

TD5

TD 5 / FILTRER EFFICACEMENT UN SIGNAL ÉLECTRIQUE

Objectifs pédagogiques

A la fin de cette thématique, les étudiant·e·s seront capables de :

- définir un protocole expérimental pour :
 - ▷ caractériser un filtre linéaire dans le domaine fréquentiel (n'importe quel ordre)
 - ▷ valider le fonctionnement d'un tel filtre vis-à-vis d'un cahier des charges (contraintes et performances)
- comparer différents types de filtre
- choisir et mettre en oeuvre une solution analogique adaptée à un cahier des charges pour le filtrage de certaines composantes fréquentielles, à partir d'un gabarit donné (filtres actifs - ordre 1 et 2 - et universels)

Activités pédagogiques

- Lectures (hors temps présentiel - en ligne)
 - ▷ Fiche résumé : Systèmes linéaires / Superposition
 - ▷ Fiche résumé : Régime Harmonique
 - ▷ Fiche résumé : Filtrage actif / Analyse harmonique / Ordre 2
- Séance de **TD5**
- Séances de **TP3** à **TP6** (module TP CéTI)

Ressources Complémentaires

- Site OKAWA Electric Design / Rubrique Filter Tools / <http://sim.okawa-denshi.jp/en/Fkeisan.htm>
- Exercices supplémentaires proposés sur eCampus (avec correction)

TD5

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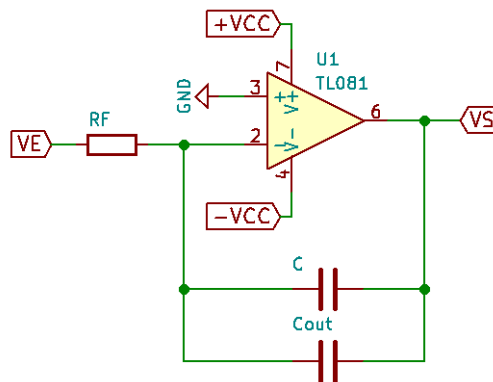
Exercice 1 - Filtre universel

Notions abordées

- ▷ utilisation de 2 circuits à ALI
- ▷ mise en cascade de systèmes
- ▷ étude d'un filtre universel

Bloc intégrateur

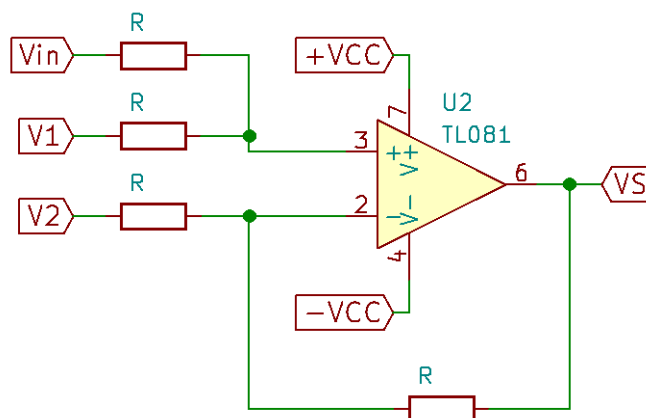
On se propose d'étudier la réponse du système suivant :



Donner la relation entre V_S et V_E .

Bloc additionneur

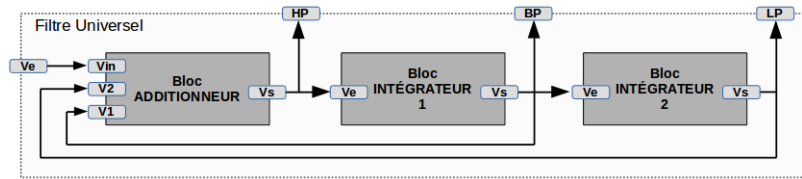
On s'intéresse à présent au bloc suivant :



Donner la relation entre V_S , V_1 , V_2 et V_{in} .

Structure universelle

Soit la structure suivante, basée sur les montages vus précédemment :



1. Calculer V_{HP} en fonction de V_{in} et des divers composants.
2. Calculer V_{BP} et V_{LP} .
3. Que peuvent signifier les noms donnés aux signaux de sortie ?

Etude du composant UAF42

On souhaite s'intéresser au composant UAF42, dont quelques pages de documentation technique sont données en annexe.

1. Retrouve-t-on la structure étudiée précédemment dans le schéma de la page 1 de la documentation technique ?
2. Le câblage de la figure 1 de la page 6 de la documentation technique est-il conforme à la structure universelle proposée précédemment ?
3. Retrouve-t-on la fonction de transfert calculée précédemment ?
4. Que doivent valoir R_{F1} et R_{F2} pour obtenir une pulsation de coupure de $30 \cdot 10^3$ rd/s ?

