

# Senzorové systémy v CIM

Ing. Richard Balogh

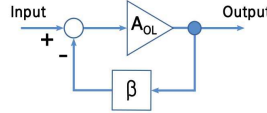
# Operačné zosilňovače

máj 2013



# 11. História Prvé pokusy

• Dr. C. A. Lovell (Bell Telephone Laboratories) navrhol operačný zosilňovač pre stabilizáciu zosilnenia



PROCEEDINGS OF THE I.R.E.

### Analysis of Problems in Dynamics by Electronic Circuits\*

JOHN R. KAGAZZINI, MEMBER, I.R.E., ROBERT H. RANDALL, AND FREDERICK A. RUSSELL, JR., I.R.E.

**Summary**—This paper describes a method for obtaining an engineering solution for integrodifferential equations of physical systems using an electronic system. The components consist of diodes, resistors, capacitors, and inductors, as well as a mechanical integrator. The method is applied to a control problem involving a ship's steering system. A simple method for assembling the particular circuit for any equation is described, and a general design procedure is given. The system is used, however, to illustrate the use of the method in the study of the dynamics of physical systems.

**I. INTRODUCTION**

THE FORMULATION of electrical analogs of dynamic problems in fields other than electrical has long been used to obtain solutions for such problems. There, in most cases, a physically realizable network may be synthesized to fit the equations and a network used to obtain the electrical outputs representing the solution of the equations. For complicated problems this method does not usually result in a network whose individual parameters correspond to the individual parameters of the original system, so that representation in the nature of varying the parameters is not simple. This objection is largely overcome through the generous use of isolating amplifiers within the electrical network. Until the modern methods of feedback stabilization were developed, the use of amplifiers in isolated amplifying circuit elements which allowed variation in tube characteristics. The earlier method of attack on problems of this type has been through the use of the mechanical differential analyzer having as its basic tool an impulse mechanical integrator, recently improved through the use of a photoelectric servo-operated torque amplifier.<sup>1,2</sup>

The technique described herein employs as its basic tool a stabilized feedback amplifier of standard design,<sup>3</sup> which by mere external changes in connection will serve as integrator, differentiator and sign changer. Professor J. R. Russell of Columbia University first brought these techniques to the attention of the authors in the circuits employed in the Western Electric M-IX autodyne gun director.<sup>4</sup> An amplifier so connected can perform the mathematical operations of arithmetic and calculus on the voltages applied to its input; it is hereafter termed an "operational amplifier." The operations can be performed to any desired degree of precision, providing power supplies of excellent regulation and circuit components of high precision are used. For most engineering computations, ordinary circuit components are adequate.

**II. OPERATIONAL AMPLIFIERS**

The term "operational amplifier" is a generic term applied to amplifiers whose gain functions are such as to enable them to perform certain useful operations such as summation, integration, differentiation, or a combination of such operations. In view of the fact that many operations involve steady or slowly changing signals, the inherent frequency response of such amplifiers must extend down to zero frequency. The basic unit in the operational amplifier is generally a direct-current amplifier having an odd number of stages. The unit shown in Fig. 1 was developed specifically for general laboratory use. However, any well-developed, stable, direct-current amplifier having an odd number of stages, or an equivalent phase shift, is adaptable to this use which will be described.

\* Introduction booklet prepared by the Bell Telephone Laboratories for the Western Electric M-IX autodyne gun director.

Fig. 1—Direct-current amplifier for use in electronic computers.

# 11. História Spätaná väzba - feedback

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5. 5. 2013 11:48 | Richard Balogh | Práškovo | Richard Balogh | 0 | 0 | 2 | Dokumenty | 0 | 0

### Senzorové systémy CIM (37117\_31 - LS 2012/2013 - FEJ)

Základné údaje	Zoznamy študentov	Študentská anketa	Výpisovanie termínov
Dochádzka	Priebežné hodnotenie	Skúšková správa	Dokumentový server
Automobílna hodnota	Rozpis témy a miesta odovzdania	Testy a skúšky	et.examinovacie osnovy

Základný prehľad    Štatistika    **Anketný listok**    Grafy    OLAP funkcie    Náhľad ankety

Prezeranie anketových háčkov. Anketový háčok predstavuje odpoveď jedného študenta na anketu k jednému zobrazeniu na stránke po desiatich, k ďalším stránkam je možné sa dostať pomocou listovania v navigačnom riadku na orientáciu -- môžete si poznačiť číslo háčika, ktorý ste prezerali naposledy a na budúce čítať až od neho.

