OP-AMP ve FİLTRELER

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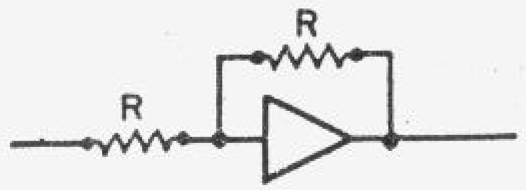
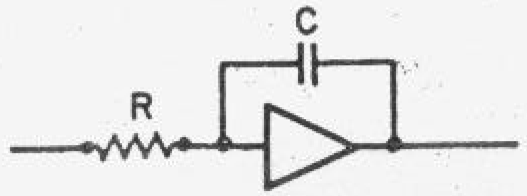
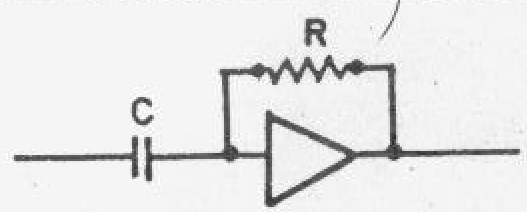
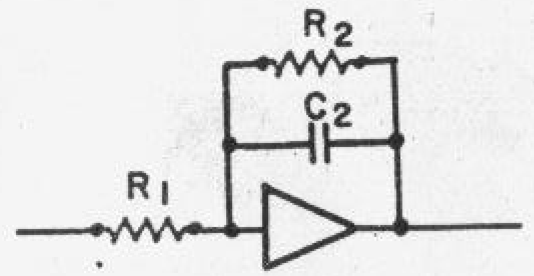
2016-AYBÜ-ANKARA

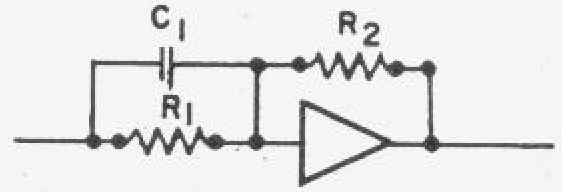
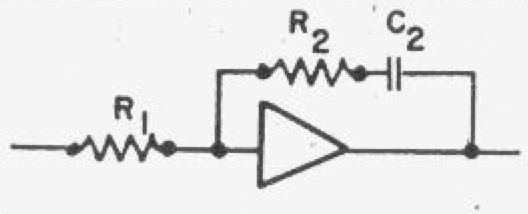
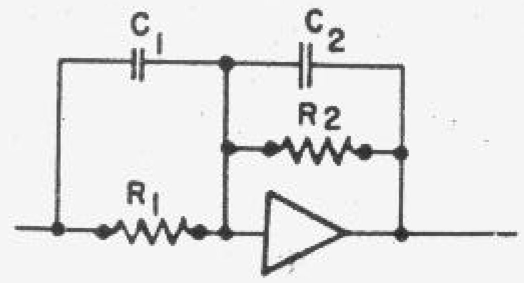
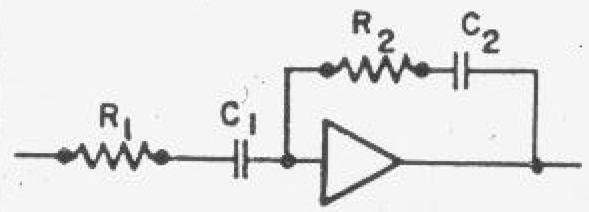
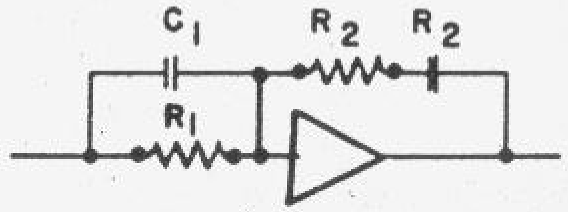
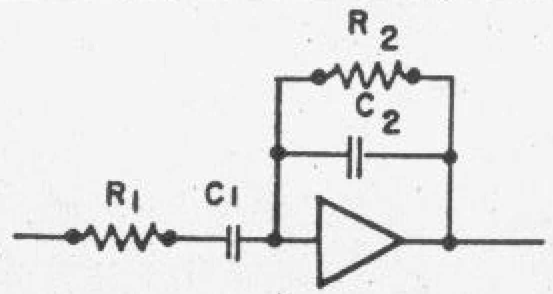
Giriş ve geri-besleme çevrimlerinde bir çok gerçekleştirilmesi mümkün transfer çevrimi kullanılabilir. (Tablo 2.4) de, uygulamada en çok kullanılan haller bir akım, şeması takib edilerek verilmiştir.

(Tablo 2.5) de, işlem yükselteçlerinin giriş ve geri-besleme çevrimlerinde kullanılabilecek genelleştirilmiş transfer empedansları verilmiştir. Bu çevrimler ve tekabül ettikleri transfer-empedans fonksiyonlarının oranlanması ile istenilen karmaşık işlemler gerçekleştirilebilir. (Tablo 2.5) in bağıntılar sütununda transfer empedans katsayıları, çevrim parametrelerinin fonksiyonu olarak verilmiştir. Ters bağıntılar ise çevrim parametrelerini transfer empedansı katsayıları cinsinden vermektedir. (Tablo 2.5) in nasıl kullanıldığının bir örneğini vermek üzere, (Tablo 2.4) ün (10.) işlem çevriminin transfer fonksiyonu (2.5) tablosu yardımıyla elde edilişini göz önüne alalım. Burada geri-besleme transfer empedansı çevrimi:

TABLO 2.4

TRANSFER FONKSİYONU $\bar{e}_0 / \bar{e}_i$	İŞLEM ÇEVRİMİ
-1	 ①
$-\frac{1}{sRC}$	 ②
$-sRC$	 ③
$-\frac{R_2}{R_1} \cdot \left[\frac{1}{1+sR_2C_2} \right]$	 ④

TABLO 2.4 (Devam)

$-\frac{R_2}{R_1} \cdot \left[1+sR_1C_1 \right]$	 ⑤
$-\left[\frac{R_2}{R_1} + \frac{1}{sR_1C_2} \right]$	 ⑥
$-\left[\frac{R_2}{R_1} \cdot \frac{1+sC_1R_1}{1+sC_2R_2} \right]$	 ⑦
$-\left[\frac{sC_1}{sC_2} \cdot \frac{1+sR_2C_2}{1+sR_1C_1} \right]$	 ⑧
$-\frac{(1+sR_1C_1)\cdot(1+sR_2C_2)}{sC_2R_1}$	 ⑨
$-\frac{s \cdot R_2C_1}{(1+sR_1C_1)(1+sR_2C_2)}$	 ⑩

$X_c = \frac{1}{2\pi f c}$

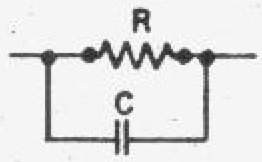
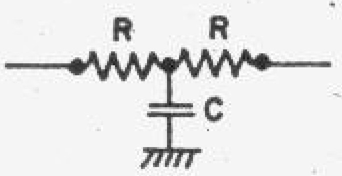
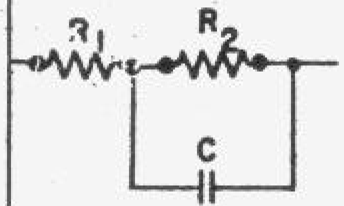
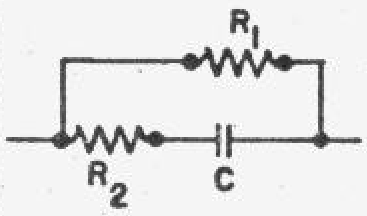
$\frac{\left(R \cdot \frac{1}{2\pi f c}\right) 2\pi f c}{\left(R + \frac{1}{2\pi f c}\right) 2\pi f c}$

$2\pi f c + 1$

$\frac{R}{1 + \underbrace{2\pi f}_{s} \underbrace{RC}_{\tau}}$

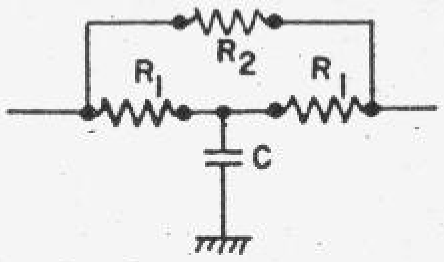
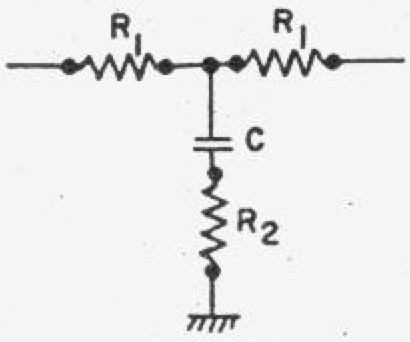
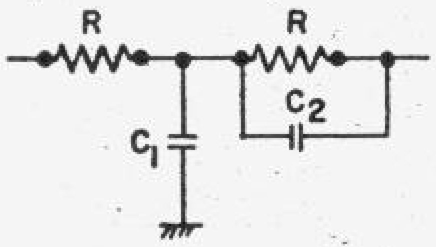
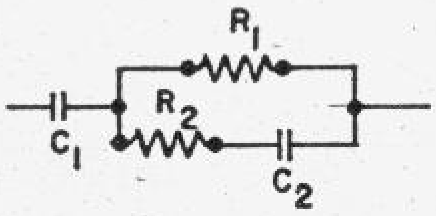
$\frac{R \to A}{\tau s + 1}$

TABLO 2.5

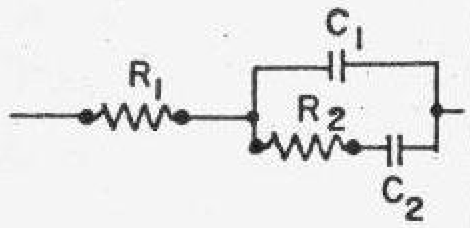
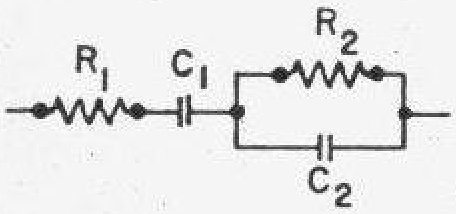
No.	Transfer Empedansı Fonksiyonu	Çevrim	Bağıntılar	Ters Bağıntılar
1	A		A = R	R = A
2	$\frac{A}{\tau s + 1}$ $\frac{R \cdot X_c}{R + X_c}$		A = R τ = RC	R = A C = $\frac{\tau}{A}$
3	$A(\tau s + 1)$		A = 2R $\tau = \frac{RC}{2}$	$R = \frac{A}{2}$ $C = \frac{4\tau}{A}$
4	$A\left\lvert\frac{\theta\tau s + 1}{\tau s + 1}\right\rvert$ $\theta < 1$		$A = R_1 + R_2$ $\tau = R_2 C$ $\theta = \frac{R_2}{R_1 + R_2}$	$R_1 = A\theta$ $R_2 = A(1-\theta)$ $C = \frac{\tau}{A(1-\theta)}$
			$A = R_1$ $\tau = (R_1 + R_2)C$ $\theta = \frac{R_2}{R_1 + R_2}$	$R_1 = A$ $R_2 = \frac{A\theta}{1-\theta}$ $C = \frac{\tau(1-\theta)}{A}$