Exercice 2 - Filtre paramétrable

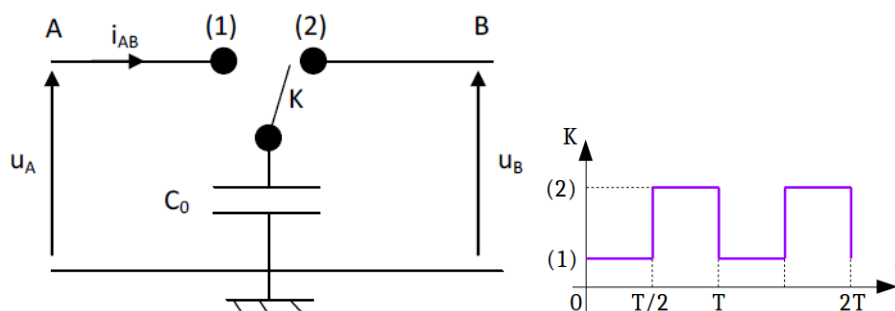
Notions abordées

- ▷ étude de l'effet capacité commutée
- ▷ structure intégratrice à capacité commutée
- ▷ étude d'un filtre actif intégré

Nous allons nous intéresser à présent à des filtres dont la fréquence de coupure est pilotable par un signal extérieur.

Capacité commutée

On donne dans un premier temps la structure suivante, dont l'interrupteur K est piloté par le signal de commande ci-dessous :

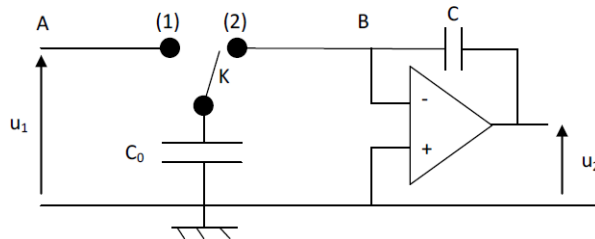


1. Calculer la charge stockée dans C_0 entre les instants 0 et $T/2$, puis entre les instants $T/2$ et T .
2. Quelle quantité de charges passe de A vers B entre les instants 0 et T ?
3. Calculer alors le courant moyen circulant du point A au point B pendant une période T .
4. Donner l'expression de la résistance équivalente R_{AB} vue entre les bornes A et B de cette cellule.

Intégrateur à capacité commutée

On réalise un intégrateur à partir du circuit de la figure 2.

1. Donner la fonction de transfert du circuit $T(j\omega) = u_2/u_1$ en fonction de R_{AB} et de C .



2. Que devient alors la fonction de transfert $T(j\omega) = u_2/u_1$ en fonction des éléments du système (C_0 et C)?
3. Quel est l'intérêt d'un tel circuit?

Etude du MAX296

On s'intéresse au composant MAX296 dont une partie de la documentation technique est donnée en annexe.

1. Quelles sont les fréquences maximales utilisables sur l'entrée INPUT? Sur l'entrée CLOCK? Quelles sont les applications visées?
2. Quelle fréquence faut-il appliquer sur l'entrée CLOCK pour avoir une fréquence de coupure de 3 kHz? Que vaut alors l'amplification théorique du signal à : (a) 300 Hz? (b) 30 kHz? (c) 5 kHz?
3. Avec un filtre du second ordre (type Rauch) avec une pulsation de coupure à la même valeur, quelle aurait été l'amplification : (a) à 30 kHz? (b) à 5 kHz?



UNIVERSAL ACTIVE FILTER

 Check for Samples: [UAF42](#)

FEATURES

- **VERSATILE:**
 - Low-Pass, High-Pass
 - Band-Pass, Band-Reject
- **SIMPLE DESIGN PROCEDURE**
- **ACCURATE FREQUENCY AND Q:**
 - Includes On-Chip 1000pF $\pm 0.5\%$ Capacitors

APPLICATIONS

- TEST EQUIPMENT
- COMMUNICATIONS EQUIPMENT
- MEDICAL INSTRUMENTATION
- DATA ACQUISITION SYSTEMS
- MONOLITHIC REPLACEMENT FOR UAF41

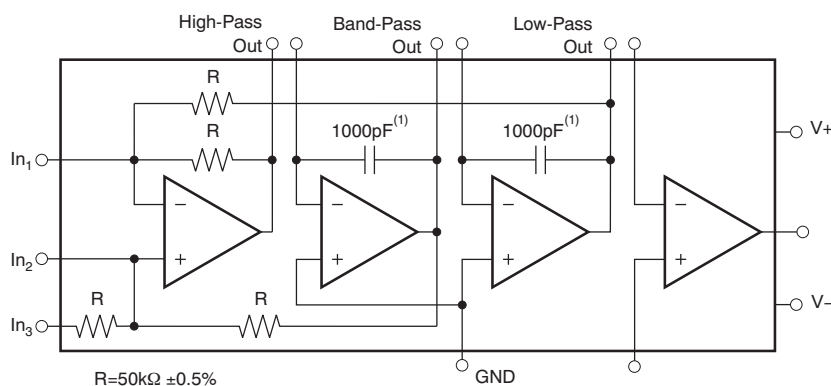
DESCRIPTION

The UAF42 is a universal active filter that can be configured for a wide range of low-pass, high-pass, and band-pass filters. It uses a classic state-variable analog architecture with an inverting amplifier and two integrators. The integrators include on-chip 1000pF capacitors trimmed to 0.5%. This architecture solves one of the most difficult problems of active filter design—obtaining tight tolerance, low-loss capacitors.

