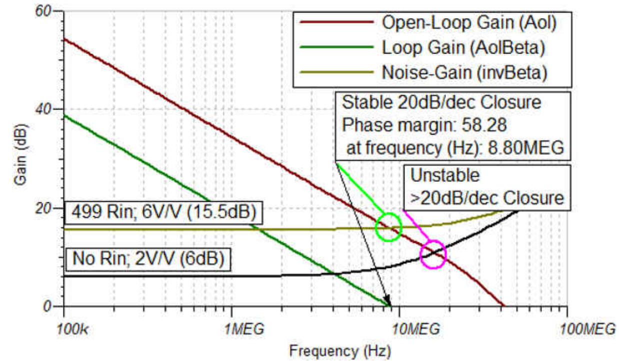
Compensation Circuit 1: Differential Input Resistor (R_{IN})



Circuit 1 Schematic



Frequency Response



Noise-Gain (Amount of Feedback) Stability Analysis

Design Notes

Add a resistor (R_{IN}) between the two inputs that is small enough to decrease the amount-of-feedback (β) to ≤ 1/6, and increase the noise-gain (1/ β) to ≥ 6. R_{IN} does not affect the signal gain because of the virtual short between the two inputs. This method increases the noise gain of the amplifier uniformly across all frequencies, but sacrifices the least bandwidth.

Design Steps

In this difference amplifier circuit example, $\Delta V(R_{IN})$ is the voltage across resistor R_{IN} in the circuit 1 schematic, and ΔV(OUT) is the voltage at Vout. β is the ratio $\Delta V(R_{IN})$ / ΔV(OUT) that is divided across the feedback. This ratio can be factored into:

$$\beta = \frac{\Delta V(R_{IN})}{\Delta V(OUT)} = \frac{\Delta V(IN-)}{\Delta V(OUT)} \times \frac{\Delta V(R_{IN})}{\Delta V(IN-)}$$

First, the amount of ΔV(OUT) fed back to ΔV(IN–) across the feedback resistor R_F is:

$$\frac{\Delta V(IN-)}{\Delta V(\mathrm{OUT})} = \frac{Z_G}{Z_G + R_F}$$

Z_G represents the resistance out of IN–. To calculate Z_G, add R_{IN} to the resistance out of IN+, which is the parallel combination of R4 ll R5 ll R6. The result adds in parallel with the gain resistor R_G at IN– to form Z_G.

$$Z_G = (R_{IN} + R4\|R5\|R6)\|R_G$$

Second, because of the series resistance out of IN+, the voltage $\Delta V(R_{IN})$ is only a fraction of ΔV(IN–).

$$\frac{\Delta V(R_{IN})}{\Delta V(IN-)} = \frac{R_{IN}}{R_{IN} + R4\|R5\|R6}$$

When R_{IN} = ∞, β = 1/2 in this example circuit, where R4 ll R5 ll R6 = 500 Ω, R_G= 1 kΩ, and R_F= 1 kΩ. To stabilize the OPA607, set β = 1/6 and solve for R_{IN}. This can also be solved with simulation, as shown in the noise-gain stability analysis image. R_{IN} = 500 Ω raises the noise-gain up from 2 V/V to 6 V/V. A smaller R_{IN} further increases 1/β.

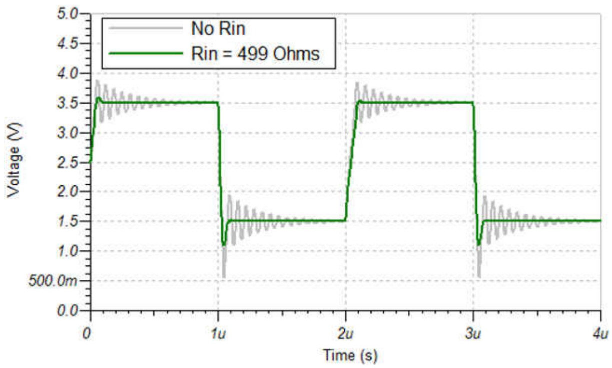
$$\frac{\Delta V(IN-)}{\Delta V(\mathrm{OUT})} = \frac{(R_{IN} + 500\,\Omega)\|1\,k\Omega}{(R_{IN} + 500\,\Omega)\|1\,k\Omega + 1\,k\Omega} = \frac{1}{3}$$

$$\frac{\Delta V(R_{IN})}{\Delta V(IN-)} = \frac{R_{IN}}{R_{IN} + 500} = \frac{1}{2}$$

