LINEAR INTEGRATED CIRCUITS

HIGH PERFORMANCE QUAD OPERATIONAL AMPLIFIERS

- SINGLE OR SPLIT SUPPLY OPERATION
- VERY LOW POWER CONSUMPTION
- SHORT CIRCUIT PROTECTION
- LOW DISTORTION, LOW NOISE
- HIGH GAIN–BANDWIDTH PRODUCT
- HIGH CHANNEL SEPARATION

The LS 404 is a high performance quad operational amplifier with frequency and phase compensation built into the chip. The internal phase compensation allows stable operation as voltage follower in spite of its high gain–bandwidth product. The circuit presents very stable electrical characteristics over the entire supply voltage range, and it is particularly intended for professional and telecom applications (active filters, etc.).

The patented input stage circuit allows small input signal swings below the negative supply voltage and prevents phase inversion when the input is over driven.
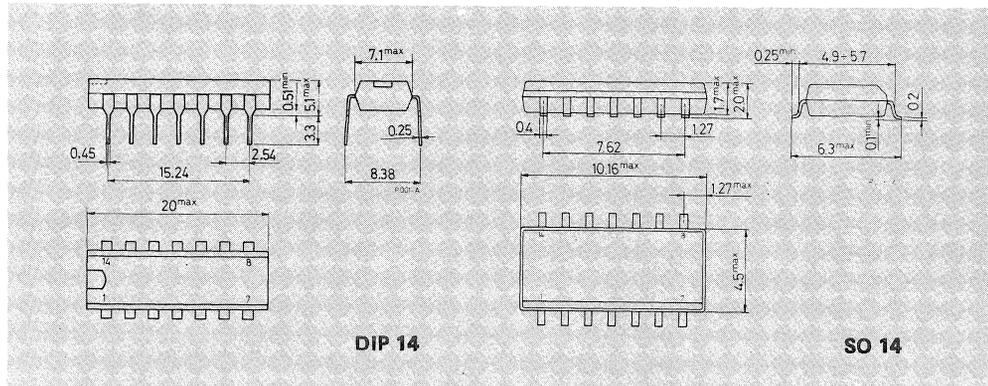
The LS 404 is available with hermetic gold chip (8000 series).

ABSOLUTE MAXIMUM RATINGS

V_s	Supply voltage		± 18	V
V_i	Input voltage	(positive)	$+ V_s$	
		(negative)	$-V_s - 0.5$	V
V_i	Differential input voltage		$\pm (V_s - 1)$	
T_{op}	Operating temperature	**LS 404**	-25 to + 85	°C
		LS 404C	0 to + 70	°C
P_{tot}	Power dissipation	($T_{amb} = 70°C$)	400	mW
T_{stg}	Storage temperature		-55 to + 150	°C