A DOS-compatible filter design program allows easy implementation of many filter types, such as Butterworth, Bessel, and Chebyshev. A fourth, uncommitted FET-input op amp (identical to the other three) can be used to form additional stages, or for special filters such as band-reject and Inverse Chebyshev.

The classical topology of the UAF42 forms a time-continuous filter, free from the anomalies and switching noise associated with switched-capacitor filter types.

The UAF42 is available in 14-pin plastic DIP and SOIC-16 surface-mount packages, specified for the -25°C to $+85^{\circ}\text{C}$ temperature range.


 NOTE: (1) $\pm 0.5\%$.


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ELECTRICAL CHARACTERISTICS

At $T_A = +25^\circ\text{C}$, and $V_S = \pm 15\text{V}$, unless otherwise noted.

PARAMETER	CONDITIONS	UAF42AP, AU			UNIT
		MIN	TYP	MAX	
FILTER PERFORMANCE					
Frequency Range, f_n			0 to 100		kHz
Frequency Accuracy vs Temperature	$f = 1\text{kHz}$		0.01	1	%/°C
Maximum Q			400		—
Maximum (Q • Frequency) Product			500		kHz
Q vs Temperature	$(f_o \cdot Q) < 10^4$		0.01		%/°C
	$(f_o \cdot Q) < 10^5$		0.025		%/°C
Q Repeatability	$(f_o \cdot Q) < 10^5$		2		%
Offset Voltage, Low-Pass Output				±5	mV
Resistor Accuracy			0.5	1	%
OFFSET VOLTAGE⁽¹⁾					
Input Offset Voltage vs Temperature vs Power Supply	$V_S = \pm 6\text{V to } \pm 18\text{V}$		±0.5 ±3	±5	mV μV/°C
		80	96		dB
INPUT BIAS CURRENT⁽¹⁾					
Input Bias Current	$V_{CM} = 0\text{V}$		10	50	pA
Input Offset Current	$V_{CM} = 0\text{V}$		5		pA
NOISE					
Input Voltage Noise					
Noise Density: $f = 10\text{Hz}$			25		nV/√Hz
Noise Density: $f = 10\text{kHz}$			10		nV/√Hz
Voltage Noise: BW = 0.1Hz to 10Hz			2		μV _{PP}
Input Bias Current Noise					
Noise Density: $f = 10\text{kHz}$			2		fA/√Hz
INPUT VOLTAGE RANGE⁽¹⁾					
Common-Mode Input Range			±11.5		V
Common-Mode Rejection	$V_{CM} = \pm 10\text{V}$	80	96		dB
INPUT IMPEDANCE⁽¹⁾					
Differential			$10^{13} \parallel 2$		Ω pF
Common-Mode			$10^{13} \parallel 6$		Ω pF
OPEN-LOOP GAIN⁽¹⁾					
Open-Loop Voltage Gain	$V_O = \pm 10\text{V}, R_L = 2\text{k}\Omega$	90	126		dB
FREQUENCY RESPONSE					
Slew Rate			10		V/μs
Gain-Bandwidth Product	$G = +1$		4		MHz
Total Harmonic Distortion	$G = +1, f = 1\text{kHz}$		0.1		%
OUTPUT⁽¹⁾					
Voltage Output	$R_L = 2\text{k}\Omega$	±11	±11.5		V
Short Circuit Current			±25		mA

(1) Specifications apply to uncommitted op amp, A_4 . The three op amps forming the filter are identical to A_4 but are tested as a complete filter.

APPLICATION INFORMATION

The UAF42 is a monolithic implementation of the proven state-variable analog filter topology. This device is pin-compatible with the popular UAF41 analog filter, and it provides several improvements.

The slew rate of the UAF42 has been increased to 10V/μs, versus 1.6V/μs for the UAF41. Frequency • Q product of the UAF42 has been improved, and the useful natural frequency extended by a factor of four to 100kHz. FET input op amps on the UAF42 provide very low input bias current. The monolithic construction of the UAF42 provides lower cost and improved reliability.

DESIGN PROGRAM

Application report [SBFA002](#) (available for download at www.ti.com) and a computer-aided design program also available from Texas Instruments, make it easy to design and implement many kinds of active filters. The DOS-compatible program guides you through the design process and automatically calculates component values.

Low-pass, high-pass, band-pass and band-reject (notch) filters can be designed. The program supports the three most commonly-used all-pole filter types: Butterworth, Chebyshev and Bessel. The less-familiar inverse Chebyshev is also supported, providing a smooth passband response with ripple in the stop band.

With each data entry, the program automatically calculates and displays filter performance. This feature allows a spreadsheet-like *what-if* design approach. For example, a user can quickly determine, by trial and error, how many poles are required for a desired attenuation in the stopband. Gain/phase plots may be viewed for any response type.