1-10 11-20 21-30 31-33

Háčok č. 39566

Informácie

17. Meno predkladateľa (ak ich bolo viac, tak iba jedného): Balogh

18. Meno odovzdača (ak ich bolo viac, tak iba jedného): Tichý

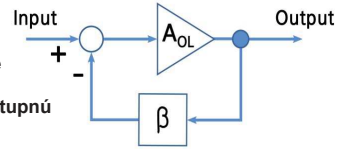
19. Miesta záberu na prednáškach k predmetu bolo: 1803 (1 až 4 vzá)

21. Na predmete by sa malo zlepšiť: je zbytočne cokolvek zlepšovať, nestojí to tu za nič a ani som sa nič nenaučil

ZLÁ spätaná väzba

# 11. História Spätaná väzba - feedback

- Zosilnenie obvodu je menej citlivé na zmeny hodnôt jednotlivých súčiastok
- Vplyv šumov je menší
- Dá sa znížiť nelineárne skreslenie
- Môžeme ovplyvniť vstupnú aj výstupnú impedanciu
- Môžeme rozšíriť šírku pásma zosilňovača



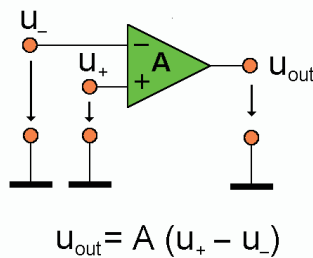
DOBRA spätaná väzba môže byť aj ZÁPORNÁ

# 11. História Prvé pokusy

• George A. Philbrick nezávisle na ňom navrhol elektrónkový operačný zosilňovač v r. 1948



# Operačný zosilňovač operational amplifier, Op-Amp



Ideálny zosilňovač:

- $A = \infty$
- $R_{vst} = \infty$
- $R_{vyšt} = 0$
- $f_{max} = \infty$
- $U_{out} = 0$  ak  $U_{diff} = 0$
- $U_{max} = \infty$

# Základné vzťahy

The basic equation of the operational amplifier may be derived by reference to Fig. 2. Here, if it is assumed that the box marked A is a direct-current amplifier and

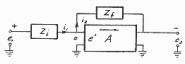


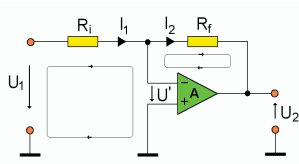
Fig. 2—Block diagram for basic feedback computation.

that the input at *o* is connected directly to the grid of the first tube, the currents at the junction *o* must add up to zero. Thus,

$$i_1 = i_2$$

or,

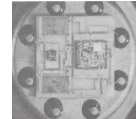
$$\frac{e_1 - e_1'}{Z_i(p)} = \frac{e_1' + e_2}{Z_f(p)} \quad (1)$$



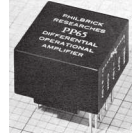
# 11. História Technology



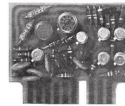
TI's OPA2188: first zero-drift, 36-V operational amplifier (2012)



ADI's HOS-050: a high speed hybrid IC op-amp (1979)



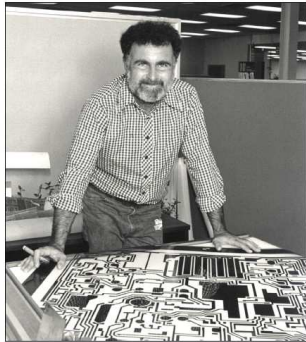
Early FET input AD op-amp (1970)



GAP/R's model P45: a solid-state, discrete op-amp (1961)



# 11. História Technology



Bob Widlar reviewing his LM10 op-amp, circa 1977 (Photo courtesy: Bob Pease and National Semiconductor)

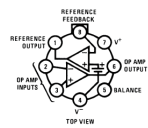


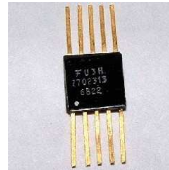
Figure 1. TO Package (NEV) See Package Number NEV0008A



# 11. História Fairchild 702

generally regarded as the first commercially successful operational amplifier chip

although other manufacturers produced earlier IC amplifiers, in particular TI with their SN520 and SN521, and also the manufacturers Westinghouse and Sperry Semiconductor.