(D)

TABLO 2.5 (Devam)

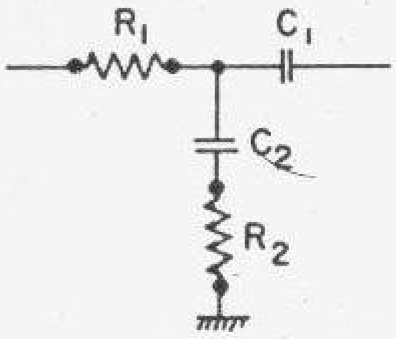
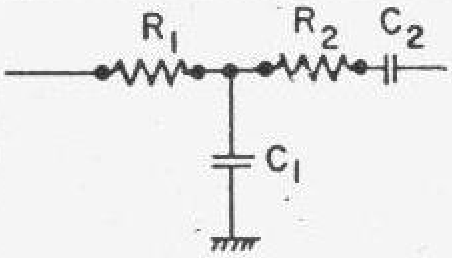
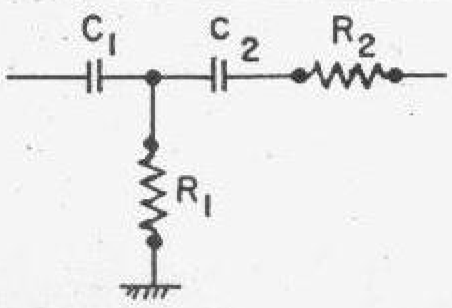
5	$A\left\lvert\frac{\tau s + 1}{\theta\tau s + 1}\right\rvert$ $\theta < 1$		$A = \frac{2R_1 R_2}{2R_1 + R_2}$ $\tau = \frac{R_1 C}{2}$ $\theta = \frac{2R_1}{2R_1 + R_2}$	$R_1 = \frac{A}{2(1-\theta)}$ $R_2 = \frac{A}{\theta}$ $C = \frac{4\tau(1-\theta)}{A}$
			A = 2R $\tau = \left\lvert R_2 + \frac{R_1}{2}\right\rvert C$ $\theta = \frac{2R_2}{2R_2 + R_1}$	$R_1 = \frac{A}{2}$ $R_2 = \frac{A\theta}{4(1-\theta)}$ $C = \frac{4\tau(1-\theta)}{A}$
			A = 2R $\tau = \frac{R}{2}(C_1 + C_2)$ $\theta = \frac{2C_2}{C_1 + C_2}$	$R = \frac{A}{2}$ $C_1 = \frac{2\tau(2-\theta)}{A}$ $C_2 = \frac{2\tau\theta}{A}$
6	$\frac{1}{Bs}\left\lvert\frac{(\tau_1 s + 1)(\tau_3 s + 1)}{\tau_2 s + 1}\right\rvert$ $\tau_1 < \tau_2 < \tau_3$		$B = C_1$ $\tau_2 = (R_1 + R_2)C_2$	$R_1 = \frac{\tau_1 + \tau_3 - \tau_2}{B}$ $R_2 = \frac{\tau_1\tau_3(\tau_1 + \tau_3 - \tau_2)}{B(\tau_3 - \tau_2)(\tau_2 - \tau_1)}$

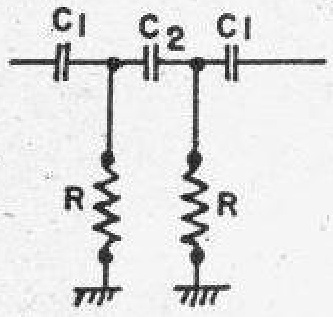
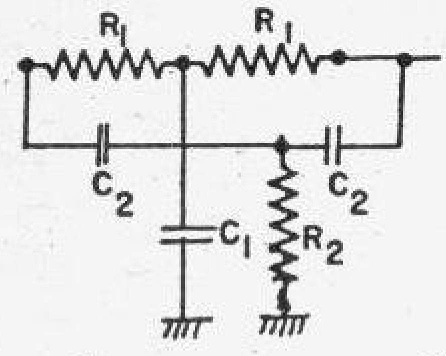
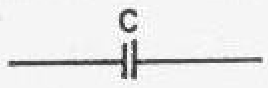
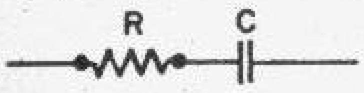
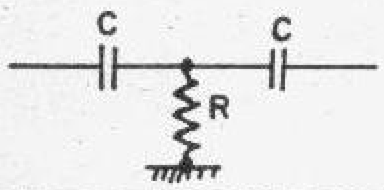
TABLO 2.5 (Devam)

6	$\frac{1}{Bs}\left\lvert\frac{(\tau_1 s+1)(\tau_3 s+1)}{\tau_2 s+1}\right\rvert$ $\tau_1<\tau_2<\tau_3$		$\tau_1\tau_3 = R_1R_2C_1C_2$ $\tau_1+\tau_3 = R_1C_1+R_2C_2+R_1C_2$	$C_1 = B$ $C_2 = \frac{B(\tau_3-\tau_2)(\tau_2-\tau_1)}{(\tau_1+\tau_3-\tau_2)^2}$
			$B = C_1 + C_2$ $\tau_2 = R_2\left\lvert\frac{C_1C_2}{C_1+C_2}\right\rvert$ $\tau_1\tau_3 = R_1 + R_2C_1C_2$ $\tau_1+\tau_3 = R_1C_1+R_2C_2+R_1C_2$	$R_1 = \frac{\tau_1+\tau_3}{B\tau_2}$ $R_2 = \frac{(\tau_1\tau_2+\tau_2\tau_3-\tau_1\tau_3)^2}{B\tau_2(\tau_3-\tau_2)(\tau_2-\tau_4)}$ $C_1 = \frac{B\tau_2^2}{\tau_1+\tau_2+\tau_2\tau_3-\tau_1\tau_3}$ $C_2 = -\frac{B(\tau_3-\tau_2)(\tau_2-\tau_1)}{\tau_1\tau_2+\tau_2\tau_3-\tau_1\tau_3}$
			$B = C_1$ $\tau_2 = R_2C_2$ $\tau_1\tau_3 = R_1R_2C_1C_2$ $\tau_1+\tau_3 = R_1C_1+R_2C_2+R_2C_1$	$R_1 = \frac{\tau_1\tau_3}{B\tau_2}$ $R_2 = \frac{(\tau_3-\tau_2)(\tau_2-\tau_1)}{B\tau_2}$ $C_1 = B$ $C_2 = \frac{B\tau_2^2}{(\tau_3-\tau_2)(\tau_2-\tau_1)}$

3

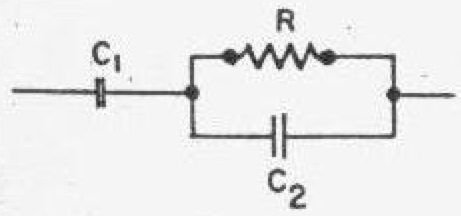
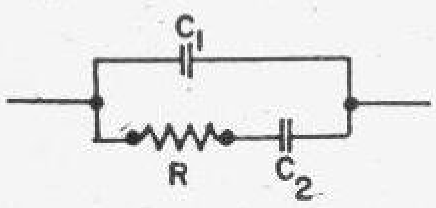
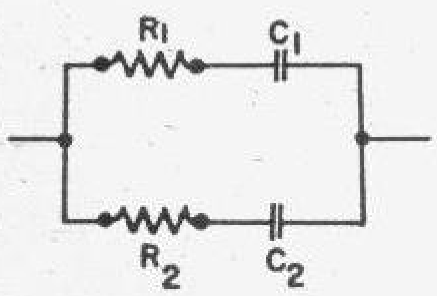
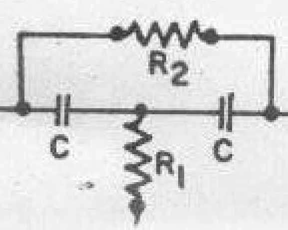
TABLO 2.5 (Devam)

6	$\frac{1}{Bs}\left\lvert\frac{(\tau_1 s+1)(\tau_3 s+1)}{\tau_2 s+1}\right\rvert$ $\tau_1<\tau_2<\tau_3$		$B = C_1$ $\tau_2 = R_2C_2$ $\tau_1\tau_3 = R_1R_2C_1C_2$ $\tau_1+\tau_3 = R_1C_1+R_2C_2+R_1C_2$	$R_1 = \frac{\tau_1\tau_3}{B\tau_2}$ $R_2 = \frac{\tau_1\tau_2\tau_3}{B(\tau_3-\tau_2)(\tau_2-\tau_1)}$ $C_1 = B$ $C_2 = \frac{B(\tau_3-\tau_2)(\tau_2-\tau_1)}{\tau_1\tau_3}$
7	$\frac{1}{Bs}(1+\tau_1 s)(1+\tau_2 s)$ $\tau_1\neq\tau_2$		$B = C_2$ $\tau_1\tau_2 = R_1R_2C_1C_2$ $\tau_1+\tau_2 = R_1C_1+R_2C_2+R_1C_2$	$R_1 = \frac{(\sqrt{\tau_1}-\sqrt{\tau_2})^2}{B}$ $R_2 = \frac{\sqrt{\tau_1\tau_2}}{B}$ $C_1 = \frac{B\sqrt{\tau_1\tau_2}}{(\sqrt{\tau_1}-\sqrt{\tau_2})^2}$ $C_2 = B$
8	$\frac{1}{Bs}\left\lvert\frac{(1+\tau_1 s)(1+\tau_2 s)}{\sqrt{\tau_1\tau_2}\,s}\right\rvert$ $\tau_1\neq\tau_2$		$B = C$ $\tau_1\tau_2 = R_1R_2C_1C_2$ $\tau_1+\tau_2 = R_1C_1+R_2C_2+R_1C_2$	$R_1 = \frac{(\sqrt{\tau_1}-\sqrt{\tau_2})^2}{B}$ $R_2 = \frac{\sqrt{\tau_1\tau_2}}{B}$ $C_1 = \frac{B\sqrt{\tau_1\tau_2}}{(\sqrt{\tau_1}-\sqrt{\tau_2})^2}$ $C_2 = B$