The basic building element of the most commonly-used filter types is the second-order section. This section provides a complex-conjugate pair of poles. The natural frequency, ω_n , and Q of the pole pair determine the characteristic response of the section. The low-pass transfer function is shown in [Equation 1](#):

$$\frac{V_o(s)}{V_i(s)} = \frac{A_{LP}\omega_n^2}{s^2 + s \frac{\omega_n}{Q} + \omega_n^2} \quad (1)$$

The high-pass transfer function is given by [Equation 2](#):

$$\frac{V_{HP}(s)}{V_i(s)} = \frac{A_{HP}s^2}{s^2 + s \frac{\omega_n}{Q} + \omega_n^2} \quad (2)$$

The band-pass transfer function is calculated using [Equation 3](#):

$$\frac{V_{BP}(s)}{V_i(s)} = \frac{A_{BP}(\omega_n/Q)s}{s^2 + s \frac{\omega_n}{Q} + \omega_n^2} \quad (3)$$

A band-reject response is obtained by summing the low-pass and high-pass outputs, yielding the transfer function shown in [Equation 4](#):

$$\frac{V_{BR}(s)}{V_i(s)} = \frac{A_{BR}(s^2 + \omega_n^2)}{s^2 + s \frac{\omega_n}{Q} + \omega_n^2} \quad (4)$$

The most common filter types are formed with one or more cascaded second-order sections. Each section is designed for ω_n and Q according to the filter type (Butterworth, Bessel, Chebyshev, etc.) and cutoff frequency. While tabulated data can be found in virtually any filter design text, the design program eliminates this tedious procedure.

Second-order sections may be noninverting ([Figure 1](#)) or inverting ([Figure 2](#)). Design equations for these two basic configurations are shown for reference. The design program solves these equations, providing complete results, including component values.