The image on the left shows a version from 1968 in a flatpack. The image on the right shows a later ceramic dual-inline version dated 1973.

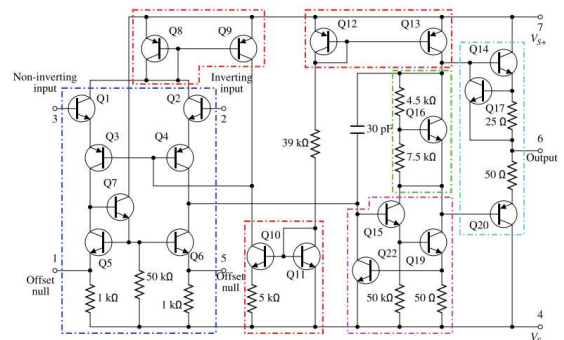
# 11. História Fairchild uA709

even more successful than the rather quirky uA702 and paved the way for the classic 741



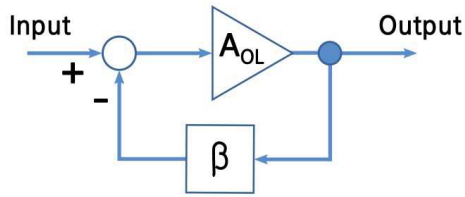
- The image on the left shows an original Fairchild 1967 example in an 8-lead TO-99 can.
- That on the right shows a 1970 device made by Microsystems International in a dual-inline package. Both top and bottom of the chip are covered by gold

# Internal circuitry of 741 type op-amp



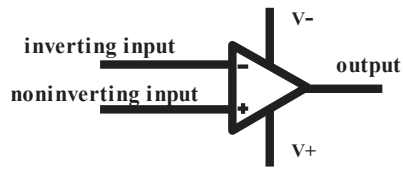
A component level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

# Internal circuitry of 741 type op-amp



A component level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

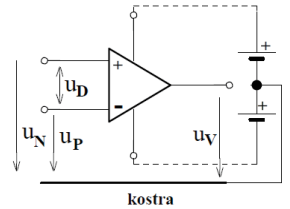
# Operačné zosilňovače



Operačný zosilňovač s napájaním.

a.) symetrický vstup - asymetrický výstup

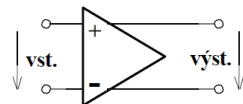
Poznámka: Je to najbežnejšie použitie a zapojenie OZ



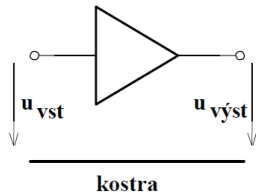
kostra

# Operačné zosilňovače

b.) symetrický vstup - symetrický výstup



c.) asymetrický vstup - asymetr. výstup



kostra

# Operačné zosilňovače

**Komparátor**  
A = ∞

# Operačné zosilňovače Základné vlastnosti

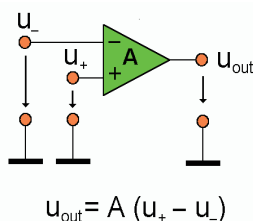
## Jednosmerné zosilnenie

- súhlasné (súfázne)
- rozdielové

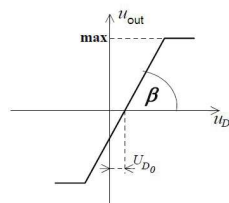
A je jednosmerné rozdielové zosilnenie naprázdno (ideál A = ∞)

$$A = \frac{\Delta u_{out}}{\Delta u_D} = tg \beta$$

U<sub>D0</sub> je vstupná napätová nesymetria (tiež napätový ofset - U<sub>D0</sub> je potrebné do vstupu na U<sub>out</sub> = 0)



$$u_{out} = A (u_+ - u_-)$$



# Operačné zosilňovače Základné vlastnosti

## Jednosmerné zosilnenie súhlasné

Reálny OZ zosilňuje i súhlasné u<sub>CM</sub>

$$u_{CM} = \frac{u_- + u_+}{2}$$

jednosmerné súhlasné zosilnenie B<sub>0</sub>

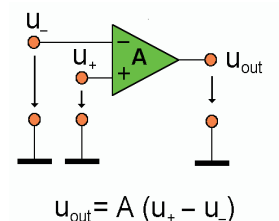
$$u_{out} = A \cdot u_D + B_0 \cdot u_{CM}$$