MECHANICAL DATA

Dimensions in mm

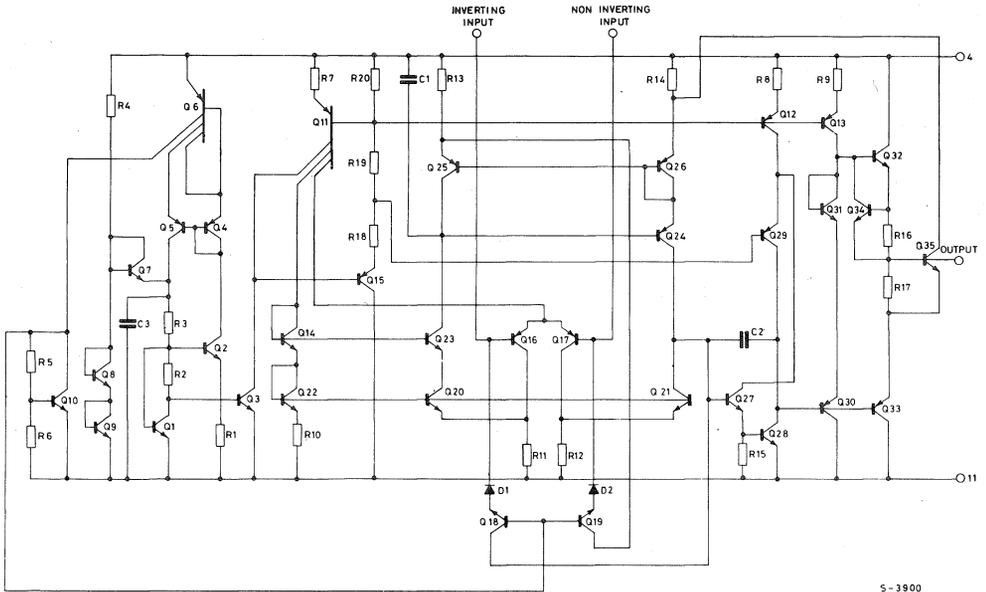DIP 14   SO 14

CONNECTION DIAGRAM AND ORDERING NUMBERS
(top view)

Type	DIP 14	SO-14
LS 404	—	LS 404M
LS 404C	LS 404CB	LS 404CM

```
OUTPUT A      1    14   OUTPUT  D
INV. INP. A   2    13   INV. INP. D
NON INV. INP. A   3   12   NON INV. INP.  D
+ VS          4    11   -VS
NON INV. INP. B   5   10   NON INV. INP. C
INV. INP.  B  6    9    INV. INP. C
OUTPUT B      7    8    OUTPUT C
```
S-3901
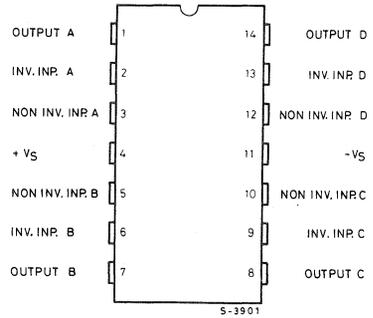
SCHEMATIC DIAGRAM (one section)

S-3900

THERMAL DATA

			DIP 14	SO-14
$R_{thj-amb}$	Thermal resistance junction–ambient	max	200°C/W	200°C/W

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ELECTRICAL CHARACTERISTICS ($V_s = \pm 12V$, $T_{amb} = 25°C$, unless otherwise specified)

| Parameter		Test conditions	LS 404			LS 404C			Unit
			Min.	Typ.	Max.	Min.	Typ.	Max.	
I_s	Supply current			1.3	2		1.5	3	mA
I_b	Input bias current			50	200		100	300	nA
R_i	Input resistance	$f = 1KHz$		0.7			0.5		$M\Omega$
V_{os}	Input offset voltage	$R_g = 10K\Omega$		1	2.5		1	5	mV
$\dfrac{\Delta V_{os}}{\Delta T}$	Input offset voltage drift	$R_g = 10K\Omega$ $T_{min} < T_{op} < T_{max}$		5			5		$\mu V/°C$
I_{os}	Input offset current			10	40		20	80	nA
$\dfrac{\Delta I_{os}}{\Delta T}$	Input offset current drift	$T_{min} < T_{op} < T_{max}$		0.08			0.1		$\dfrac{nA}{°C}$
I_{sc}	Output short circuit current			23			23		mA
G_v	Large signal open loop voltage gain	$R_L = 2K\Omega$ $V_s = \pm12V$ $V_s = \pm4V$	90	100 95		86	100 95		dB
B	Gain–bandwidth product	$f = 20KHz$	1.8	3		1.5	2.5		MHz
e_N	Total input noise voltage	$f = 1KHz$ $R_g = 50\Omega$ $R_g = 1K\Omega$ $R_g = 10K\Omega$		8 10 18	15		10 12 20		$\dfrac{nV}{\sqrt{Hz}}$
d	Distortion	unity gain $R_L = 2K\Omega$ $f = 1 KHz$ $V_o = 2Vpp$ $f = 20 KHz$		0.01 0.03	0.04		0.01 0.03		%
V_o	DC output voltage swing	$R_L = 2K\Omega$ $V_s = \pm 12V$ $V_s = \pm 4V$	± 10	± 3		± 10	± 3		V
V_o	Large signal voltage swing	$f = 10KHz$ $R_L = 10 K\Omega$ $R_L = 1 K\Omega$		22 20			22 20		Vpp
SR	Slew rate	unity gain $R_L = 2K\Omega$	0.8	1.5			1		$V/\mu s$
CMR	Comm. mode rejection	$V_i = 10V$	90	94		80	90		dB
SVR	Supply voltage rejection	$V_i = 1V$ $f = 100Hz$	90	94		86	90		dB
CS	Channel separation	$f = 1KHz$	100	120			120		dB