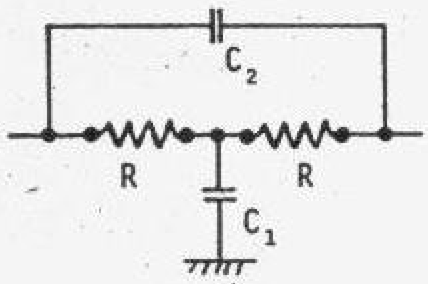
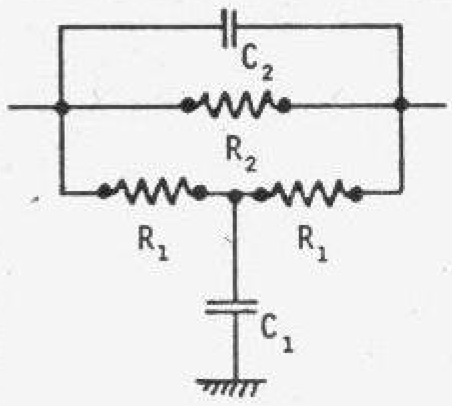
9	$\frac{1}{Bs} \cdot \left\| \frac{(\tau_1 s+1)(\tau_2 s+1)}{\tau_1\tau_2 s^2} \right\|$ $\tau_1 < \tau_2$		$B = \frac{C_1C_2}{C_1+2C_2}$ $\tau_1 = RC_1$ $\tau_2 = R(C_1+2C_2)$	$R = \frac{\tau_1(\tau_2-\tau_1)}{2B\tau_2}$ $C_1 = \frac{2B\tau_2}{\tau_2-\tau_1}$ $C_2 = \frac{B\tau_2}{\tau_1}$
10	$A \cdot \left\| \frac{\tau_1 s+1}{\tau_1\tau_2 s^2+1} \right\|$	 $R_1C_1 = 4R_2C_2$	$A = 2R_1$ $\tau_1 = \frac{R_1C_1}{2} = 2R_2C_2$ $\tau_2 = R_1C_2$	$R_1 = \frac{A}{2}$ $R_2 = \frac{A\tau_1}{4\tau_2}$ $C_1 = \frac{4\tau_1}{A}$ $C_2 = \frac{2\tau_2}{A}$
11	$\frac{1}{Bs}$		$B = C$	$C = B$
12	$\frac{(\tau s+1)}{Bs}$		$B = C$ $\tau = RC$	$R = \frac{\tau}{B}$ $C = B$
13	$\frac{1}{Bs} \cdot \left\| \frac{\tau s+1}{\tau s} \right\|$		$B = \frac{C}{2}$ $\tau = 2RC$	$R = \frac{\tau}{4B}$ $C = 2B$

(4)

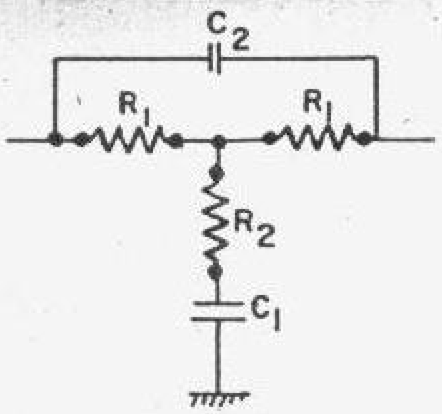
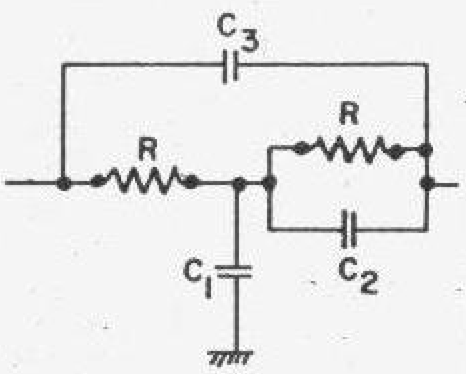
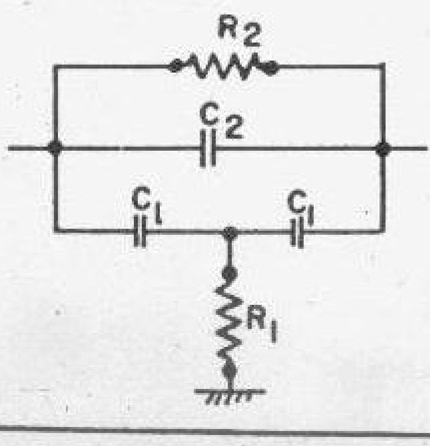
TABLO 2.5 (Devam)

14	$\frac{1}{Bs} \cdot \left\| \frac{\tau s+1}{\tau s} \right\|$ $\theta < 1$		$B = C_1$ $\tau = R(C_1+C_2)$ $\theta = \frac{C_2}{C_1+C_2}$	$R = \tau(1-\theta)$ $C_1 = B$ $C_2 = \frac{B\theta}{1-\theta}$
			$B = C_1 + C$ $\tau = RC_2$ $\theta = \frac{C_2}{C_1+C_2}$	$R = \frac{\tau}{B(1-\theta)}$ $C_1 = B\theta$ $C_2 = B(1-\theta)$
15	$\frac{1}{Bs} \left\| \frac{(\tau_1 s+1)(\tau_3 s+1)}{\tau_2 s+1} \right\|$ $\tau_1 < \tau_2 < \tau_3$		$B = C_1 + C_2$ $\tau_1 = R_1C_1$ $\tau_2 = (R_1+R_2) \left\| \frac{C_1C_2}{C_1+C_2} \right\|$ $\tau_3 = R_2C_2$	$R_1 = \frac{\tau_1(\tau_3-\tau_1)}{B(\tau_2-\tau_1)}$ $R_2 = \frac{\tau_3(\tau_3-\tau_1)}{B(\tau_3-\tau_2)}$ $C_1 = \frac{B(\tau_2-\tau_1)}{\tau_3-\tau_3}$ $C_2 = \frac{B(\tau_3-\tau_2)}{\tau_3-\tau_1}$
16	$A \cdot \left\| \frac{\tau_1 s+1}{\tau_1\tau_2 s^2+\tau_1 s+1} \right\|$		$A = R_2$ $\tau_1 = 2R_1C$ R_2C	$R_1 = \frac{A\tau_1}{4\tau_2}$ $R_2 = A$ $2\tau_2$

TABLO 2.5 (Devam)

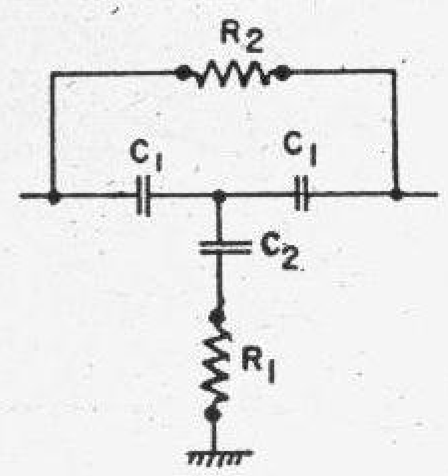
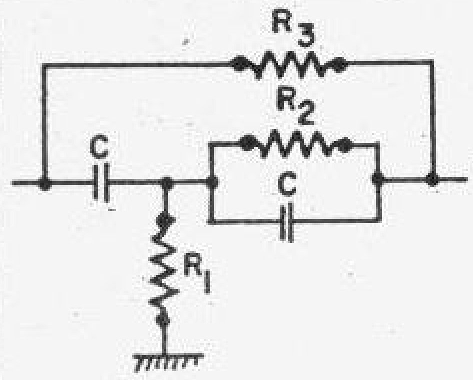
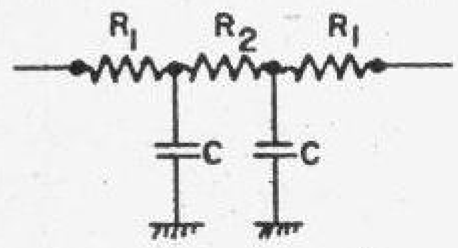
17	$A \cdot \left\lvert \dfrac{\tau_2 s + 1}{\tau_1 \tau_2 s^2 + \tau_1 s + 1} \right\rvert$		$A = 2R$ $\tau_1 = 2RC_2$ $\tau_2 = \dfrac{RC_1}{2}$	$R = \dfrac{A}{2}$ $C_1 = \dfrac{4\tau_2}{A}$ $C_2 = \dfrac{\tau_1}{A}$
18	$A \cdot \left\lvert \dfrac{\tau_3 s + 1}{\tau_1 \tau_2 s^2 + \tau_1 s + 1} \right\rvert$ $\tau_2 > \dfrac{\tau_1}{4}$ (kompleks kökler) $\tau_3 > \tau_2$		$A = \dfrac{2R_1R_2}{(2R_1 + R_2)}$ $\tau_1 = \dfrac{R_1(R_1C_1 + 2R_2C_2)}{2R_1 + R_2}$ $\tau_2 = \dfrac{R_1R_2C_1C_2}{R_1C_1 + 2R_2C_2}$ $\tau_3 = \dfrac{R_1C_1}{2}$	$R_1 = \dfrac{A\tau_3^2}{2\lvert\tau_3^2 - \tau_1(\tau_3 - \tau_2)\rvert}$ $R_2 = \dfrac{A\tau_3^2}{\tau_1(\tau_3 - \tau_2)}$ $C_1 = \dfrac{4\lvert\tau_3^2 - \tau_1(\tau_3 - \tau_2)\rvert}{A\tau_3}$ $C_2 = \dfrac{\tau_1\tau_2}{A\tau_3}$

TABLO 2.5 (Devam)

18	$A \cdot \left\lvert \dfrac{\tau_3 s + 1}{\tau_1 \tau_2 s^2 + \tau_1 s + 1} \right\rvert$ $\tau_2 > \dfrac{\tau_1}{4}$ (kompleks kökler) $\tau_3 > \tau_2$		$A = 2R_1$ $\tau_1 = R_2C_1 + 2R_1C_2$ $\tau_2 = \dfrac{R_1(R_1 + 2R_2)C_1C_2}{R_2C_1 + 2R_1C_2}$ $\tau_3 = \left\lvert R_2 + \dfrac{R_1}{2} \right\rvert C_1$	$R_1 = \dfrac{A}{2}$ $R_2 = \dfrac{A\tau_1(\tau_3 - \tau_2)}{4\lvert\tau_3^2 - \tau_1(\tau_3 - \tau_2)\rvert}$ $C_1 = \dfrac{4\lvert\tau_3^2 - \tau_1(\tau_3 - \tau_2)\rvert}{A\tau_3}$ $C_2 = \dfrac{\tau_1\tau_2}{A\tau_3}$
			$A = 2R$ $\tau_1 = R(C_2 + 2C_3)$ $\tau_2 = \dfrac{RC_3(C_1 + C_2)}{C_2 + 2C_3}$ $\tau_3 = \dfrac{R}{2}(C_1 + C_2)$	$R = \dfrac{A}{2}$ $C = \dfrac{2\lvert 2\tau_3^2 - \tau_1(\tau_3 - \tau_2)\rvert}{A\tau_3}$ $C_2 = \dfrac{2\tau_1(\tau_3 - \tau_2)}{A\tau_3}$ $C_3 = \dfrac{\tau_1\tau_2}{A\tau_3}$
19	$A \cdot \left\lvert \dfrac{\tau_3 s + 1}{\tau_1 \tau_2 s^2 + \tau_1 s + 1} \right\rvert$ $\tau_2 > \dfrac{\tau_1}{4}$ (kompleks kökler) $\tau_3 < \tau_1$		$A = R_2$ $\tau_1 = 2R_1C_1 + R_2C_2$ $\tau_2 = \dfrac{R_1R_2C_1(C_1 + 2C_2)}{2R_1C_1 + R_2C_2}$ $\tau_3 = 2R_1C_1$	$R_1 = \dfrac{A\tau_3^2}{4\lvert\tau_1\tau_2 - \tau_3(\tau_1 - \tau_3)\rvert}$ $R_2 = A$ $C = \dfrac{2\lvert\tau_1\tau_2 - \tau_3(\tau_1 - \tau_3)\rvert}{A\tau_3}$ $C_2 = \dfrac{\tau_1 - \tau_3}{A}$

Transfer Fonk

TABLO 2.5 (Devam)