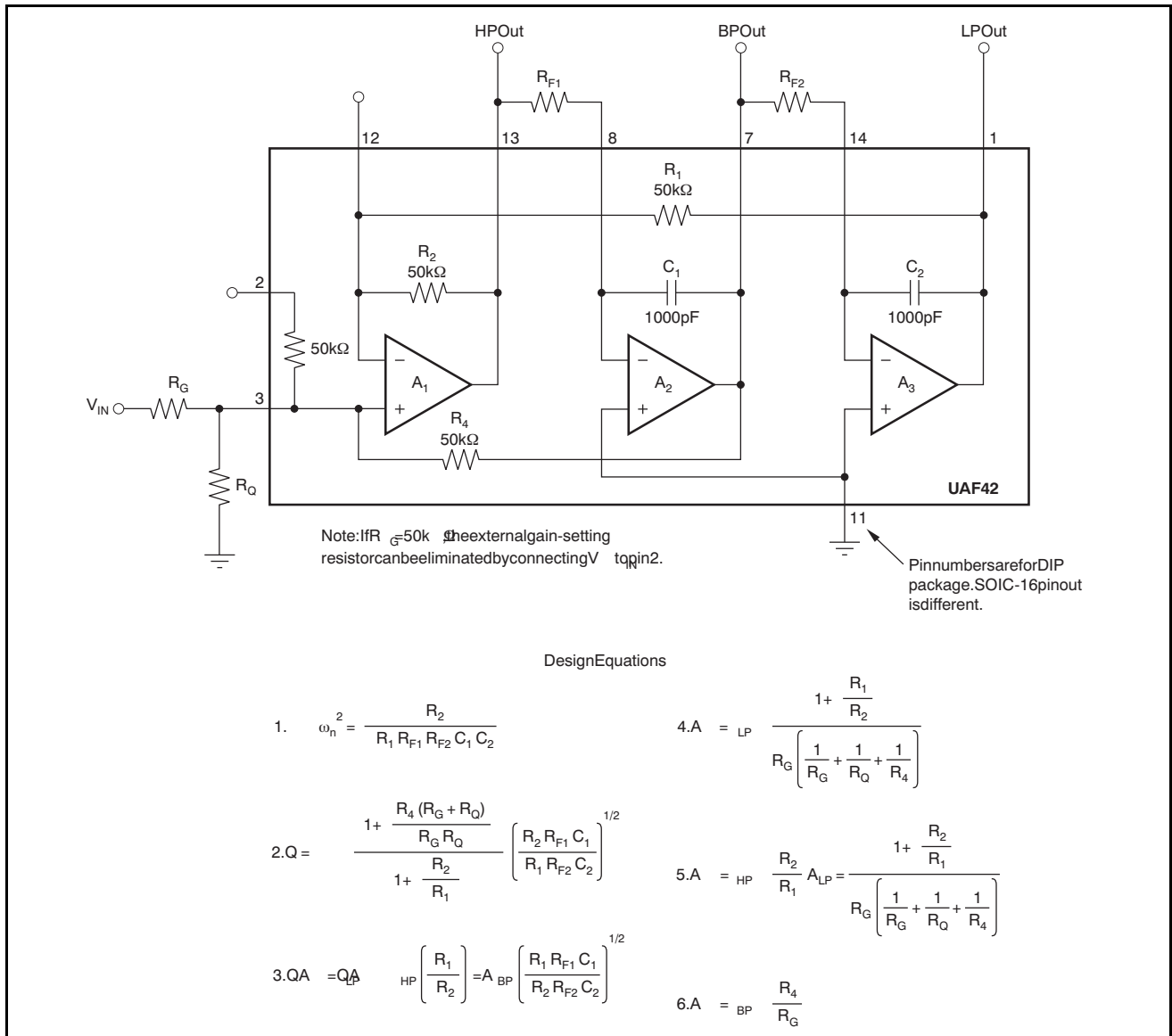


Figure 1. Noninverting Pole-Pair

MAX291/MAX292/ MAX295/MAX296

8th-Order, Lowpass, Switched-Capacitor Filters

General Description

The MAX291/MAX292/MAX295/MAX296 are easy-to-use, 8th-order, lowpass, switched-capacitor filters that can be set up with corner frequencies from 0.1Hz to 25kHz (MAX291/MAX292) or 0.1Hz to 50kHz (MAX295/MAX296).

The MAX291/MAX295 Butterworth filters provide maximally flat passband response, and the MAX292/MAX296 Bessel filters provide low overshoot and fast settling. All four filters have fixed responses, so the design task is limited to selecting the clock frequency that controls the filter's corner frequency.

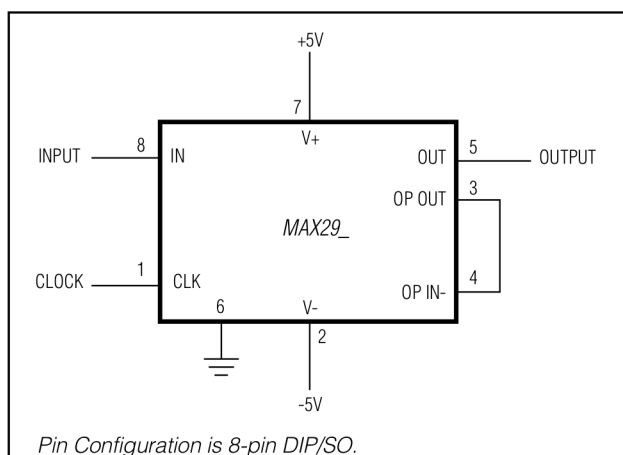
An external capacitor is used to generate a clock using the internal oscillator, or an external clock signal can be used. An uncommitted operational amplifier (noninverting input grounded) is provided for building a continuous-time lowpass filter for post-filtering or anti-aliasing.

Produced in an 8-pin DIP/SO and a 16-pin wide SO package, and requiring a minimum of external components, the MAX291 series delivers very aggressive performance from a tiny area.

Applications

- ADC Anti-Aliasing Filter
- Noise Analysis
- DAC Post-Filtering
- 50Hz/60Hz Line-Noise Filtering

Typical Operating Circuit



Features

- ◆ 8th-Order Lowpass Filters:
 - Butterworth (MAX291/MAX295)
 - Bessel (MAX292/MAX296)
- ◆ Clock-Tunable Corner-Frequency Range:
 - 0.1Hz to 25kHz (MAX291/MAX292)
 - 0.1Hz to 50kHz (MAX295/MAX296)
- ◆ No External Resistors or Capacitors Required
- ◆ Internal or External Clock
- ◆ Clock to Corner Frequency Ratio:
 - 100:1 (MAX291/MAX292)
 - 50:1 (MAX295/MAX296)
- ◆ Low Noise: -70dB THD + Noise (Typ)
- ◆ Operate with a Single +5V Supply or Dual ±5V Supplies
- ◆ Uncommitted Op Amp for Anti-Aliasing or Clock-Noise Filtering
- ◆ 8-Pin DIP and SO Packages

Ordering Information

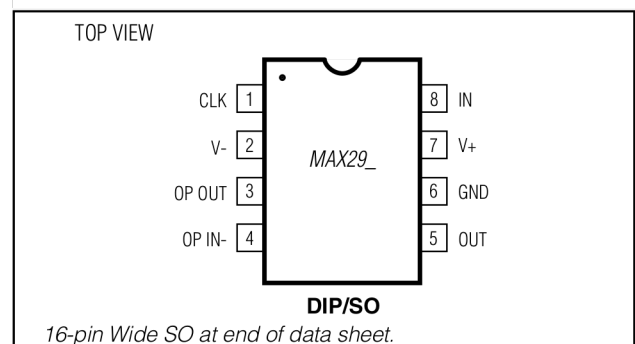
PART	TEMP. RANGE	PIN-PACKAGE
MAX291CPA	0°C to +70°C	8 Plastic DIP
MAX291CSA	0°C to +70°C	8 SO
MAX291CWE	0°C to +70°C	16 Wide SO
MAX291C/D	0°C to +70°C	Dice*
MAX291EPA	-40°C to +85°C	8 Plastic DIP
MAX291ESA	-40°C to +85°C	8 SO
MAX291EWE	-40°C to +85°C	16 Wide SO
MAX291MJA	-55°C to +125°C	8 CERDIP**

Ordering Information continued at end of data sheet.