Fig. 1 – Supply current vs. supply voltage
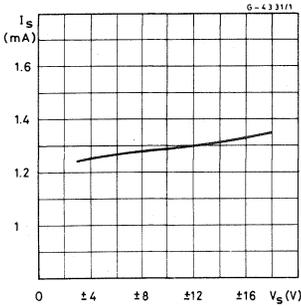
Fig. 2 – Supply current vs. ambient temperature
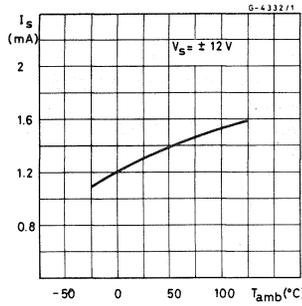
Fig. 3 – Output short circuit current vs. ambient temperature
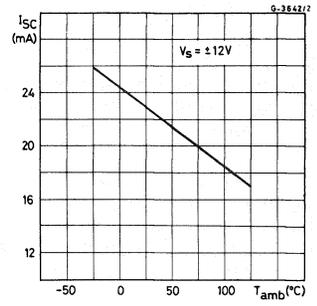
Fig. 4 – Open loop frequency and phase response
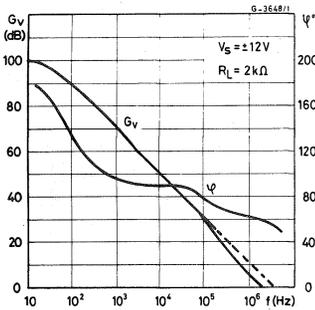
Fig. 5 – Open loop gain vs. ambient temperature
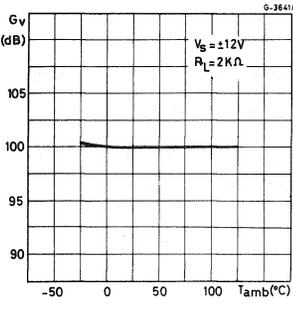
Fig. 6 – Supply voltage rejection vs. frequency
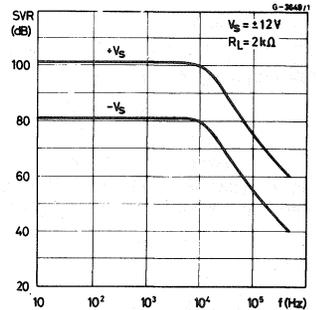
Fig. 7 – Large signal frequency response
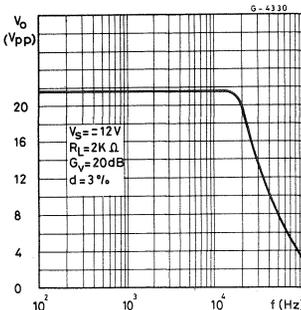
Fig. 8 – Output voltage swing vs. load resistance
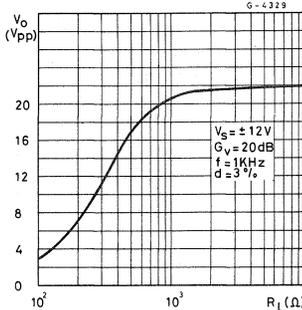
Fig. 9 – Total input noise vs. frequency
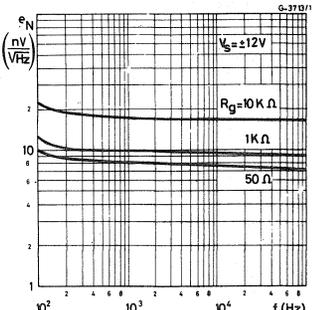
APPLICATION INFORMATION
Active low-pass filter:

BUTTERWORTH

The Butterworth is a "maximally flat" amplitude response filter. Butterworth filters are used for filtering signals in data acquisition systems to prevent aliasing errors in sampled-data applications and for general purpose low-pass filtering.

The cutoff frequency, f_c, is the frequency at which the amplitude response in down 3 dB. The attenuation rate beyond the cutoff frequency is $-n6$ dB per octave of frequency where n is the order (number of poles) of the filter.