19	$A \cdot \left\lvert \frac{\tau_3 s + 1}{\tau_1 \tau_2 s^2 + \tau_1 s + 1} \right\rvert$ $\tau_2 > \frac{\tau_1}{4}$ (kompleks kökler) $\tau_3 < \tau_1$		$A = R_2$ $\tau_1 = \frac{C_1(2R_1C_2 + R_2C_1)}{2C_1 + C_2}$ $\tau_2 = \frac{R_1R_2C_1C_2}{2R_1C_2 + R_2C_1}$ $\tau_3 = \frac{2R_1C_1C_2}{(2C_1 + C_2)}$	$R_1 = \frac{A\tau_3^2}{4\lvert\tau_1\tau_2 - \tau_3(\tau_1 - \tau_3)\rvert}$ $R_2 = A$ $C_1 = \frac{2\tau_1\tau_2}{A\tau_3}$ $C_2 = \frac{4\tau_1\tau_2\lvert\tau_1\tau_2 - \tau_3(\tau_1-\tau_3)\rvert}{A\tau_3^2(\tau_1 - \tau_3)}$
			$A = R_3$ $\tau_1 = \frac{R_1(2R_2 + R_3)C}{R_1 + R_2}$ $\tau_2 = \frac{R_2R_3C}{(2R_2 + R_3)}$ $\tau_3 = \frac{2R_1R_2C}{(R_1 + R_2)}$	$R_1 = \frac{A\tau_3^2}{2\lvert 2\tau_1\tau_2 - \tau_3(\tau_1 - \tau_3)\rvert}$ $R_2 = \frac{A\tau_3}{2(\tau_1 - \tau_3)}$ $R_3 = A$ $C = \frac{2\tau_1\tau_2}{A\tau_3}$
20	$A(\tau_1 s + 1)(\tau_2 s + 1)$ $\tau_1 < \tau_2$		$A = 2R_1 + R_2$ $\tau_1 = \left\lvert \frac{R_1R_2}{2R_1 + R_2} \right\rvert C$ $\tau_2 = R_1C$	$R_1 = A \left\lvert \frac{\tau_2 - \tau_1}{2\tau_2} \right\rvert$ $R_2 = A\frac{\tau_1}{\tau^2}$ $C = \frac{2\tau_2^2}{A(\tau_2 - \tau_1)}$

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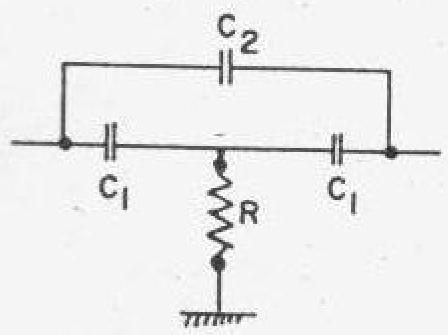
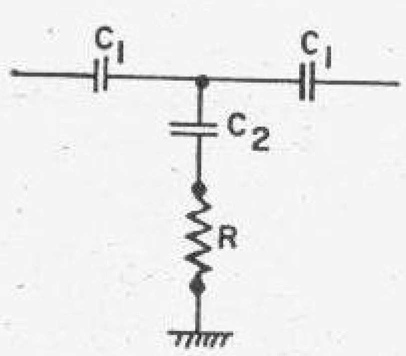
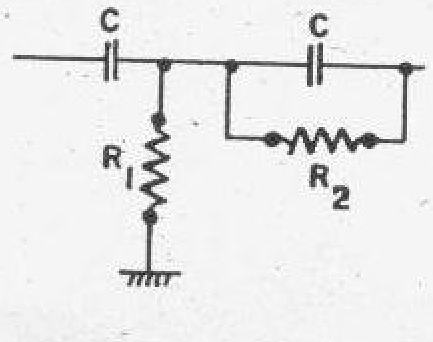
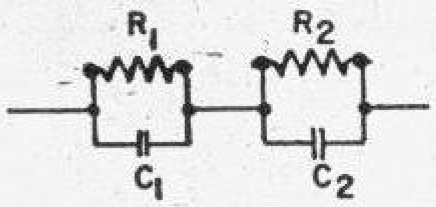
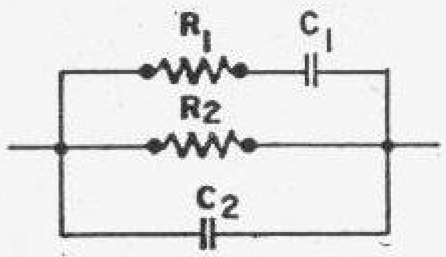
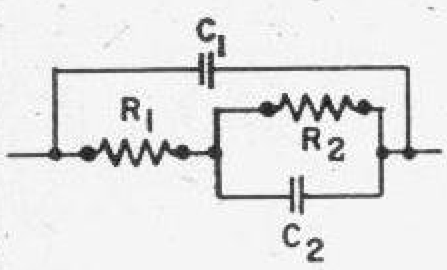
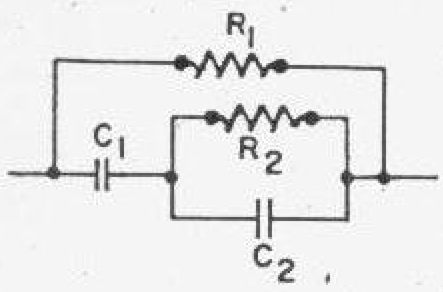
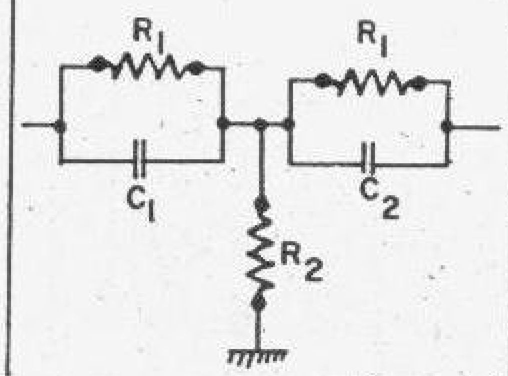
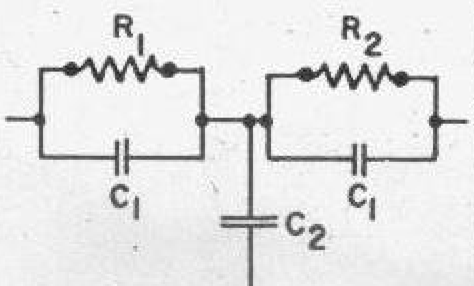
21	$\frac{1}{Bs} \cdot \left\lvert \frac{\theta\tau s + 1}{\tau s + 1} \right\rvert$ $\theta < 1$		$B_2 = C_2$ $\tau = RC_1 \left\lvert \frac{2C_2 + C}{C_2} \right\rvert$ $\theta = \frac{2C_2}{2C_2 + C_1}$	$R = \frac{\tau\theta^2}{4B(1-\theta)}$ $C_1 = \frac{2B(1-\theta)}{\theta}$ $C_2 = B$
			$B = \frac{C_1^2}{2C_1 + C_2}$ $\tau = RC_2$ $\theta = \frac{2C_1}{2C_1 + C_2}$	$R = \frac{\tau\theta^2}{4B(1-\theta)}$ $C_1 = \frac{2B}{\theta}$ $C_2 = \frac{4B(1-\theta)}{\theta^2}$
			$B = \left\lvert \frac{R_1}{R_1 + R_2} \right\rvert C$ $\tau = R_2C$ $\theta = \frac{2R_1}{R_1 + R_2}$	$R_1 = \frac{\tau\theta^2}{2B(2-\theta)}$ $R_2 = \frac{\tau\theta}{2B}$ $C = \frac{2B}{\theta}$

22	$A\left\lvert\dfrac{\tau_2 s+1}{(\tau_1 s+1)(\tau_3 s+1)}\right\rvert$ $\tau_1<\tau_2<\tau_3$		$A=R_1+R_2$ $\tau_1=R_1C_1$ $\tau_2=\left\lvert\dfrac{R_1R_2}{R_1R_2}\right\rvert(C_1+C_2)$ $\tau_3=R_2C_2$	$R_1=\dfrac{A(\tau_2-\tau_1)}{\tau_3-\tau_1}$ $R_2=\dfrac{A(\tau_3-\tau_2)}{\tau_3-\tau_1}$ $C_1=\dfrac{\tau_1(\tau_3-\tau_1)}{A(\tau_2-\tau_1)}$ $C_2=\dfrac{\tau_3(\tau_3-\tau_1)}{A(\tau_3-\tau_2)}$
			$A=R_2$ $\tau_2=R_1C_1$ $\tau_1\tau_3=R_1R_2C_1C_2$ $\tau_1+\tau_3=R_1C_1+R_2C_2+R_2C_1$	$R_1=\dfrac{A\tau_2^2}{(\tau_3-\tau_2)(\tau_2-\tau_1)}$ $R_2=A$ $C_1=\dfrac{(\tau_3-\tau_2)(\tau_2-\tau_1)}{A\tau_2}$ $C_2=\dfrac{\tau_1\tau_3}{\tau_2}$
			$A=R_1+R_2$ $\tau_2\quad\left\lvert\dfrac{R_1R_2}{R_1+R_2}\right\rvert C$ $\tau_1\tau_3=R_1R_2C_1C_2$ $\tau_1+\tau_3=R_1C_1+R_2C_2+R_2C_1$	$R_1=\dfrac{A\tau_2^2}{\tau_1\tau_2+\tau_2\tau_3-\tau_1\tau_3}$ $R_2=\dfrac{A(\tau_3-\tau_2)(\tau_2-\tau_1)}{\tau_1\tau_2+\tau_2\tau_3-\tau_1\tau_3}$ $C_1=\dfrac{\tau_1\tau_3}{A\tau_2}$ $C_2=\dfrac{(\tau_1\tau_2+\tau_2\tau_3-\tau_1\tau_3)^2}{A\tau_2(\tau_3-\tau_2)(\tau_2-\tau_1)}$

22	$A\left\lvert\dfrac{\tau_2 s+1}{(\tau_1 s+1)(\tau_3 s+1)}\right\rvert$ $\tau_1<\tau_2<\tau_3$		$A=R_1$ $\tau_2=R_2(C_1\quad C_2)$ $\tau_1\tau_3=R_1R_2C_1C_2$ $\tau_1+\tau_3=R_1C_1+R_2C_2+R_2C_1$	$R_1=A$ $R_2=\dfrac{A(\tau_3-\tau_2)(\tau_2-\tau_1)}{(\tau_1+\tau_3-\tau_2)^2}$ $C_1=\dfrac{\tau_1+\tau_3-\tau_2}{A}$ $C_2=\dfrac{\tau_1\tau_3(\tau_1+\tau_3-\tau_2)}{A(\tau_3-\tau_2)(\tau_2-\tau_1)}$
23	$A\left\lvert\dfrac{\tau_2 s+1}{(\tau_1 s+1)(\tau_3 s+1)}\right\rvert$ $\tau_2\le\tau_1\le\tau_3$		$A=2R+\dfrac{R_1^2}{R}$ $\tau_1=R_1C_1$ $\tau_2=\left\lvert\dfrac{R_1R_2}{R_1+2R_2}\right\rvert(C_1+C_2)$ $\tau_3=R_1C_2$	$R_1=\dfrac{A\tau_2}{(\tau_1+\tau_3)}$ $R_2=\dfrac{A\tau_2^2}{(\tau_1+\tau_3)(\tau_1+\tau_3-2\tau_2)}$ $C_1=\dfrac{\tau_1(\tau_1+\tau_3)}{A}$ $C_2=\dfrac{\tau_3(\tau_1+\tau_3)}{A\tau_2}$
24	$A\left\lvert\dfrac{\tau_2 s+1}{(\tau_1 s+1)(\tau_3 s+1)}\right\rvert$ $\tau_1\le\tau_3\le\tau_2$		$A=R_1+R_2$ $\tau_1=R_1C_1$ $\tau_2=\dfrac{R_1R_2}{R_1+R_2}\quad(2C_1+C_2)$ $\tau_3=R_2C_1$	$R_1=\dfrac{A\tau_1}{(\tau_1+\tau_3)}$ $R_2=\dfrac{A\tau_3}{(\tau_1+\tau_3)}$ $C_1=\dfrac{(\tau_1+\tau_3)}{A}$ $C_2=\dfrac{(\tau_1+\tau_3)}{A}\left\lvert\dfrac{\tau_2}{\tau_3}+\dfrac{\tau_2}{\tau_1}-2\right\rvert$

Dr. Rüegi [illegible]

The most troublesome faults are those that occur erratically. As a rule, they are caused by a loose soldered joint, less often by a broken resistor and only seldom by a fault inside a semiconductor component. In a functional model, pull the components gently and watch the suspected joint. When checking an evaluation sample, evoke the fault by twisting the printed-circuit board and watch (on an oscilloscope permanently connected to the output) whether the fault persists.