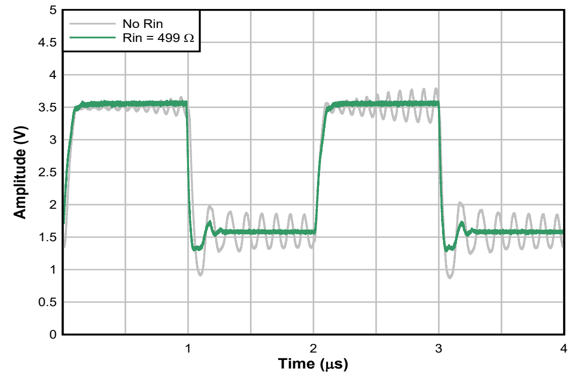
$$\beta = \frac{\Delta V(IN-)}{\Delta V(\mathrm{OUT})} \times \frac{\Delta V(R_{IN})}{\Delta V(IN-)} = \frac{1}{3} \times \frac{1}{2} = \frac{1}{6}$$

Design Results

The silver peaking in the Frequency Response and ringing in the Square-Wave Response are signs of < 45° of phase margin and instability. Simulation and measurement of this circuit (see the following images) show that R_{IN} = 499 Ω is sufficient for external compensation and stability. The higher undershoot shown is due to the faster falling edge slew rate of the OPA607.

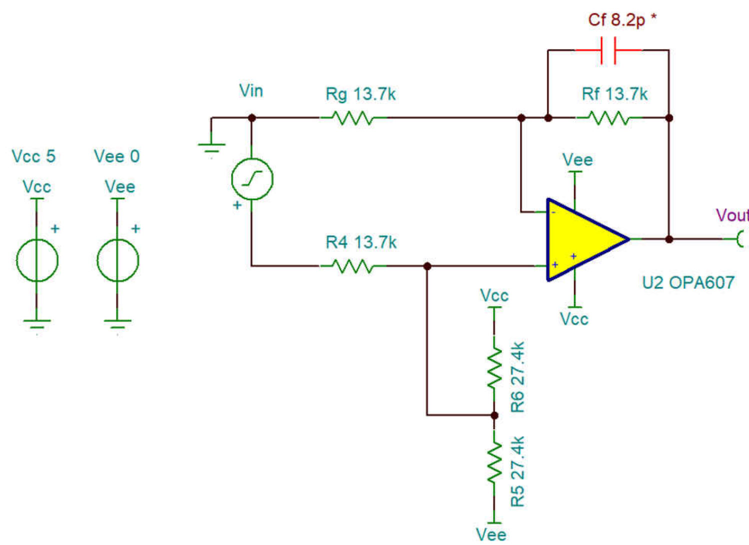


500 kHz, 2 Vpp Square-Wave Response

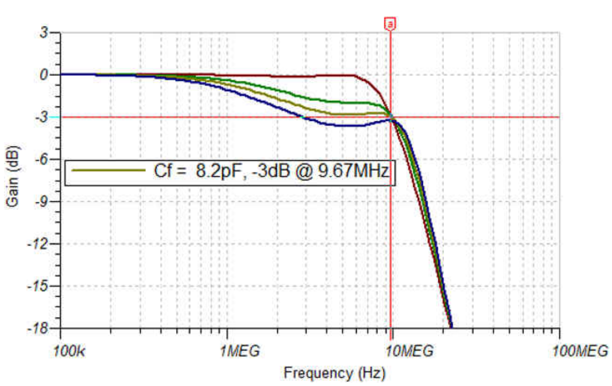


Circuit 1 Measurement

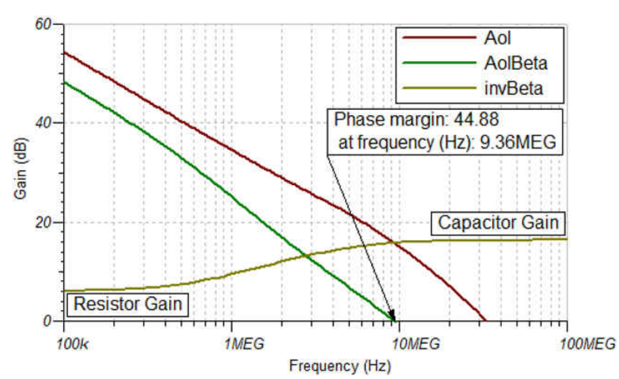
Compensation Circuit 2: Feedback Capacitor (C_F)



Circuit 2 Schematic



Frequency Response



Noise-Gain (Amount of Feedback) Stability Analysis

Design Notes

Add a feedback capacitor (C_F) which creates a high-frequency gain ≥ 6 V/V in conjunction with the amplifier input capacitance, but use R_F / R_G to set a lower signal gain at low frequency and DC. Ensure that the high-frequency noise-gain both is ≥ 6 V/V and is achieved within the gain-bandwidth of the amplifier. That is, in the noise-gain stability analysis image, the maroon A_{OL} curve must intersect the olive 1/β (invBeta) curve where both the A_{OL} curve is –20 dB/decade and the 1/β curve is flat versus frequency.