Other characteristics:
- Flattest possible amplitude response.
- Excellent gain accuracy at low frequency end of passband.

BESSEL

The Bessel is a type of "linear phase" filter. Because of their linear phase characteristics, these filters approximate a constant time delay over a limited frequency range. Bessel filters pass transient waveforms with a minimum of distortion. They are also used to provide time delays for low pass filtering of modulated waveforms and as a "running average" type filter.

The maximum phase shift is $\frac{-n\pi}{2}$ radians where n is the order (number of poles) of the filter. The cutoff frequency, f_c, is defined as the frequency at which the phase shift is one half to this value. For accurate delay, the cutoff frequency should be twice the maximum signal frequency. The following table can be used to obtain the -3 dB frequency of the filter.

	2 pole	4 pole	6 pole	8 pole
-3 dB frequency	$0.77 f_c$	$0.67 f_c$	$0.57 f_c$	$0.50 f_c$

Other characteristics:
- Selectivity not as great as Chebyschev or Butterworth.
- Very small overshoot response to step inputs
- Fast rise time.

CHEBYSCHEV

Chebyschev filters have greater selectivity than either Bessel or Butterworth at the expense of ripple in the passband.

Chebyschev filters are normally designed with peak-to-peak ripple values from 0.2 dB to 2 dB.

Increased ripple in the passband allows increased attenuation above the cutoff frequency.

The cutoff frequency is defined as the frequency at which the amplitude response passes through the specified maximum ripple band and enters the stop band.

Other characteristics:
- Greater selectivity
- Very nonlinear phase response
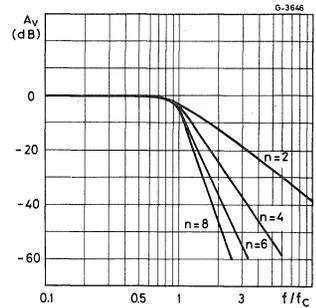- High overshoot response to step inputs.

Fig. 10 - Amplitude response

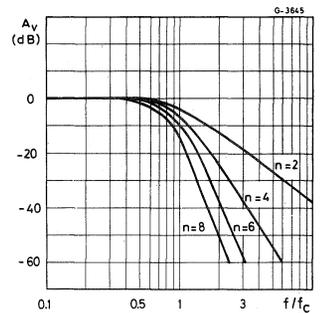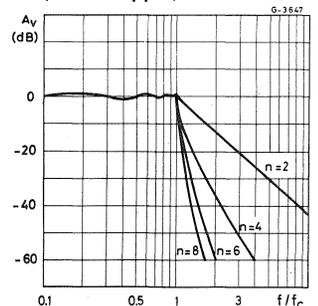

Fig. 11 - Amplitude response


Fig. 12 - Amplitude response ($\pm$ 1 dB ripple)

APPLICATION INFORMATION (continued)

The table below shows the typical overshoot and settling time response of the low pass filter to a step input.

	NUMBER OF POLES	PEAK OVERSHOOT	SETTLING TIME (% of final value)		
		% Overshoot	± 1%	± 0.1%	± 0.01%
BUTTERWORTH	2	4	$1.1/f_c$ sec.	$1.7/f_c$ sec.	$1.9/f_c$ sec.
	4	11	$1.7/f_c$	$2.8/f_c$	$3.8/f_c$
	6	14	$2.4/f_c$	$3.9/f_c$	$5.0/f_c$
	8	16	$3.1/f_c$	$5.1/f_c$	$7.1/f_c$
BESSEL	2	0.4	$0.8/f_c$	$1.4/f_c$	$1.7/f_c$
	4	0.8	$1.0/f_c$	$1.8/f_c$	$2.4/f_c$
	6	0.6	$1.3/f_c$	$2.1/f_c$	$2.7/f_c$
	8	0.3	$1.6/f_c$	$2.3/f_c$	$3.2/f_c$
CHEBYSCHEV (RIPPLE ± 0.25 dB)	2	11	$1.1/f_c$	$1.6/f_c$	—
	4	18	$3.0/f_c$	$5.4/f_c$	—
	6	21	$5.9/f_c$	$10.4/f_c$	—
	8	23	$8.4/f_c$	$16.4/f_c$	—
CHEBYSCHEV (RIPPLE ± 1 dB)	2	21	$1.6/f_c$	$2.7/f_c$	—
	4	28	$4.8/f_c$	$8.4/f_c$	—
	6	32	$8.2/f_c$	$16.3/f_c$	—
	8	34	$11.6/f_c$	$24.8/f_c$	—