Faults, frequently occurring in manufacture are as follows: loose soldered joints, unsoldered joints, interrupted copper, solder bridge between two points, broken resistor, an order-of magnitude error in resistor value, interchanged resistors, back to front diode or electrolytic capacitor, interchanged pins of a transistor or operational amplifier, contact between two transistor cases, left out wire link.

Ac faults are relatively rare. If the operational circuit oscillates, the frequency compensations are usually not in order. The ceramic capacitor is a reliable component, its orientation does not matter, so that almost the only possible cause of failure is an incorrect value. If everything seems all right, re-solder all the soldered joints and check the series resistors. An oscillating power supply is a tricky fault to locate.

SUMMARY

Better than the best advice is one's own experience. Therefore, take an operational amplifier and build something on your own!

REFERENCES

[1] J. I. Smith, Modern Operational Circuit Design, Wiley, New York, 1971, Chap. 15

SUMMARY TABLES

TABLE I

Ideal properties of basic operational circuits. For practical reasons, the voltage follower is shown explicitely

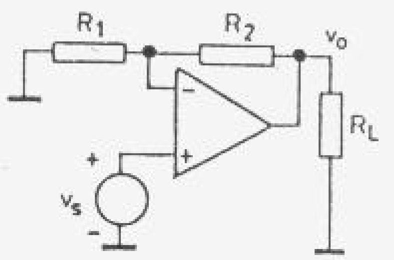
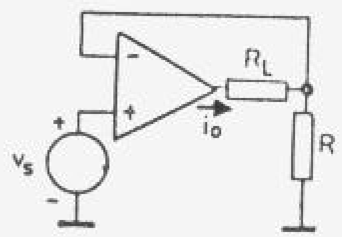
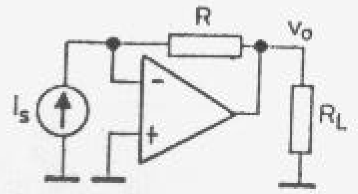
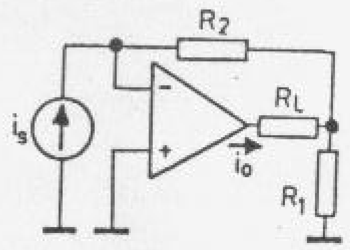
	Operational circuit	*Closed-loop gain* G_1	*Input resistance* R_{i1}	*Output resistance* R_{o1}
A Voltage amplifier		$\frac{R_2}{R_1}+1$	∞	0
B V/I converter		$\frac{1}{R}$	∞	∞
C I/V converter		$-R$	0	0
D Current amplifier		$-\left(\frac{R_2}{R_1}+1\right)$	0	∞

TABLE I (continued)

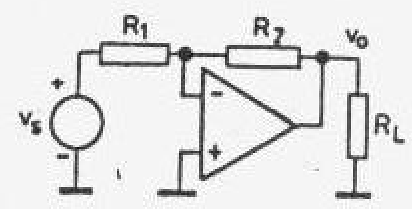
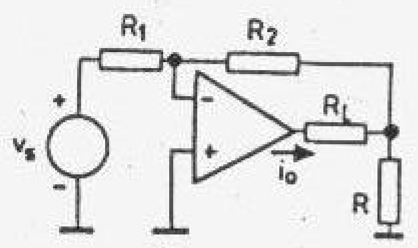
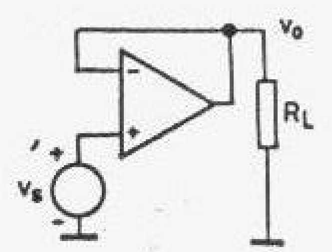
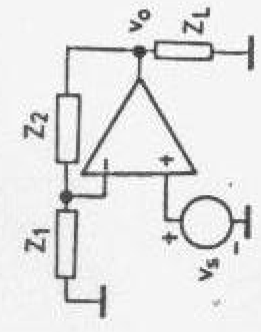
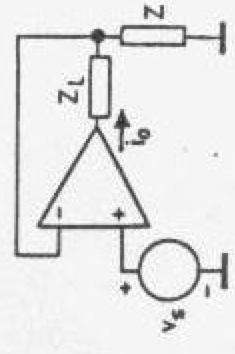
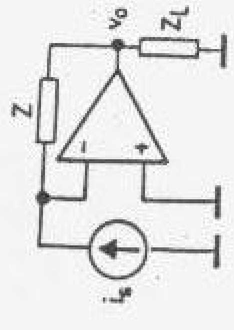
Operational circuit		Closed-loop gain G_1	Input resis-tance R_{i1}	Output resis-tance R_{o1}
E Voltage inverter		$-\frac{R_2}{R_1}$	R_1	0
F Parallel V/I converter		$-\frac{1}{R_1}\left(\frac{R_2}{R}+1\right)$	R_1	∞
G Voltage follower		1	∞	0

TABLE II

Inverse feedback factor $1/\beta$ of basic operational circuits. Simplified expressions in the first column correspond to the ideal operational amplifier. All expressions make the assumption of an ideal signal source

Operational circuit		Inverse feedback factor $1/\beta$ ideal	Inverse feedback factor $1/\beta$ actual
A		$1+\frac{Z_2}{Z_1}$	$1+\frac{Z_2}{Z_1 \parallel Z_d \parallel Z_{cm}^-}+\frac{Z_0}{Z_L}\left(1+\frac{Z_2+Z_L}{Z_1 \parallel Z_d \parallel Z_{cm}^-}\right)$
B		$1+\frac{Z_L}{Z}$	$1+\frac{Z_L+Z_0}{Z \parallel Z_d \parallel Z_{cm}^-}$
C		1	$1+\frac{Z}{Z_d \parallel Z_{cm}^-}+\frac{Z_0}{Z_L}\left(1+\frac{Z+Z_L}{Z_d \parallel Z_{cm}^-}\right)$

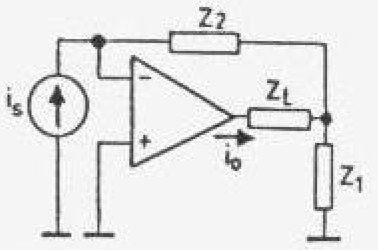
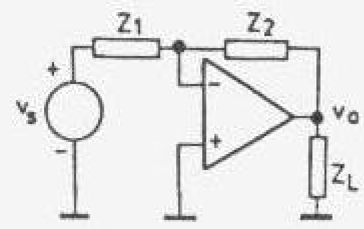
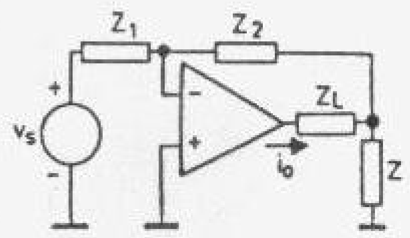
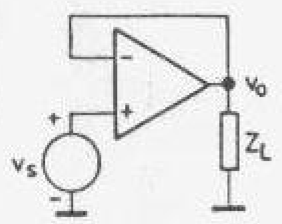
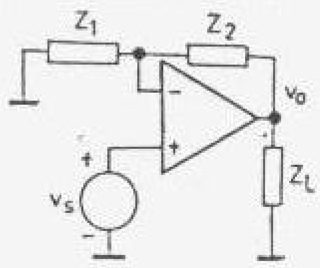
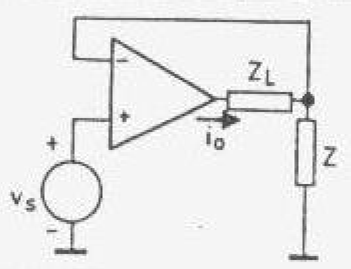
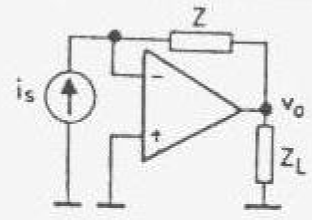
D		$1+\frac{Z_L}{Z_1}$	$1+\frac{Z_2}{Z_d \parallel Z_{cm}^-}+\frac{Z_L+Z_0}{Z_1}\left(1+\frac{Z_2+Z_1}{Z_d \parallel Z_{cm}^-}\right)$
E		$1+\frac{Z_2}{Z_1}$	$1+\frac{Z_2}{Z_1 \parallel Z_d \parallel Z_{cm}^-}+\frac{Z_0}{Z_L}\left(1+\frac{Z_2+Z_L}{Z_1 \parallel Z_d \parallel Z_{cm}^-}\right)$
F		$\left(1+\frac{Z_2}{Z_1}\right)\left(1+\frac{Z_L}{Z \parallel (Z_1+Z_2)}\right)$	$1+\frac{Z_2}{Z_1 \parallel Z_d \parallel Z_{cm}^-}+\frac{Z_L+Z_0}{Z}\left(1+\frac{Z_2+Z}{Z_1 \parallel Z_d \parallel Z_{cm}^-}\right)$
G		1	$1+\frac{Z_0}{Z_L \parallel Z_d \parallel Z_{cm}^-}$

TABLE III

Components of closed-loop gain G of basic operational circuits,

$$G=\left(G_\infty+\frac{G_0}{\beta A}\right)\frac{\beta A}{1+\beta A}.$$

Expressions for the feedback factor β are in Tab. II

Operational circuit		*Operational-circuit closed-loop gain*		
		ideal G_I	*idealized* G_∞	*feedforward* $G_0/\beta A$
A		$\frac{Z_2}{Z_1}+1$	$\left(\frac{Z_2}{Z_1}+1\right)\left(1+\frac{1}{X}\right)+\frac{Z_2}{Z_{cm}^-}$	$\frac{Z_0}{A}\left(\frac{1}{Z_d}+\frac{1}{X(Z_d \parallel Z_{cm}^-)}\right)$
B		$\frac{1}{Z}$	$\frac{1}{Z}\left(1+\frac{1}{X}\right)+\frac{1}{Z_{cm}^-}$	$-\frac{1}{A}\left(\frac{1}{Z_d}+\frac{1}{X(Z_d \parallel Z_{cm}^-)}\right)$
C		$-Z$	$-Z$	$\frac{Z_0}{A}$