- kvalitný zosilňovač → B<sub>0</sub> << A

činiteľ potlačenia súhlasného napätia CMRR (Common Mode Rejection Ratio)

$$CMRR = \frac{A_0}{B_0}$$

Poznámka: V katalógoch tiež ako diskriminačný súčiniteľ k<sub>v</sub>. Reálne býva 10<sup>4</sup> + 10<sup>7</sup>, resp. 80 + 100 dB.



$$u_{out} = A (u_+ - u_-)$$

## Operačné zosilňovače Základné vlastnosti

### Vstupný offset

nežiaduce signály na vstupe

→ v konečnom dôsledku na výstupe OZ

- **napätový** ( $U_{Do}$  také, aby na výstupe bola naozaj 0) vstupná napätová nesymetria (ext. kompenzácia)

- **prúdový**

- $i_{Nu}$  a  $i_{Po}$  od vst. napätia (žiadané)
- $I_{No}$  a  $I_{Po}$  parazitné „kľudové prúdy“

- Priemerný vst. kľudový prúd

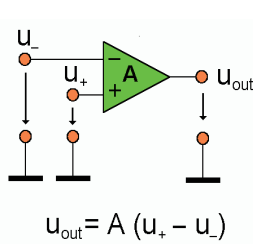
$$I_0 = \frac{I_{N0} + I_{P0}}{2}$$

- Prúdová nesúmernosť (asyme (čo najmenšia))

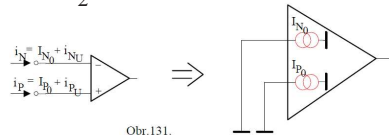
$$I_{OZ} = I_{N0} - I_{P0}$$

**Kolísanie offsetu = drift**

- časový, teplotný, napájací

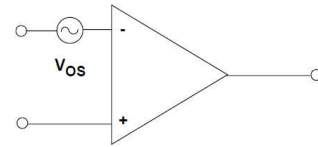


$$u_{out} = A(u_+ - u_-)$$



Obr. 131.

## Operačné zosilňovače Základné vlastnosti



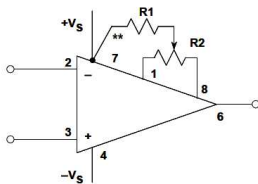
- ◆ **Offset Voltage:** The differential voltage which must be applied to the input of an op amp to produce zero output.

- ◆ **Ranges:**

- Chopper Stabilized Op Amps: <math><1\mu V</math>
- General Purpose Precision Op Amps: 50-500 $\mu V$
- Best Bipolar Op Amps: 10-25 $\mu V$
- Best FET Op Amps: 100-1,000 $\mu V$
- High Speed Op Amps: 100-2,000 $\mu V$
- Untrimmed CMOS Op Amps: 5,000-50,000 $\mu V$
- DigiTrim™ CMOS Op Amps: <math><1,000\mu V</math>

Figure 1-37: Input offset voltage

## Operačné zosilňovače Základné vlastnosti



- ◆ \*\* Wiper connection may be to either + $V_S$  or - $V_S$  depending on op amp
- ◆ R values depend on op amp. Consult data sheet
- ◆ Use to null out input offset voltage, not system offsets!
- ◆ There may be high gain from offset pins to output — Keep them quiet!
- ◆ Nulling offset causes increase in offset temperature coefficient, approximately 4 $\mu V/^{\circ}C$  for 1mV offset null for FET inputs

Figure 1-40: Offset adjustment pins

## Operačné zosilňovače Základné vlastnosti

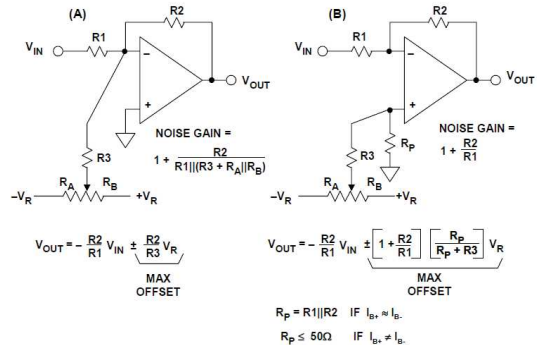
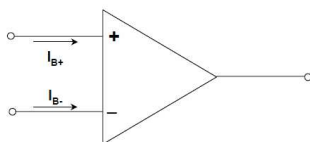


Figure 1-41: Inverting op amp external offset trim methods

## Operačné zosilňovače Základné vlastnosti



- ◆ A very variable parameter!
- ◆  $I_B$  can vary from 60 fA (1 electron every 3  $\mu s$ ) to many  $\mu A$ , depending on the device.
- ◆ Some structures have well-matched  $I_B$ , others do not.
- ◆ Some structures'  $I_B$  varies little with temperature, but a FET op amp's  $I_B$  doubles with every 10 $^{\circ}C$  rise in temperature.
- ◆ Some structures have  $I_B$  which may flow in either direction.