Design of 2nd order active low pass filter
(Sallen and Key configuration unity gain op–amp)

Fig. 13 – Filter configuration
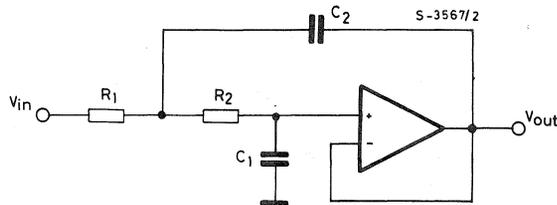
$$\frac{V_o}{V_i} = \frac{1}{1 + 2\xi\frac{S}{\omega_c} + \frac{S^2}{\omega_c^2}}$$

where:
$\omega_c = 2\pi f_c$ with f_c = cutoff frequency

ξ = damping factor.

APPLICATION INFORMATION (continued)

Three parameters are needed to characterize the frequency and phase response of a 2nd order active filter: the gain (G_v), the damping factor (ξ) or the Q-factor ($Q = (2\xi)^{-1}$), and the cutoff frequency (f_c).

The higher order responses are obtained with a series of 2nd order sections. A simple RC section is introduced when an odd filter is required. The choice of 'ξ' (or Q-factor) determines the filter response (see table).

TAB. 1

Filter response	ξ	Q	Cutoff frequency f_c
Bessel	$\dfrac{\sqrt{3}}{2}$	$\dfrac{1}{\sqrt{3}}$	Frequency at which phase shift is –90°
Butterworth	$\dfrac{\sqrt{2}}{2}$	$\dfrac{1}{\sqrt{2}}$	Frequency at which $G_v = -3$ dB
Chebyschev	$<\dfrac{\sqrt{2}}{2}$	$>\dfrac{1}{\sqrt{2}}$	Frequency at which the amplitude response passes through specified max. ripple band and enters the stop band

Fig. 14 – Filter response vs. damping factor
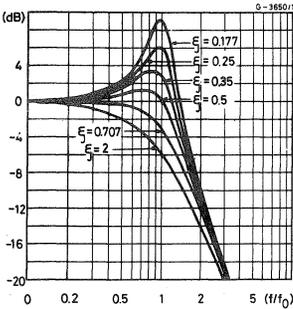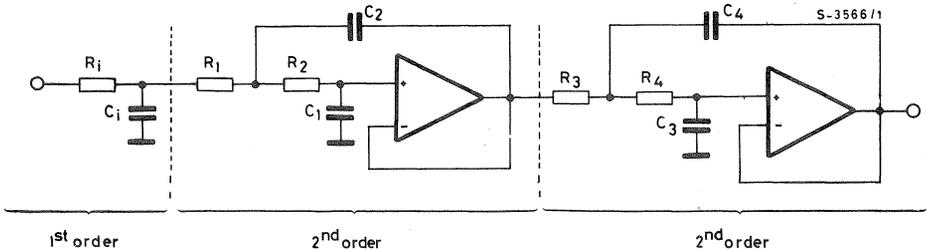

Fixed $R = R_1 = R_2$, we have (see fig. 13)

$$C_1 = \frac{1}{R}\frac{\xi}{\omega_c}$$

$$C_2 = \frac{1}{R}\frac{1}{\xi\,\omega_c}$$

The diagram of fig. 14 shows the amplitude response for different values of damping factor ξ in 2nd order filters.

EXAMPLE:

Fig. 15 – 5th order low pass filter (Butterworth) with unity gain configuration.