* Contact factory for dice specifications.

** Contact factory for availability and processing to MIL-STD-883.

Pin Configurations



For pricing, delivery, and ordering information, please contact Maxim Direct at 1-888-629-4642, or visit Maxim's website at www.maximintegrated.com.

MAX291/MAX292/MAX295/MAX296

8th-Order, Lowpass, Switched-Capacitor Filters

ELECTRICAL CHARACTERISTICS (continued)

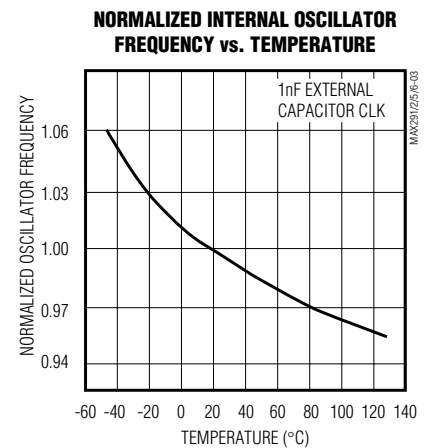
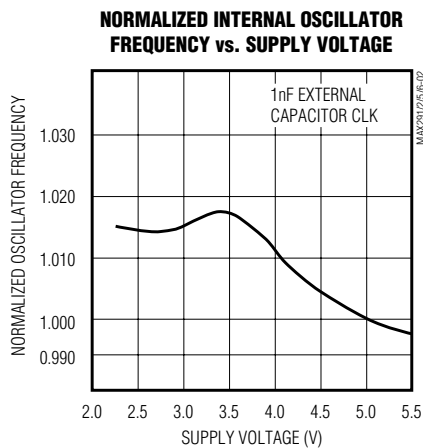
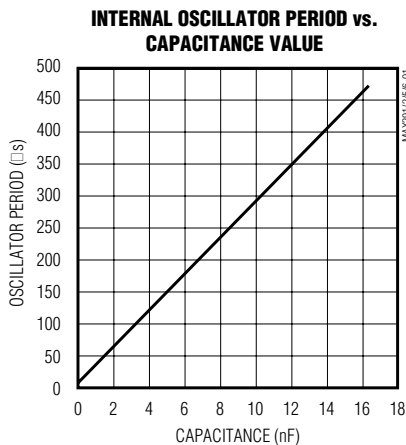
(V+ = 5V, V- = -5V, filter output measured at OUT pin, 20kΩ load resistor to ground at OUT and OP OUT, f_{CLK} = 100kHz (MAX291/MAX292) or f_{CLK} = 50kHz (MAX295/MAX296), T_A = T_{MIN} to T_{MAX}, unless otherwise noted.)

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
Output DC Swing		±4			V
Output Offset Voltage	IN = GND		±150	±400	mV
DC Insertion Gain Error with Output Offset Removed		0.15	0	-0.15	dB
Total Harmonic Distortion plus Noise	T _A = +25°C, f _{CLK} = 100kHz		-70		dB
Clock Feedthrough	f _{CLK} = 100kHz		6		mVp-p
CLOCK					
Internal Oscillator Frequency	C _{OSC} = 1000pF	29	35	43	kHz
Internal Oscillator Current Source/Sink	V _{CLK} = 0V or 5V		±70	±120	μA
Clock Input High (Note 1)		4.0			V
Low				1.0	V
UNCOMMITTED OP AMP					
Input Offset Voltage			±10	±50	mV
Output DC Swing		±4			V
Input Bias Current			0.05		μA
POWER REQUIREMENTS					
Supply Voltage Dual Supply		±2.375		±5.500	V
Single Supply	V- = 0V, GND = V±2	4.750		11.000	V
Supply Current	V+ = 5V, V- = -5V, V _{CLK} = 0V to 5V		15	22	mA
	V+ = 2.375V, V- = -2.375V, V _{CLK} = -2V to 2V		7	12	

Note 1. Guaranteed by design.

Typical Operating Characteristics

(V+ = 5V, V- = -5V, T_A = +25°C, f_{CLK} = 100kHz (MAX291/MAX292) or f_{CLK} = 50kHz (MAX295/MAX296), unless otherwise noted.)