Figure 1-43: Op amp input bias current

## Operačné zosilňovače Základné vlastnosti

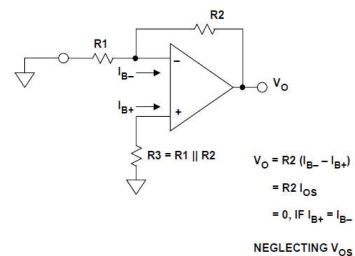


Figure 1-46: Canceling the effects of input bias current within an application

# Operačné zosilňovače Základné vlastnosti

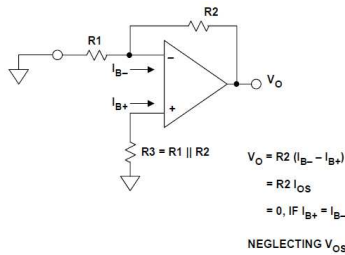


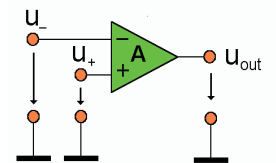
Figure 1-46: Canceling the effects of input bias current within an application

# Operačné zosilňovače Základné vlastnosti

## Vstupný odpor

$R_D$  - rozdielový (diferenčný) vst. odpor  
(teoreticky  $\infty$ , reálne  $M\Omega$ )

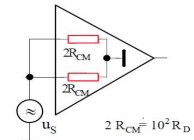
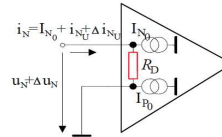
$R_{CM}$  - súhlasný (súfázny) odpor  
- paralelne 2  $R_{CM}$



$$u_{out} = A (u_+ - u_-)$$

$$R_D = \frac{\Delta u_N}{\Delta i_{NU}} \text{ pre } u_P = 0 \quad \text{resp.}$$

$$R_D = \frac{\Delta u_P}{\Delta i_{PU}} \text{ pre } u_N = 0$$



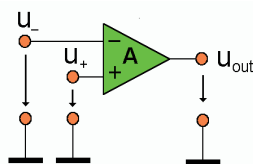
Obr. 132

# Operačné zosilňovače Základné vlastnosti

## Výstupný odpor

$R_{OUT} = 0$  ideálne, reálne však

$R_{OUT} = 10 \Omega \gg 1 k\Omega$

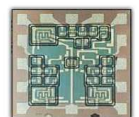


$$u_{out} = A (u_+ - u_-)$$

# Operačné zosilňovače Základné druhy

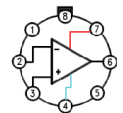
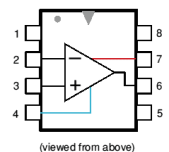
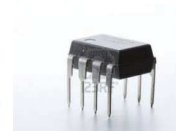
## Technológia

- monolitické
- hybridné



## Prevedenie

- kovové diskové púzdro TO ( 8 vývodov)
- plastové radové púzdro DIL
- plastové púzdro SMD



# Operačné zosilňovače Základné druhy

## Vstup

- súmerný
- nesúmerný
- vstup bipolárny
- vstup FET, JFET
- vstup CMOS

## Podľa určenia

- univerzálne (monolitické)
- prístrojové (malé  $U_{D0}$  a drift, veľké  $A_0$  a CMMR)
- elektrometrické (malé  $I_0$ , veľké  $R_{vst.}$ )
- izollačné
- rýchle (širokopásmové, impulzné)

# Operačné zosilňovače Napájanie

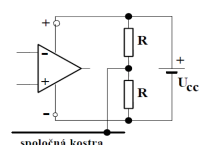
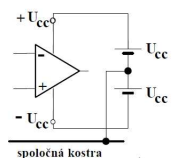
## Súmerné