1st order 2nd order 2nd order

APPLICATION INFORMATION (continued)

In the circuit of fig. 15, for f_c = 3.4 KHz and R_i= R_1= R_2= R_3= R_4= 10 KΩ, we obtain:

$$C_i = 1.354 \cdot \frac{1}{R} \cdot \frac{1}{2\pi f_c} = 6.33 \text{ nF}$$

$$C_1 = 0.421 \cdot \frac{1}{R} \cdot \frac{1}{2\pi f_c} = 1.97 \text{ nF}$$

$$C_2 = 1.753 \cdot \frac{1}{R} \cdot \frac{1}{2\pi f_c} = 8.20 \text{ nF}$$

$$C_3 = 0.309 \cdot \frac{1}{R} \cdot \frac{1}{2\pi f_c} = 1.45 \text{ nF}$$

$$C_4 = 3.325 \cdot \frac{1}{R} \cdot \frac{1}{2\pi f_c} = 15.14 \text{ nF}$$

The attenuation of the filter is 30 dB at 6.8 KHz and better than 60 dB at 15 KHz.

The same method, referring to Tab. II and fig. 16, is used to design high-pass filter. In this case the damping factor is found by taking the reciprocal of the numbers in Tab. II. For f_c = 5KHz and C_i = C_1 = C_2 = C_3 = C_4 = 1 nF we obtain:

$$R_i = \frac{1}{1.354} \cdot \frac{1}{C} \cdot \frac{1}{2\pi f_c} = 23.5 \text{ K}\Omega$$

Tab. II
Damping factor for low-pass Butterworth filters

Order	C_i	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
2		0.707	1.41						
3	1.392	0.202	3.54						
4		0.92	1.08	0.38	2.61				
5	1.354	0.421	1.75	0.309	3.235				
6		0.966	1.035	0.707	1.414	0.259	3.86		
7	1.336	0.488	1.53	0.623	1.604	0.222	4.49		
8		0.98	1.02	0.83	1.20	0.556	1.80	0.195	5.125

$$R_1 = \frac{1}{0.421} \cdot \frac{1}{C} \cdot \frac{1}{2\pi f_c} = 75.6 \text{ K}\Omega$$

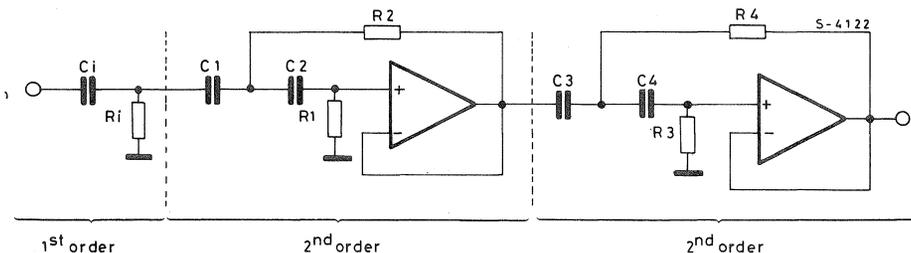$$R_2 = \frac{1}{1.753} \cdot \frac{1}{C} \cdot \frac{1}{2\pi f_c} = 18.2 \text{ K}\Omega$$

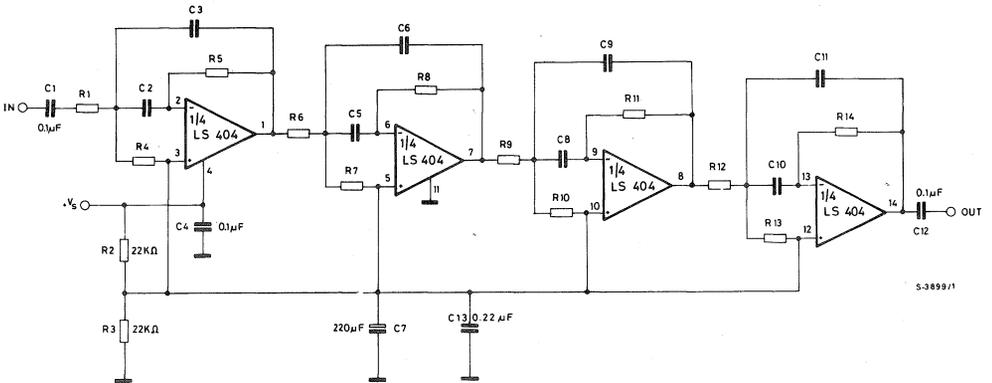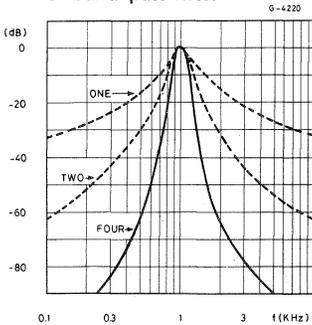$$R_3 = \frac{1}{0.309} \cdot \frac{1}{C} \cdot \frac{1}{2\pi f_c} = 103 \text{ K}\Omega$$

