Wroclaw University of Science and Technology

Analog to Digital Converters (ADC)

Lecture 7

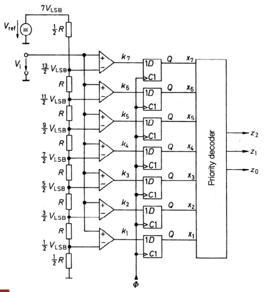
Rferences

- U. Tietze, Ch.Schenk, Electronics Circuits – Handbook for Design and Applications, Springer,2010
- W. Kester, Analog_Digital conversion, Analog Devices Inc. 2012 (http://www.analog.com/library/analogdialogue/archives/39-06/data_conversion_handbook.html)
- Advertisement materials and Application notes of:
  - Linear Technology,
  - Analog Device,
  - Texas Instruments,
  - National Semiconductors
  - NEV Corporation

Types of AD converters

- Direct (voltage comparison)
  - parallel „flash” converter,
  - serial or „pipeline” (2-step, 3-step,….),
  - successive approximation.
- Indirect (voltage – time - counter)
  - tracking converter,
  - compensation converters (singe-,dual-, four-slop converter),
  - oversampling converter (Δ-Σ converters),
  - U/F converters.

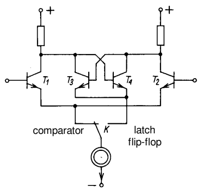
AC - direct, parallel, „flash”



Features:

- sampling frequency (>100MHz to 10GHz),
- low resolution (4,6,8,10 bits),
- high number of comparators – 2^n-1
- high power dissipation,
- technology: bipolar or ECL,

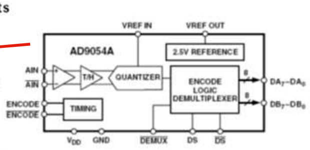
Comparator and storage flip-flop - a simplified example



Example of a „flash” converter AD9054A

FEATURES
200 MSPS Guaranteed Conversion Rate
135 MSPS Low Cost Version Available
350 MHz Analog Bandwidth
1 V p-p Analog Input Range
Internal 2.5 V Reference and T/H
Low Power: 500 mW
5 V Single Supply Operation
TTL Output Interface
Single or Demultiplexed Output Ports

APPLICATIONS
RGB Graphics Processing
High Resolution Video
Digital Data Storage Read Channels
Digital Communications
Digital Instrumentation
Medical Imaging



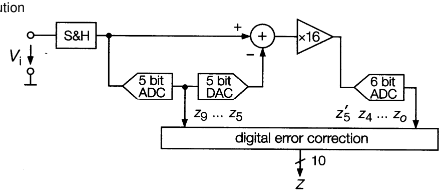
Example of a „flash” converter AD9054A - cont.

Parameter	Temp	Test Level	AD9054ABST-200 Min	AD9054ABST-200 Typ	AD9054ABST-200 Max	AD9054ABST-135 Min	AD9054ABST-135 Typ	AD9054ABST-135 Max	Unit
RESOLUTION				8			8		Bits
DC ACCURACY									
Differential Nonlinearity ←	25°C	I		±0.9	+1.5/−1.0		±0.9	+1.5/−1.0	LSB
	Full	VI		±1.0	+2.0/−1.0		±1.0	+2.0/−1.0	LSB
Integral Nonlinearity ←	25°C	I		±0.6	±1.5		±0.6	±1.5	LSB
	Full	VI		±0.9	±2.0		±0.9	±2.0	LSB
No Missing Codes ←	Full	VI		Guaranteed			Guaranteed		
Gain Error[1]	25°C	I		±2	±7		±2	±7	% FS
Gain Tempco[1]	Full	V		160			160		ppm/°C

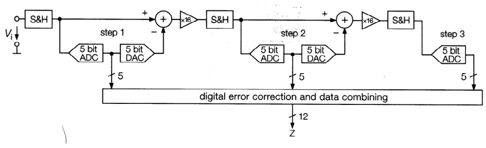
2-step converter
(direct, serial, pipeline)

Features (compared to „flash”):

- lower number comparators
- higher conversion time
- more popular (cheaper)
- higher resolution