- súmerný  $\pm U_{cc}$

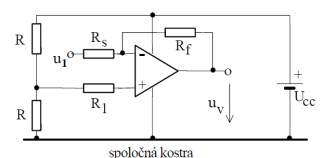
- súmerný s jedným zdrojom umelý stred

## Nesúmerné

- jeden zdroj
  - vhodnejšie pre ~ signál (oddelený kondenzátorom)
  - odpory R a R1 posúvajú prac. bod do stredu  $U_{cc}$
  - nulová úroveň vstupu i výstupu je potom  $0,5U_{cc}$
  - $u_v$  - len kladné hodnoty



Poznámka:  
Lepšie výsledky dávajú OZ priamo určené pre jeden napájací zdroj (presnejšie, menšie drifty)



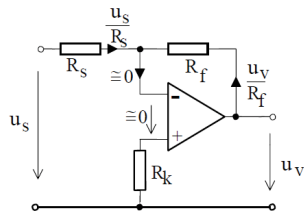
## Operačné zosilňovače Invertujúci zosilňovač

$$\frac{u_s}{R_s} = -\frac{R_f}{R_s} u_s$$

$$R_k = \frac{R_f R_s}{R_f + R_s}$$

$$R_{vst} \approx R_s \quad a \quad R_{vyst} \approx \frac{R_v}{\beta A_0}$$

- platí  $A_{sv} \ll A_0$  ( $A_{sv} < 0,01 A_0$ )
- pre odpory platí veľké – prúdy zrovnateľné s  $I_{no}$   
malé – prúdy  $< I_{vmax}$



$$u_v = -\frac{R_f}{R_s} \cdot u_s$$

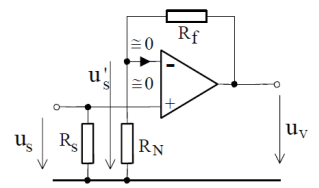
## Operačné zosilňovače Neinvertujúci zosilňovač

$$u'_s = \beta u_v = \left( \frac{R_N}{R_N + R_f} \right) u_v$$

**$\beta$  – činiteľ spätnej väzby**

$$R_{vst} \approx R_{CM} \quad \text{resp.} \quad R_{vst} = \frac{R_D}{1 + \beta A_0}$$

$$R_{vyst} \approx \frac{R_v}{\beta A_0} \quad R_s = \frac{R_f R_N}{R_f + R_N}$$



$$u_v = \left( \frac{R_f}{R_N} + 1 \right) \cdot u_s$$

ak:  $u_s \approx u'_s$

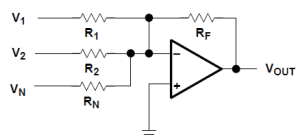
## Operačné zosilňovače Sčítačka

$$u'_s = \beta u_v = \left( \frac{R_N}{R_N + R_f} \right) u_v$$

**$\beta$  – činiteľ spätnej väzby**

$$R_{vst} \approx R_{CM} \quad \text{resp.} \quad R_{vst} = \frac{R_D}{1 + \beta A_0}$$

$$R_{vyst} \approx \frac{R_v}{\beta A_0} \quad R_s = \frac{R_f R_N}{R_f + R_N}$$

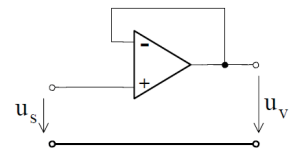


$$V_{OUT} = - \left( \frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_N} V_N \right)$$

## Operačné zosilňovače Napät'ový sledovač

Neinvertujúci zosilňovač s  $A=1$

- **Au je 1**, teda  $u_s = u_v$
- $R_{vst} \approx 10^9 \Omega$ ,  $R_{vyst} \approx 10^{-3} \Omega$  (pre bipolár. vstupy)
- **impedančný prevodník**



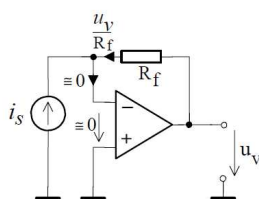
## Operačné zosilňovače Prevodník $I \rightarrow U$

Paralelná sieť z napät'ového výstupu

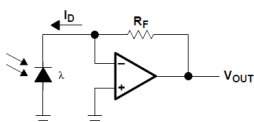
Riešenie:  $u_D \approx 0$ ,  $i_{vst} \approx 0$