$$R_4 = \frac{1}{3.325} \cdot \frac{1}{C} \cdot \frac{1}{2\pi f_c} = 9.6 \text{ K}\Omega$$

Fig. 16 - 5th order high-pass filter (Butterworth) with unity gain configuration.

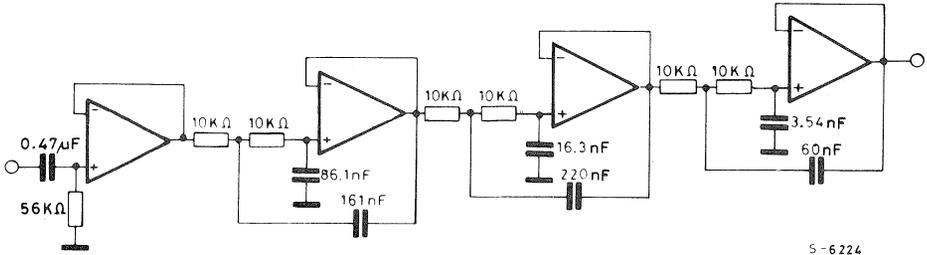## APPLICATION INFORMATION (continued)

Fig. 17 - Multiple feedback 8-pole bandpass filter.

$f_c = 1.180 Hz$; $A = 1$; $C_2 = C_3 = C_5 = C_6 = C_8 = C_9 = C_{10} = C_{11} = 3.300$ pF;
$R_1 = R_6 = R_9 = R_{12} = 160$ $K\Omega$; $R_5 = R_8 = R_{11} = R_{14} = 330 K\Omega$; $R_4 = R_7 = R_{10} = R_{13} = 5.3 K\Omega$

Fig. 18 - Frequency response of band-pass filter

Fig. 19 - Bandwidth of band-pass filter
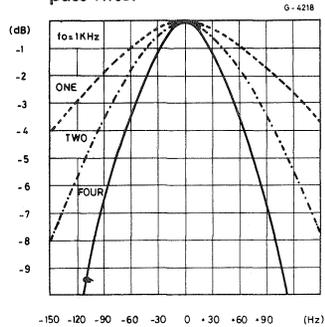
APPLICATION INFORMATION (continued)

Fig. 20 - Six-pole 355 Hz low-pass filter (Chebychev type)

S-6224

This is a 6- pole Chebychev type with ± 0.25 dB ripple in the passband. A decoupling stage is used to avoid the influence of the input impedance on the filter's characteristics. The attenuation is about 55 dB at 710 Hz and reaches 80 dB at 1065 Hz. The in band attenuation is limited in practice to the ± 0.25 dB ripple and does not exceed 0.5 dB at 0.9 fc.

Fig. 21 - Subsonic filter ($G_v = 0$ dB)
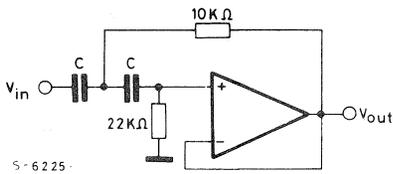
S-6225

f_c (Hz)	C (μF)
15	0.68
22	0.47
30	0.33
55	0.22
100	0.1

Fig. 22 - High cut filter ($G_v = 0$ dB)
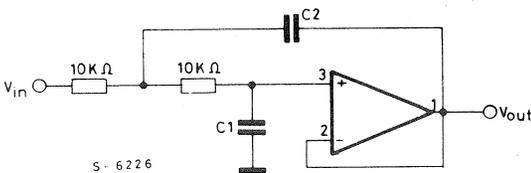
S-6226

f_c (KHz)	C1 (nF)	C2 (nF)
3	3.9	6.8
5	2.2	4.7
10	1.2	2.2
15	0.68	1.5