Design Steps

The high-frequency gain is set by a capacitor divider, formed between C_F and the three parasitic input capacitances of the OPA607: C_{IN-} = 5.5 pF; C_{IN+} = 5.5 pF; and C_{INDIFF} = 11.5 pF. β is calculated with the same factors discussed in Circuit 1, but using these internal capacitors instead of external resistors.

$$\beta = \frac{\Delta V(C_{INDIFF})}{\Delta V(OUT)} = \frac{\Delta V(IN-)}{\Delta V(OUT)} \times \frac{\Delta V(C_{INDIFF})}{\Delta V(IN-)}$$

In this noise-gain stability analysis, C_F = 8.2 pF raises the high-frequency capacitor gain to 6.57 V/V. A smaller feedback capacitor further decreases β and increases the high-frequency gain.

$$\frac{\Delta V(IN-)}{\Delta V(\mathrm{OUT})} = \frac{\left(1/C_{INDIFF} + 1/C_{IN+}\right) \| 1/C_{IN-}}{\left(1/C_{INDIFF} + 1/C_{IN+}\right) \| 1/C_{IN-} + 1/C_F} = \frac{\left(1/11.5\,pF + 1/5.5\,pF\right) \| 1/5.5\,pF}{\left(1/11.5\,pF + 1/11.5\,pF\right) \| 1/5.5\,pF + 1/8.2\,pF} = 0.47$$

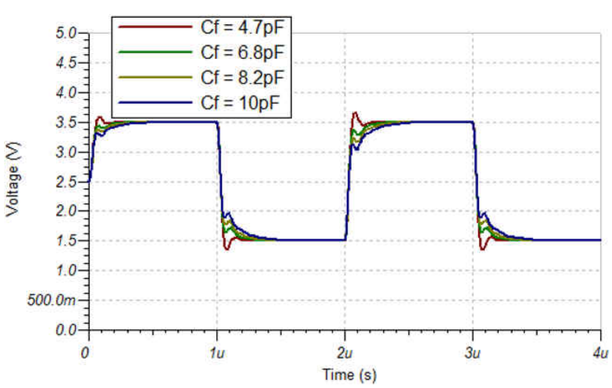
$$\frac{\Delta V(C_{INDIFF})}{\Delta V(IN-)} = \frac{1/C_{INDIFF}}{1/C_{INDIFF} + 1/C_{IN+}} = \frac{1/11.5\,pF}{1/11.5\,pF + 1/5.5\,pF} = 0.32$$

$$\beta = \frac{\Delta V(IN-)}{\Delta V(\mathrm{OUT})} \times \frac{\Delta V(C_{INDIFF})}{\Delta V(IN-)} = 0.47 \times 0.32 = 0.152 = \frac{1}{6.57}$$

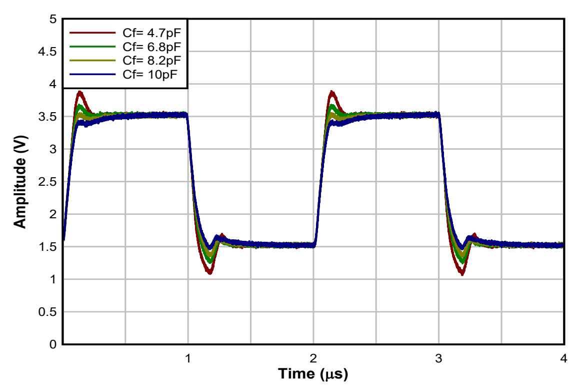
This stable β suggests that the amplifier now has a signal gain ≥ 6 V/V at high frequency. But careful selection of both C_F and R_F values can create both a stable amount of feedback and also a low-pass filter of the signal gain, to prevent the increasing 1/β over frequency from creating issues like overshoot. It is easier to achieve both of these conditions when R_F is > 10 kΩ.

Design Results

Measurement of this circuit shows that C_F = 8.2 pF and R_F = 13.7 kΩ were sufficient to both maintain a stable noise-gain = 6.57 V/V and filter overshoot.