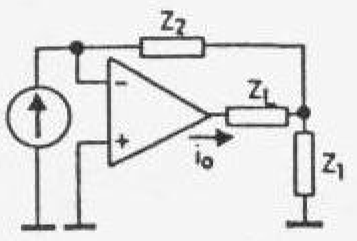
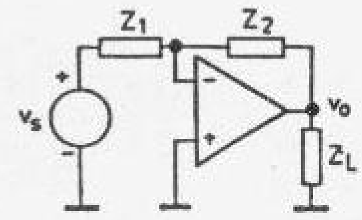
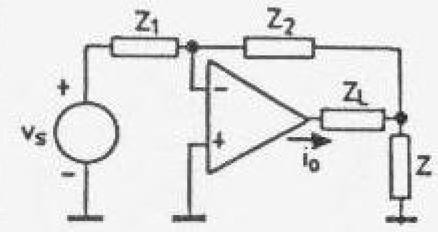
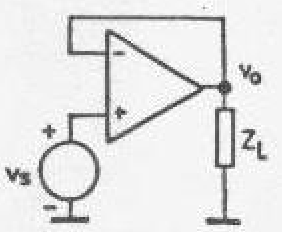
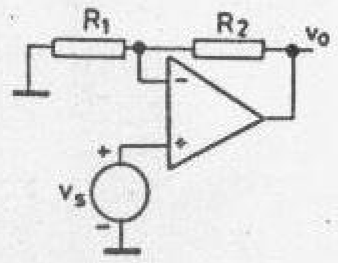
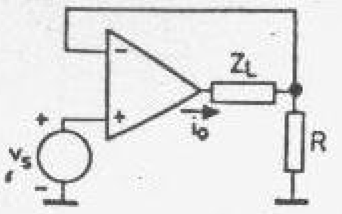
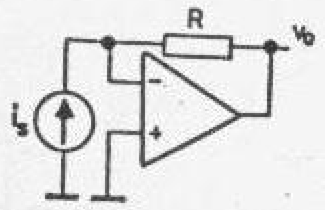
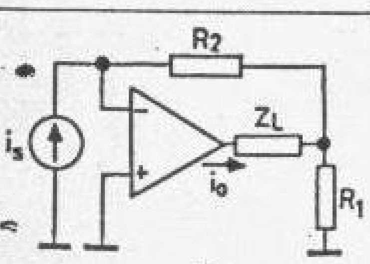
D		$-\left(\frac{Z_2}{Z_1}+1\right)$	$-\left(\frac{Z_2}{Z_1}+1\right)$	$-\frac{1}{A}$
E		$-\frac{Z_2}{Z_1}$	$-\frac{Z_2}{Z_1}$	$\frac{Z_0}{AZ_1}$
F		$-\frac{1}{Z_1}\left(\frac{Z_2}{Z}+1\right)$	$-\frac{1}{Z_1}\left(\frac{Z_2}{Z}+1\right)$	$-\frac{1}{AZ_1}$
G		1	$1+\frac{1}{X}$	$\frac{Z_0}{A}\left(\frac{1}{Z_d}+\frac{1}{X(Z_d \parallel Z_{cm}^-)}\right)$

TABLE IV

Closed-loop-gain static error due to inaccuracies of feedback-network components

	Operational circuit	*Ideal closed-loop gain G_1*	*Closed-loop-gain static error ε_0*
A		$\frac{R_2}{R_1}+1$	$\frac{1}{1+R_1/R_2}\left(\frac{\delta R_2}{R_2}-\frac{\delta R_1}{R_1}\right)$
B		$\frac{1}{R}$	$-\frac{\delta R}{R}$
C		$-R$	$\frac{\delta R}{R}$
D		$-\left(\frac{R_2}{R_1}+1\right)$	$\frac{1}{1+R_1/R_2}\left(\frac{\delta R_2}{R_2}-\frac{\delta R_1}{R_1}\right)$

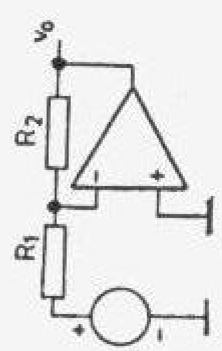
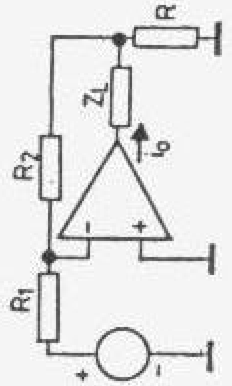
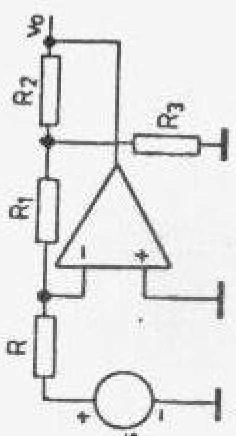
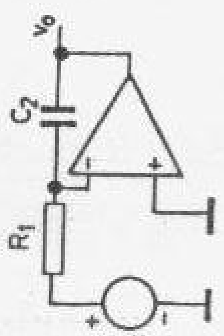
E		$-\dfrac{R_2}{R_1}$	$\dfrac{\delta R_2}{R_2} - \dfrac{\delta R_1}{R_1}$
F		$-\dfrac{1}{R_1}\left(\dfrac{R_2}{R} + 1\right)$	$-\dfrac{\delta R_1}{R_1} + \dfrac{1}{1 + R/R_2}\left(\dfrac{\delta R_2}{R_2} - \dfrac{\delta R}{R}\right)$
G		$-\dfrac{R_1}{R}\left(1 + \dfrac{R_2}{R_1 \parallel R_3}\right)$	$-\dfrac{\delta R}{R} + \dfrac{1}{1 + R_3/(R_1 \parallel R_2)} \times$ $\times \left[\left(1 + \dfrac{R_3}{R_2}\right)\dfrac{\delta R_1}{R_1} + \left(1 + \dfrac{R_3}{R_1}\right)\dfrac{\delta R_2}{R_2} - \dfrac{\delta R_3}{R_3}\right]$
H		$-\dfrac{1}{\omega C_2 R_1}$	$-\left(\dfrac{\delta R_1}{R_1} + \dfrac{\delta C_2}{C_2}\right)$

TABLE V

Simplified expressions for input impedance Z_i of basic operational circuits, assuming $X = \infty$, $Z_0 = 0$ and $Z_d, Z^-_{cm}, Z^+_{cm} \gg Z_L, Z_2, Z$

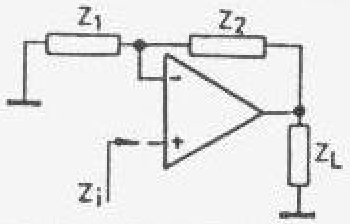
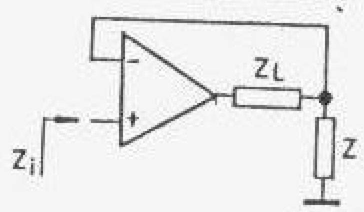
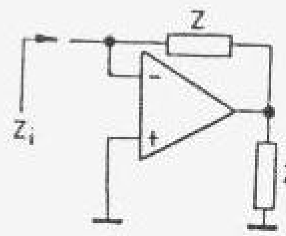
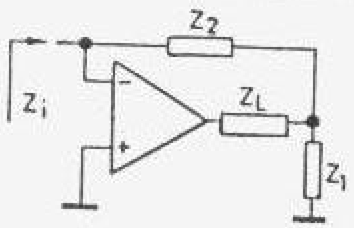
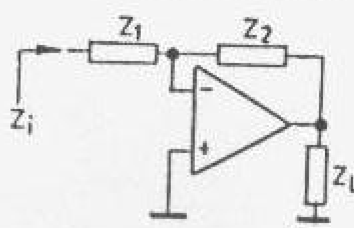
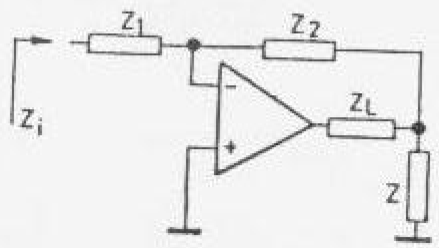
	Operational circuit	Input impedance: ideal Z_{i1}	Input impedance: actual Z_i
A		∞	$Z^+_{cm} \parallel [Z_d(1 + \beta_{sc}A)] \approx Z^+_{cm}$ for $1/\beta_{sc} = 1 + Z_2/Z_1$
B		∞	$Z^+_{cm} \parallel [Z_d(1 + \beta_{sc}A)] \approx Z^+_{cm}$ for $1/\beta_{sc} = 1 + Z_L/Z$
C		0	$\dfrac{Z}{1 + A}$
D		0	$\dfrac{Z_2 + Z_1 \parallel Z_L}{1 + \beta_{oc}A}$ for $1/\beta_{oc} = 1 + Z_L/Z_1$
E		Z_1	$Z_1 + \dfrac{Z_2}{1 + A}$
F		Z_1	$Z_1 + \dfrac{Z_2 + Z \parallel Z_L}{1 + \beta_{oc}A}$ for $1/\beta_{oc} = 1 + Z_L/Z$

TABLE V (continued)

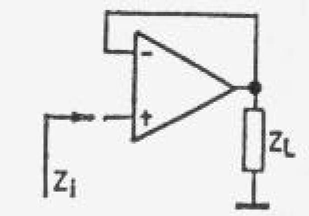
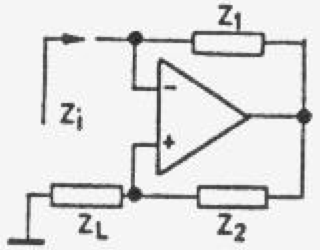
	Operational circuit	Input impedance: ideal Z_{i1}	Input impedance: actual Z_i
G		∞	$Z_{cm}^{+} \parallel [Z_d(1 + A)] \approx Z_{cm}^{+}$
H		$-\dfrac{Z_1 Z_L}{Z_2}$	$-\dfrac{Z_1 Z_L}{Z_2} + \dfrac{Z_1(1 + Z_L/Z_2)}{1 + \beta_{oc} A}$ for $1/\beta_{oc} = 1 + Z_L/Z_2$

TABLE VI

Simplified expressions for output impedance Z_o of basic operational circuits, assuming $X = \infty$, $Z_d, Z_{cm}^{-}, Z_{cm}^{+} \gg Z_0, Z_s, Z_1, Z_2, Z$ and $Z_0 = 0$ (F, H)