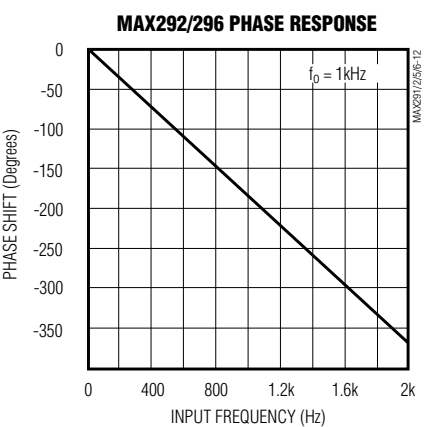
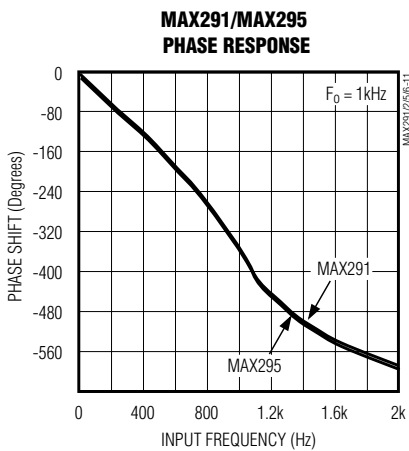
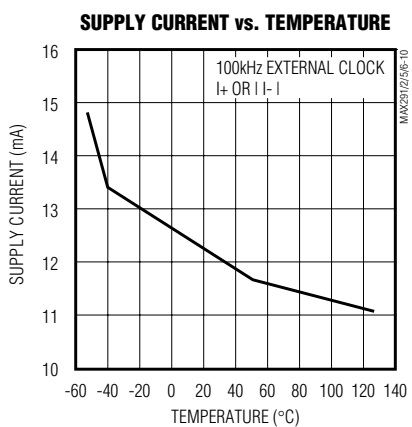
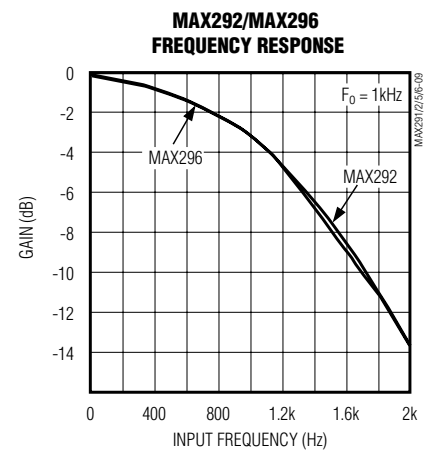
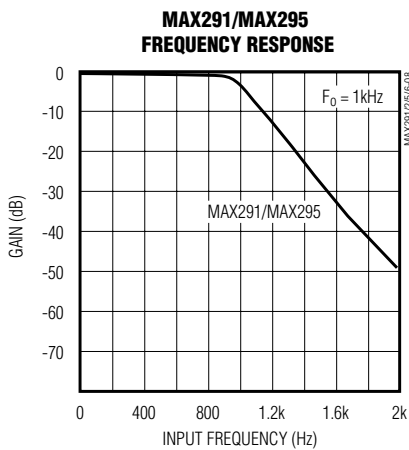
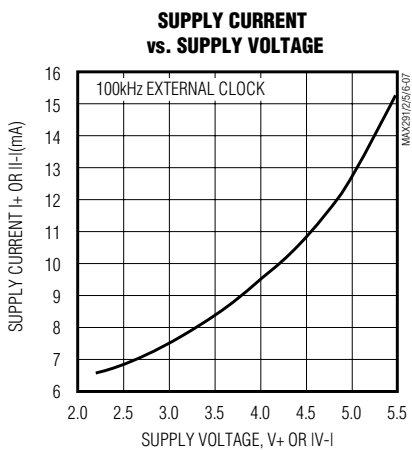
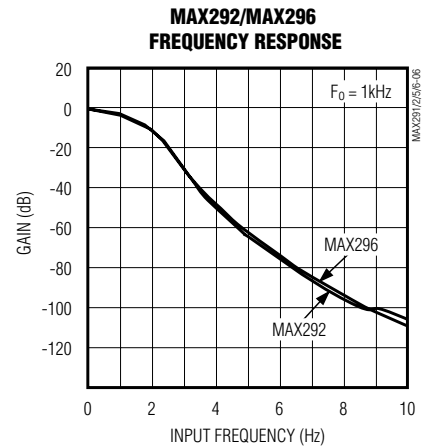
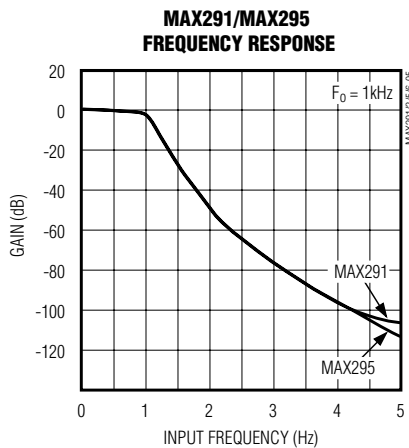
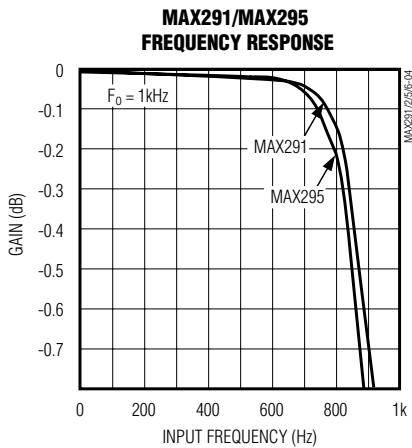


MAX291/MAX292/MAX295/MAX296

8th-Order, Lowpass, Switched-Capacitor Filters

Typical Operating Characteristics (continued)

($V_+ = 5V$, $V_- = -5V$, $T_A = +25^\circ C$, $f_{CLK} = 100kHz$ (MAX291/MAX292) or $f_{CLK} = 50kHz$ (MAX295/MAX296), unless otherwise noted.)