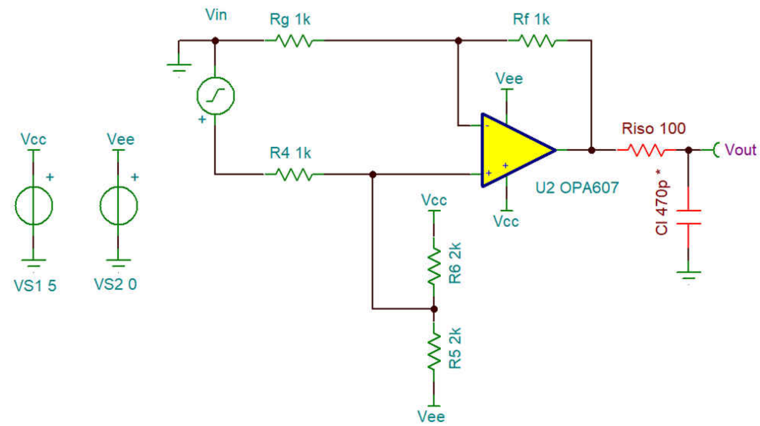


500 kHz, 2 Vpp Square-Wave Response

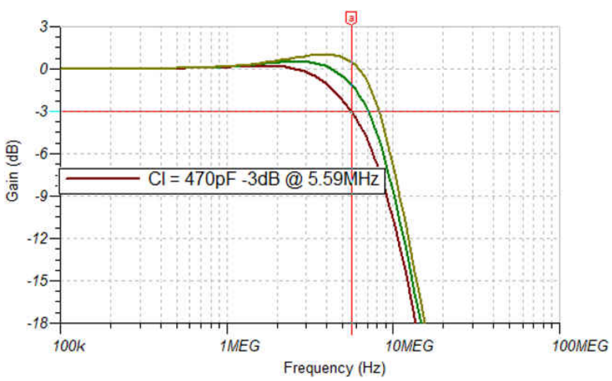


Circuit 2 Measurement

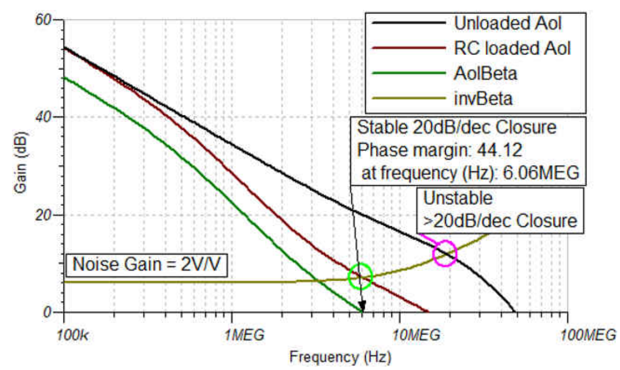
Compensation Circuit 3: High-Frequency Load (R_{ISO})



Circuit 3 Schematic



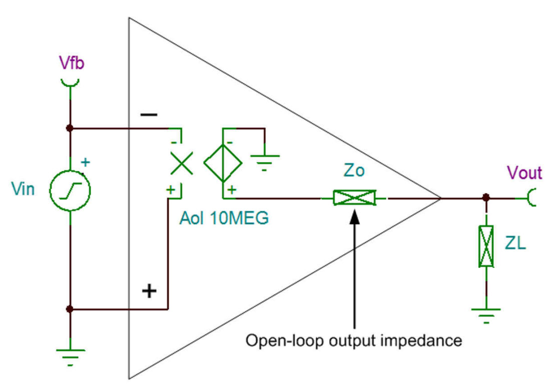
Frequency Response



Noise-Gain (Amount of Feedback) Stability Analysis

Design Notes

Add a low-resistance load (R_{ISO}) for high frequencies. The load forms a resistor divider with the amplifier open-loop output impedance (see the following image), and can attenuate the effective open-loop gain (A_{OL}) of the amplifier to a compensated level. Since the OPA607 has 500 Ω of series output impedance, a 100-Ω load resistor attenuates the A_{OL} to 1/6 (–15.5 dB).



Alone, a small resistor load burns a lot of power. But for stability purposes, attenuating the A_{OL} is like increasing the noise-gain, and only a high-frequency load is required, such as an output filter. In the noise-gain stability analysis circuit, both the black unloaded A_{OL} and the maroon A_{OL} with an RC filter load are graphed. The olive 2 V/V (6 dB) noise-gain intersects with the maroon loaded A_{OL} at a more stable, 20-dB/decade rate of closure. This compensation technique is helpful for using the OPA607 as a drop-in replacement for unity-gain stable amplifiers where an output filter is present.