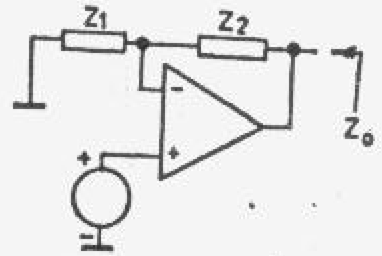
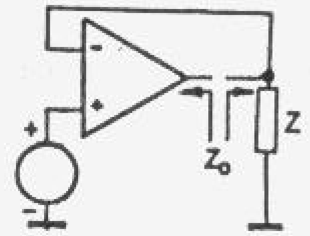
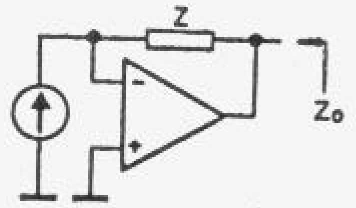
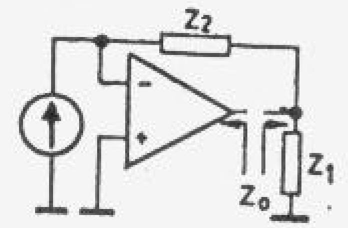
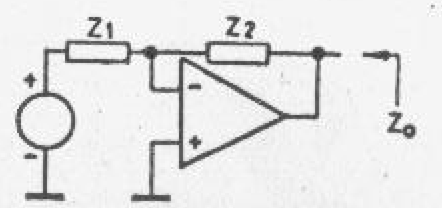
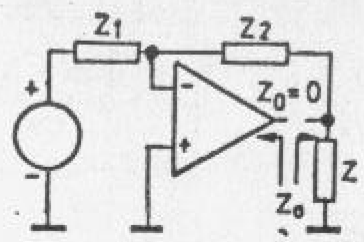
	Operational circuit	Output impedance: ideal Z_{o1}	Output impedance: actual Z_o
A		0	$\dfrac{Z_0 \parallel (Z_1 + Z_2)}{1 + \beta_{oc} A}$ for $1/\beta_{oc} = 1 + (Z_2 + Z_0)/Z_1$
B		∞	$Z_0 + Z(1 + A)$
C		0	$\dfrac{Z_0}{1 + A}$
D		∞	$Z_0 + Z_1(1 + A)$
E		0	$\dfrac{Z_0 \parallel (Z_1 + Z_2)}{1 + \beta_{oc} A}$ for $1/\beta_{oc} = 1 + (Z_2 + Z_0)/Z_1$
F		∞	$[Z \parallel (Z_1 + Z_2)](1 + \beta_{sc} A)$ for $1/\beta_{sc} = 1 + Z_2/Z_1$

TABLE VI (continued)

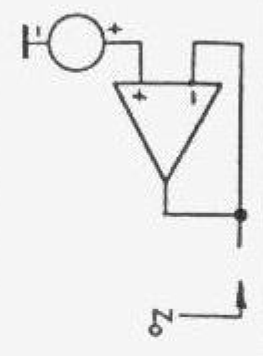
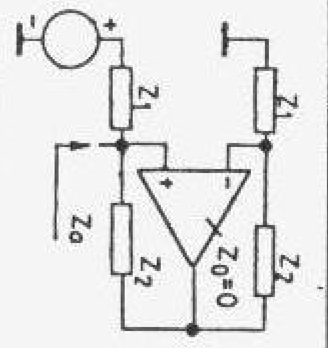
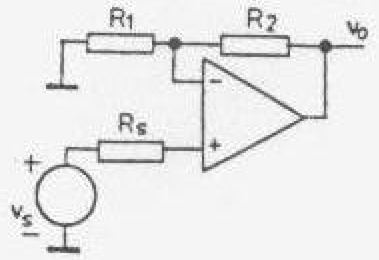
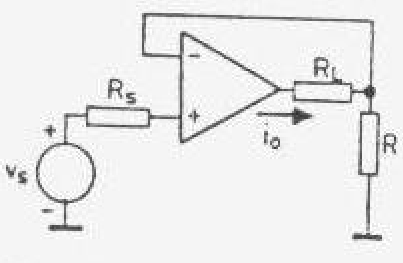
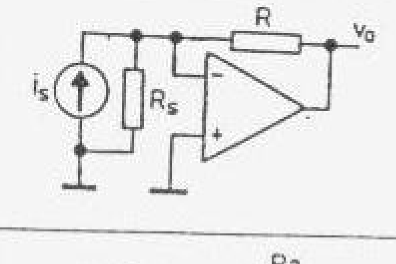
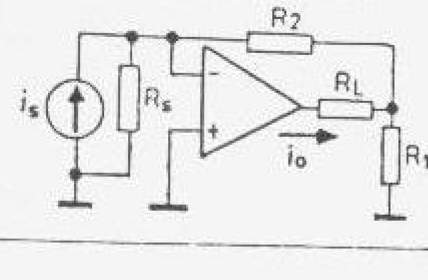
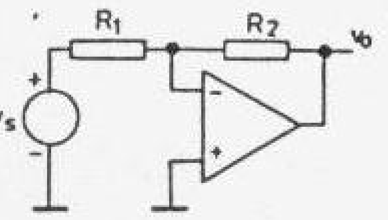
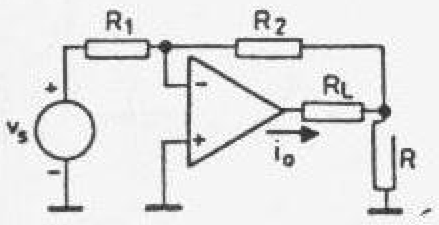
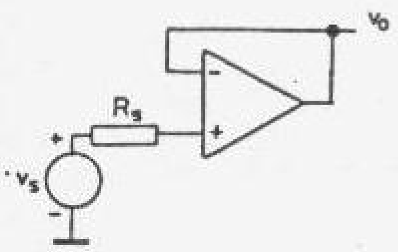
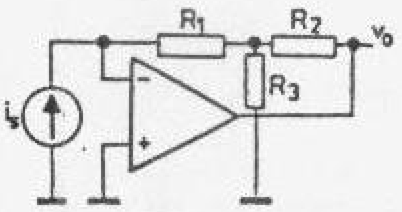
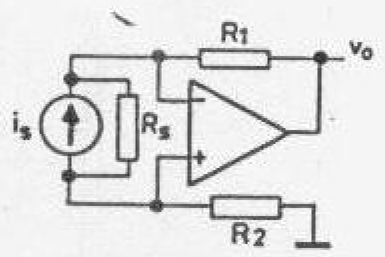
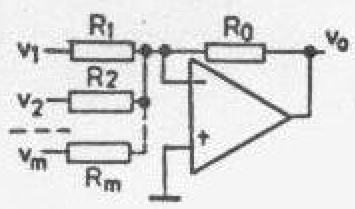
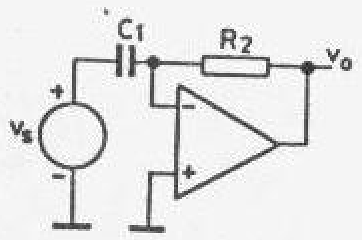
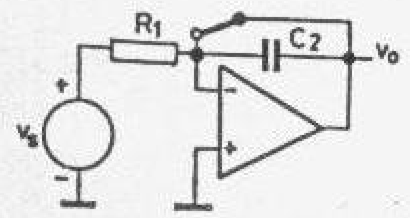
	Operational circuit	Output impedance: ideal Z_{oi}	Output impedance: actual Z_o
G		0	$\dfrac{Z_o}{1+A}$
H		∞	$(Z_1 \parallel Z_2)(1+\beta_{sc}A)$ for $1/\beta_{sc} = 1 + Z_2/Z_1$

TABLE VII

Input and output offset of unbalanced operational circuits

	Operational circuit	Input offset	Output offset
A		E_{osi} $-E_{os} - I_b^-(R_1 \parallel R_2) + I_b^+ R_s$	E_{oso} $E_{os}\left(\dfrac{R_2}{R_1}+1\right) + I_b^- R_2 - I_b^+ R_s\left(\dfrac{R_2}{R_1}+1\right)$
B		E_{osi} $-E_{os} - I_b^- R + I_b^+ R_s$	I_{oso} $\dfrac{E_{os}}{R} + I_b^- - I_b^+ \dfrac{R_s}{R}$
C		I_{osi} $\dfrac{E_{os}}{R \parallel R_s} + I_b^-$	E_{oso} $E_{os}\left(\dfrac{R}{R_s}+1\right) + I_b^- R$
D		I_{osi} $\dfrac{E_{os}}{(R_1+R_2) \parallel R_s} + I_b^-$	I_{oso} $\dfrac{E_{os}}{R_1}\left(1+\dfrac{R_1+R_2}{R_s}\right) + I_b^-\left(\dfrac{R_2}{R_1}+1\right)$

E		E_{osi} $E_{os}\left(1+\frac{R_1}{R_2}\right)+I_b^- R_1$	E_{oso} $E_{os}\left(\frac{R_2}{R_1}+1\right)+I_b^- R_2$
F		E_{osi} $E_{os}\left(1+\frac{R_1}{R_2+R}\right)+I_b^- R_1$	I_{oso} $\frac{E_{os}}{R}\left(1+\frac{R_2+R}{R_1}\right)+I_b^-\left(\frac{R_2}{R}+1\right)$
G		E_{osi} $-E_{os}+I_b^+ R_s$	E_{oso} $E_{os}-I_b^+ R_s$
H		I_{osi} $\frac{E_{os}}{R_1+R_2 \parallel R_3}+I_b^-$	E_{oso} $E_{os}\left(\frac{R_2}{R_3}+1\right)+I_b^- R_1\left(\frac{R_2}{R_1 \parallel R_3}+1\right)$

I		I_{osi} $\frac{E_{os}}{(R_1+R_2) \parallel R_s}+$ $+I_b^-\frac{R_1}{R_1+R_2}-I_b^+\frac{R_2}{R_1+R_2}$	E_{oso} $E_{os}\left(1+\frac{R_1+R_2}{R_s}\right)+I_b^- R_1-I_b^+ R_2$
J		E_{osi1} $E_{os}\frac{R_1}{R_0 \parallel R_1 \parallel \dots \parallel R_m}+I_b^- R_1$	E_{oso} $E_{os}\left(\frac{R_0}{R_1 \parallel \dots \parallel R_m}+1\right)+I_b^- R_0$
K		$\mathrm{d}E_{osi}/\mathrm{d}t$ $\frac{E_{os}}{C_1 R_2}+\frac{I_b^-}{C_1}$	E_{oso} $E_{os}+I_b^- R_2$
L		E_{osi} $E_{os}+I_b^- R_1$	E_{oso} $E_{os}\left(1+\frac{t}{C_2 R_1}\right)+\frac{I_b^- t}{C_2}$