MAX291/MAX292/MAX295/MAX296

8th-Order, Lowpass, Switched-Capacitor Filters

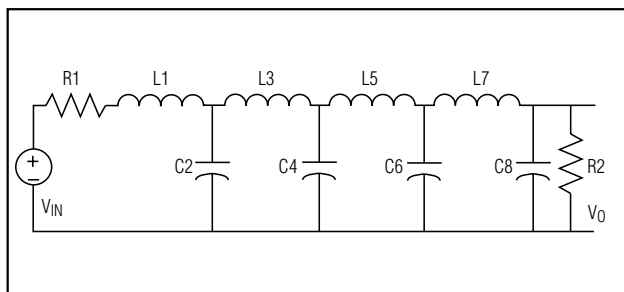


Figure 2. 8th-Order Ladder Filter Network

error on its respective poles, while the same mismatch in a ladder filter design will spread its error over all poles.

The MAX291/MAX292/MAX295/MAX296 input impedance is effectively that of a switched-capacitor resistor (see equation below, and Table 1), and it is inversely proportional to frequency. The input impedance values determined below represent average input impedance, since the input current is not continuous. The input current flows in a series of pulses that charge the input capacitor every time the appropriate switch is closed. A good rule of thumb is that the driver's input source resistance should be less than 10% of the filter's input impedance. The input impedance of the filter can be estimated using the following formula:

$$Z = 1 / (f_{CLK} * C)$$

where: f_{CLK} = Clock Frequency

The input impedance for various clock frequencies is given below:

Table 1. Input Impedance for Various Clock Frequencies

PART	C (pF)	10kHz (MΩ)	100kHz (MΩ)	1000kHz (kΩ)
MAX291	2.24	44.6	4.46	446
MAX292	3.28	30.5	3.05	305
MAX295	4.47	22.4	2.24	224
MAX296	4.22	23.7	2.37	237

Clock-Signal Requirements

The MAX291/MAX292/MAX295/MAX296 maximum recommended clock frequency is 2.5MHz, producing a cutoff frequency of 25kHz for the MAX291/MAX292 and 50kHz for the MAX295/MAX296. The CLK pin can be driven by an external clock or by the internal oscillator with an external capacitor. For external clock applications, the clock circuitry has been designed to interface with +5V CMOS logic. Drive the CLK pin with a CMOS gate powered from 0V and +5V when using either a single +5V supply or dual +5V supplies. The MAX291/MAX292/MAX295/MAX296 supply current increases slightly (<3%) with increasing

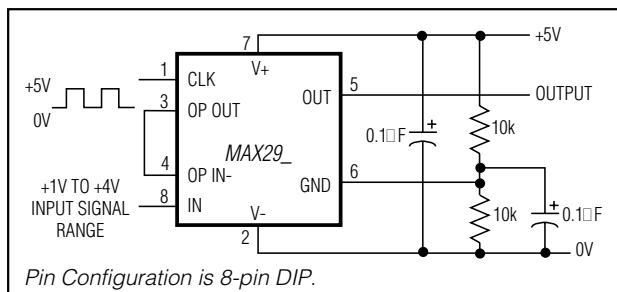


Figure 3. +5V Single-Supply Operation

clock frequency over the clock range 100kHz to 1MHz. Varying the rate of an external clock will dynamically adjust the corner frequency of the filter.

Ideally, the MAX291/MAX292/MAX295/MAX296 should be clocked symmetrically (50% duty cycle). MAX291/MAX292/MAX295/MAX296 can be operated with clock asymmetry of up to 60/40% (or 40/60%) if the clock remains HIGH and LOW for at least 200ns. For example, if the part has a maximum clock rate of 2.5MHz, then the clock should be high for at least 200ns, and low for at least 200ns.

When using the internal oscillator, the capacitance (C_{OSC}) from CLK to ground determines the oscillator frequency:

$$f_{OSC} \text{ (kHz)} \approx \frac{10^5}{3C_{OSC} \text{ (pF)}}$$

The stray capacitance at CLK should be minimized because it will affect the internal oscillator frequency.

Application Information

Power Supplies

The MAX291/MAX292/MAX295/MAX296 operate from either dual or single power supplies. The dual-supply voltage range is +2.375V to +5.500V. The $\pm 2.5V$ dual supply is equivalent to single-supply operation (Figure 3). Minor performance degradation could occur due to the external resistor divider network, where the GND pin is biased to mid-supply.

Input Signal Range

The ideal input signal range is determined by observing at what voltage level the total harmonic distortion plus noise (THD + Noise) ratio is maximized for a given corner frequency. The *Typical Operating Characteristics* show the MAX291/MAX292/MAX295/MAX296 THD + Noise response as the input signal's peak-to-peak amplitude is varied.

Uncommitted Op Amp

The uncommitted op amp has its noninverting input tied to the GND pin, and can be used to build a 1st- or 2nd-