Design Steps

The R_{ISO} + C_L filter bandwidth must be lower than the attenuated bandwidth of the loaded amplifier, because the frequency range above the filter bandwidth and below the loaded amplifier bandwidth is where the compensation is created. Otherwise, the load further decompensates the amplifier without creating a usable lower gain. In the stability analysis for this circuit, the –40 dB/decade slope in the maroon loaded A_{OL} shows that higher gains will be less stable than the compensated low gain when a filter load attenuates the A_{OL}.

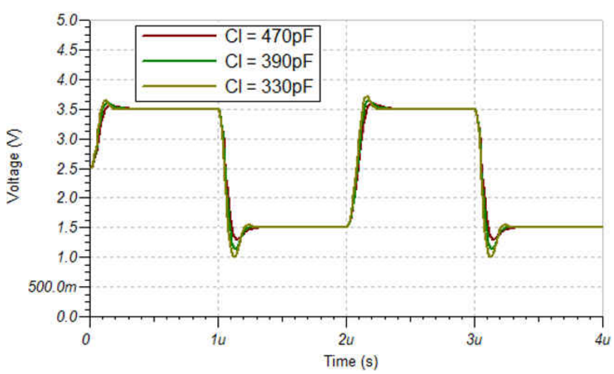
In this example circuit, GBWP = 50 MHz and β = 1/2, but attenuation = 1/6. Therefore, the attenuated amplifier bandwidth is 50/12 = 4.2 MHz. For R_{ISO} = 100 Ω, C_L should be > 380 pF.

$$GBWP \times \beta \times Attenuation > \frac{1}{2\pi \times R_{ISO} \times C_L}$$

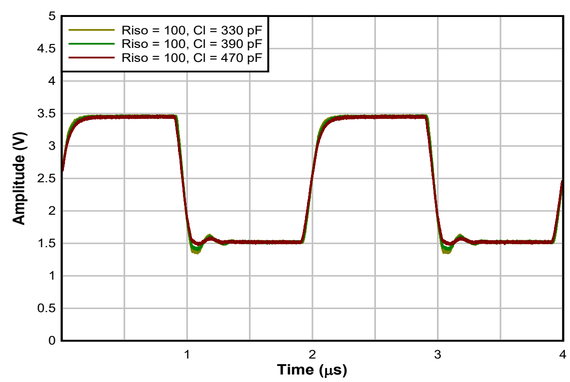
$$C_L > \frac{(2 \times 6)}{2\pi \times 100\,\Omega \times 50\,MHz} = 380\,pF$$

Design Results

Measurement of this circuit shows that a R_{ISO} = 100 Ω, 470-pF load was sufficient to make the OPA607 stable in a difference configuration with a gain of 1 V/V.



500 kHz, 2 Vpp Square-Wave Response



Circuit 3 Measurement

Design Featured Device

OPA607	
Supply Range (V_{ss})	2.2 V to 5.5 V
Gain Bandwidth Product, G = 20 V/V	50 MHz
Decompensated Gain ($A_{V/V}$)	≥ 6 V/V
Input Capacitance (C_{IN})	Differential: 11.5 pF
	Common-mode: 5.5 pF
Input Range (V_{CMVR})	(V–) to (V+) – 1.1 V
Output Range (V_{out})	Rail to Rail
Overdrive Recovery Time (t_{OR})	300 ns
Voltage Noise (e_N)	3.8 nV/√(Hz)
Offset Voltage (V_{os})	± 120 µV
Quiescent Current (I_q)	900 µA
Input Bias Current (I_b)	± 3 pA
Slew Rate	24 V/µs
Open-loop Output Impedance (Zo)	500 Ω
OPA607	

Design Alternative Devices

Decompensated High-Speed Amplifiers		
Device Name	**Gain Bandwidth**	**Decompensated Gain**
LMV793, LMV794 LMP7717, LMP7718	88 MHz	10 V/V
SM73302	88 MHz	10 V/V
OPA838	300 MHz	6 V/V
LMH6629	900 MHz	10 V/V
LMH6626	1.5 GHz	10 V/V
OPA818	2.7 GHz	7 V/V
OPA858	5.5 GHz	7 V/V

Design References

- See the Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.
- Texas Instruments, *AN-1604 Decompensated Operational Amplifiers* application note
- For hardware evaluation, see TIDA-060019

Additional Resources

- Texas Instruments, *OPAx607 50-MHz, Low-Power, Rail-to-Rail Output CMOS Operational Amplifier for Cost Sensitive Systems* data sheet