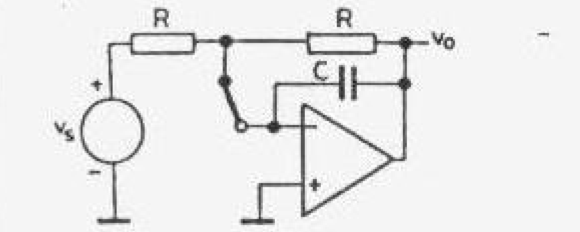
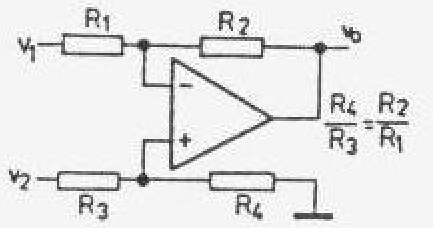
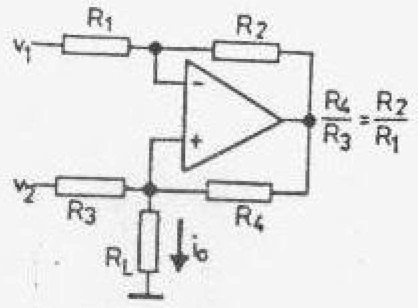
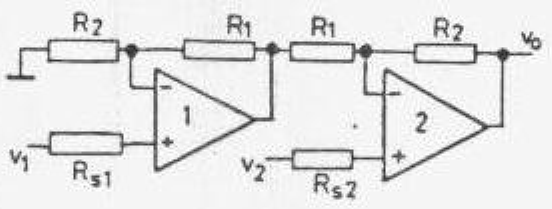
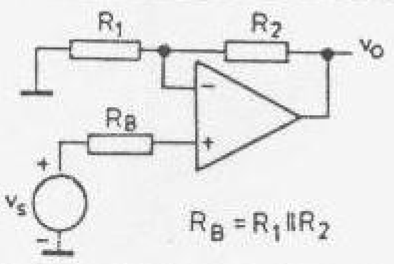
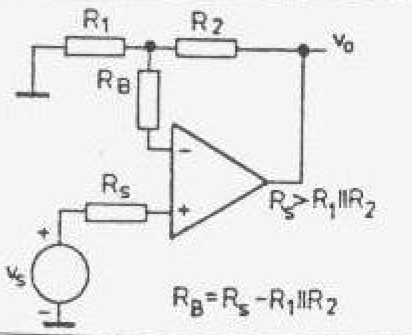
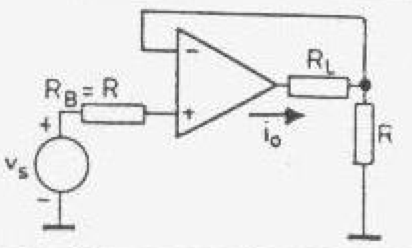
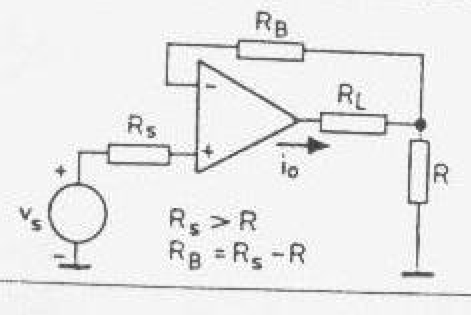
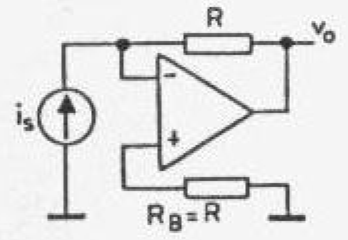
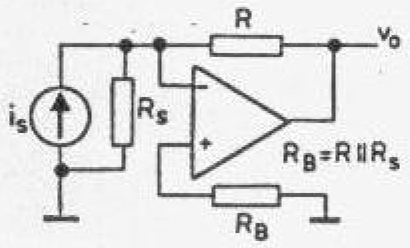
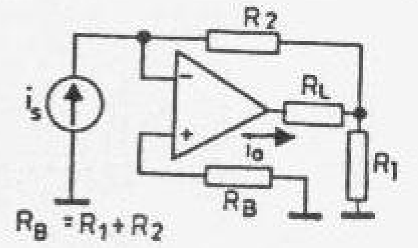
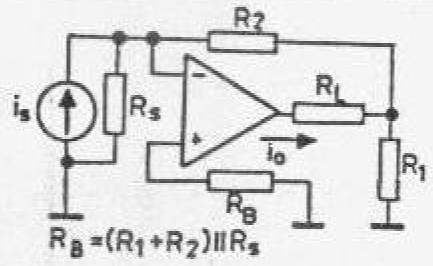
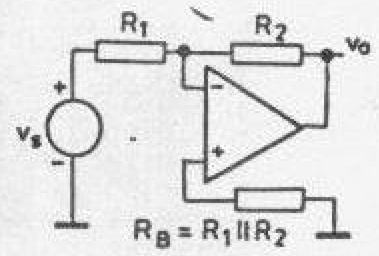
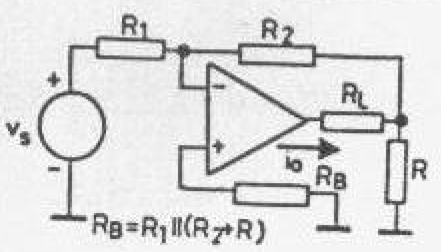
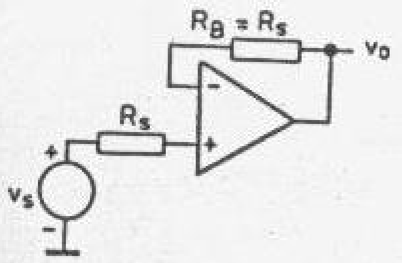
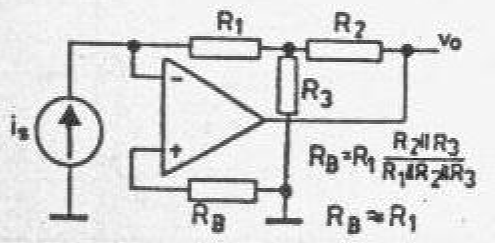
M		—	E_{oso} $2E_{os} + I_b^- R + \dfrac{I_b^- t}{C}$
N		E_{osi} $E_{os}\left(1 + \dfrac{R_1}{R_2}\right) + I_b^- R_1 - I_b^+ R_3$	E_{oso} $E_{os}\left(\dfrac{R_2}{R_1} + 1\right) + I_b^- R_2 - I_b^+ R_4$
O		E_{osi} $E_{os}\left(1 + \dfrac{R_1}{R_2}\right) + I_b^- R_1 - I_b^+ R_3$	I_{oso} $\dfrac{E_{os}}{R_3 \parallel R_4} + I_b^- \dfrac{R_2}{R_4} - I_b^+$
P		E_{osi} $E_{os2} - E_{os1} + I_{b1}^+ R_{s1} - I_{b2}^+ R_{s2} +$ $+ (I_{b2}^- - I_{b1}^-)(R_1 \parallel R_2)$	E_{oso} $(R_2/R_1 + 1) \times$ $\times (E_{os2} - E_{os1} + I_{b1}^+ R_{s1} - I_{b2}^+ R_{s2}) +$ $+ (I_{b2}^- - I_{b1}^-) R_2$

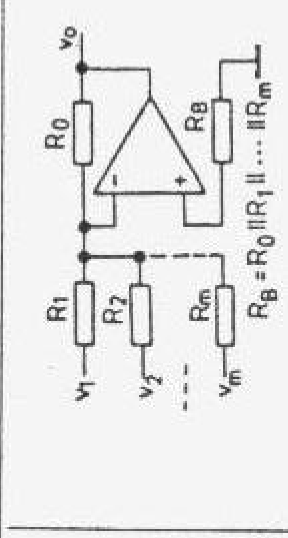
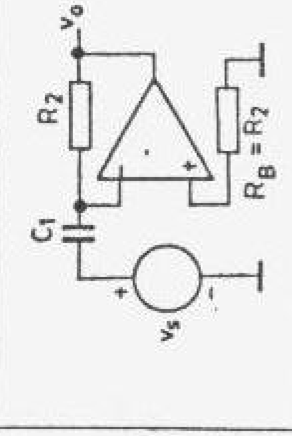
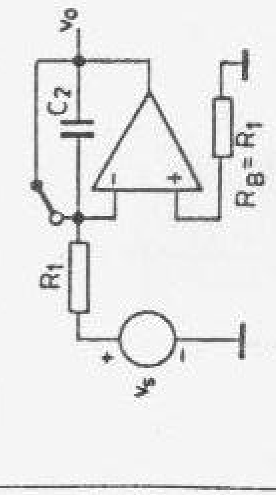
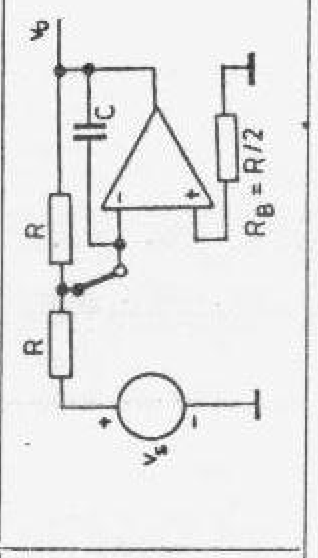
TABLE VIII

Input and output offset of balanced operational circuits

	Operational circuit	*Input offset*	*Output offset*
A1		E_{osi} $-E_{os} - I_{os}(R_1 \parallel R_2)$	E_{oso} $E_{os}\left(\dfrac{R_2}{R_1} + 1\right) + I_{os} R_2$
A2		E_{osi} $-E_{os} - I_{os} R_s$	E_{oso} $E_{os}\left(\dfrac{R_2}{R_1} + 1\right) + I_{os} R_s \left(\dfrac{R_2}{R_1} + 1\right)$
B1		E_{osi} $-E_{os} - I_{os} R$	I_{oso} $\dfrac{E_{os}}{R} + I_{os}$
B2		E_{osi} $-E_{os} - I_{os} R_s$	I_{oso} $\dfrac{E_{os}}{R} + I_{os} \dfrac{R_s}{R}$

C1		I_{osi} $\frac{E_{os}}{R} + I_{os}$	E_{oso} $E_{os} + I_{os}R$
C2		I_{osi} $\frac{E_{os}}{R \parallel R_s} + I_{os}$	E_{oso} $E_{os}\left(1 + \frac{R}{R_s}\right) + I_{os}R$
D1		I_{osi} $\frac{E_{os}}{R_1 + R_2} + I_{os}$	I_{oso} $\frac{E_{os}}{R_1} + I_{os}\left(\frac{R_2}{R_1} + 1\right)$
D2		I_{osi} $\frac{E_{os}}{(R_1 + R_2) \parallel R_s} + I_{os}$	I_{oso} $\frac{E_{os}}{R_1}\left(1 + \frac{R_1 + R_2}{R_s}\right) + I_{os}\left(\frac{R_2}{R_1} + 1\right)$

E		E_{osi} $E_{os}\left(1 + \frac{R_1}{R_2}\right) + I_{os}R_1$	E_{oso} $E_{os}\left(\frac{R_2}{R_1} + 1\right) + I_{os}R_2$
F		E_{osi} $E_{os}\left(1 + \frac{R_1}{R_2 + R}\right) + I_{os}R_1$	I_{oso} $\frac{E_{os}}{R}\left(1 + \frac{R_2 + R}{R_1}\right) + I_{os}\left(\frac{R_2}{R} + 1\right)$
G		E_{osi} $-E_{os} - I_{os}R_s$	E_{oso} $E_{os} + I_{os}R_s$
H		I_{osi} $\frac{E_{os}}{R_1 + R_2 \parallel R_3} + I_{os}$	E_{oso} $E_{os}\left(\frac{R_2}{R_3} + 1\right) + I_{os}R_1\left(\frac{R_2}{R_1 \parallel R_3} + 1\right)$

I		E_{osi1} $E_{os}\dfrac{R_1}{R_0 \parallel R_1 \parallel \ldots \parallel R_m} + I_{os}R_1$	E_{oso} $E_{os}\left(\dfrac{R_0}{R_1 \parallel \ldots \parallel R_m} + 1\right) + I_{os}R_0$
J		dE_{osi}/dt $\dfrac{E_{os}}{C_1R_2} + \dfrac{I_{os}}{C_1}$	E_{oso} $E_{os} + I_{os}R_2$
K		E_{osi} $E_{os} + I_{os}R_1$	E_{oso} $E_{os} - I_b^+R_1 + (E_{os} + I_{os}R_1)\dfrac{t}{C_2R_1}$
L		—	E_{oso} $2E_{os} + I_{os}R + \dfrac{I_b^- t}{C}$

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