$R_{vst} \rightarrow 0$  a  $R_{vyst} \rightarrow 0$  (nulové sú pre ideálny OZ)

$$i_s = \frac{u_v}{R_f}$$



$$u_v = -i_s \cdot R_f$$



## Operačné zosilňovače Aktívny mostík

Časť mostíka tvoria SV obvody zosilňovača

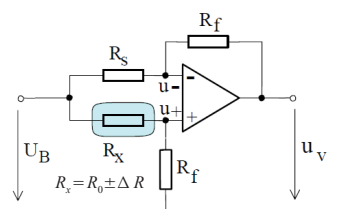
Riešenie:

$$\frac{R_f}{R_s} + 1 \gg \Delta R \Rightarrow u_v \approx -U_B \frac{R_f}{R_s} \frac{\pm \Delta R}{\frac{R_f}{R_s} + 1}$$

- ☉ **menej súčiastok**
- ☉ **linearita**
- ☉  $u_v$  **nezávisí od pomeru  $R_f/R_s$**
- ☉ **ľahšie vyváženie obvodu  $R_s$**

☉ **treba kvalitný OZ s veľkým CMRR,  $A_0$  a malými  $I_{no}$**

a ak zvolíme pomer odporov  $\frac{R_f}{R_s} \gg 1$



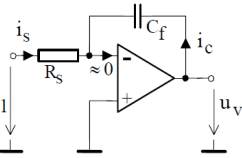
$$u_v \approx -(\pm \Delta R_x) U_B$$

## Operačné zosilňovače Integrátor

Prúd do OZ  $\approx 0 \rightarrow -i_c = i_s$

$$i_s = \frac{u_1}{R_s}; \quad i_c = C_f \frac{du_v}{dt}$$

$$\frac{u_1}{R_s} = -C_f \frac{du_v}{dt}$$



$$u_v = -\frac{1}{R_s C_f} \int u_1 dt$$

Poznámka: Kondenzátor - kvalitné dielektrikum, aby zvodové prúdy neboli na úrovni kľudových prúdov. Nie sú vhodné elektrolyty.

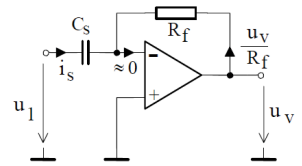
## Operačné zosilňovače Derivátor

Pre vstupný uzol (-) na obr. platí

$$i_s = -\frac{u_v}{R_f}$$

$$C_s \frac{du_1}{dt} + \frac{u_v}{R_f} = 0 \Rightarrow$$

$$u_v = -R_f C_s \frac{du_1}{dt}$$



Poznámka: Kondenzátor - kvalitné dielektrikum, aby zvodové prúdy neboli na úrovni kľudových prúdov. Nie sú vhodné elektrolyty.

## Operačné zosilňovače Analogová pamäť

"Zapamätanie si" analógovej hodnoty (napätia)  
- vzorkovací zosilňovač.

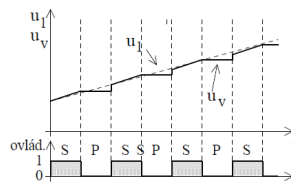
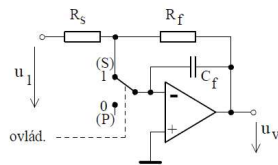
Cf - pamäťový kondenzátor

S - sledovací režim

$$u_v = -u_1 \frac{R_f}{R_s}$$

(s malým oneskorením, spôsobeným Cf)

P - režim pamätania si  
(s malým poklesom - vybíjanie Cf)

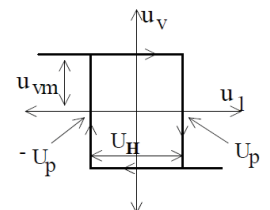
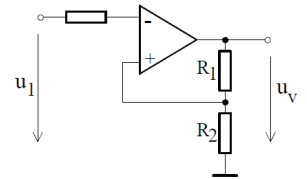


## Operačné zosilňovače Komparátor s hystereziou

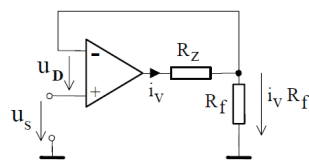
Nedochádza k rozkmitaniu okolo preklápacej úrovne

$$U_P = u_{ref} = u_p = \pm u_{max} \frac{R_2}{R_1 + R_2}$$

$$\Rightarrow U_H = 2|U_P|$$



## Operačné zosilňovače Zdroj konštantného prúdu



$u_D = u_s - i_v R_f \approx 0 \rightarrow$  výst. prúd

$$\Rightarrow i_v = \frac{1}{R_f} u_s$$