3-step converter (direct, serial, pipeline)



Example of a pipeline converter ADS5221

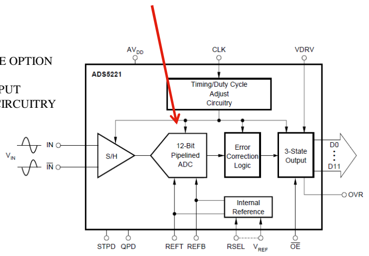
12-Bit, 65MSPS Sampling, +3.3V

FEATURES

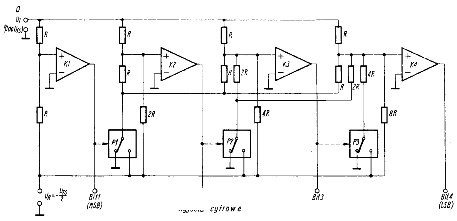
HIGH SNR: 70dB
HIGH SFDR: 88dBFS
LOW POWER: 285mW
INTERNAL/EXTERNAL REFERENCE OPTION
SINGLE-ENDED OR
FULLY DIFFERENTIAL ANALOG INPUT
FLEXIBLE DUTY CYCLE ADJUST CIRCUITRY
LOW DNL: 0.5LSB
SINGLE +3.3V SUPPLY OPERATION
TQFP-48

APPLICATIONS

WIRELESS LOCAL LOOP
COMMUNICATIONS
MEDICAL IMAGING
PORTABLE INSTRUMENTATION



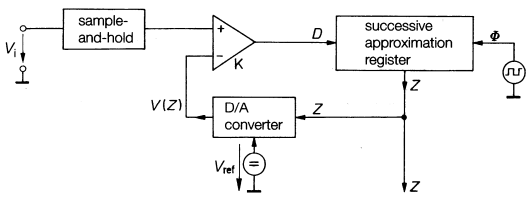
n-step converter (direct, serial, pipeline)



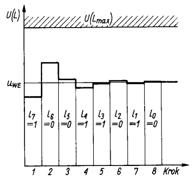
Features:

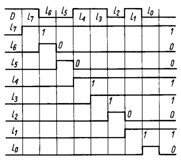
•Number of comparators = number of bits
•higher (compared to „flash") conversion time
•less popular

Successive approximation AD converters (direct)



Successive approximation AD converters - principle of operation





Example of successive approximation converter - AD7854

FEATURES
Specified for V_{DD} of 3 V to 5.5 V
Read-Only Operation
AD7854–200 kSPS; AD7854L–100 kSPS
System and Self-Calibration
Low Power
Normal Operation
AD7854: 15 mW (V_{DD} = 3 V)
AD7854L: 5.5 mW (V_{DD} = 3 V)
Automatic Power-Down After Conversion (25 μW)
AD7854: 1.3 mW 10 kSPS
AD7854L: 650 μW 10 kSPS
Flexible Parallel Interface
12-Bit Parallel/8-Bit Parallel (AD7854)
28-Lead DIP, SOIC and SSOP Packages (AD7854)

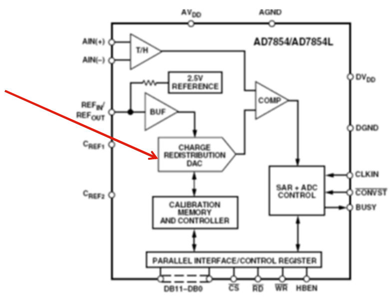
APPLICATIONS
Battery-Powered Systems (Personal Digital Assistants, Medical Instruments, Mobile Communications)
Pen Computers
Instrumentation and Control Systems
High Speed Modems

Compare with „flash"

FEATURES
200 MSPS Guaranteed Conversion Rate
135 MSPS Low Cost Version Available
350 MHz Analog Bandwidth
1 V p-p Analog Input Range
Internal 2.5 V Reference and T/H
Low Power: 500 mW
5 V Single Supply Operation
TTL Output Interface
Single or Demultiplexed Output Ports

APPLICATIONS
RGB Graphics Processing
High Resolution Video
Digital Data Storage Read Channels
Digital Communications
Digital Instrumentation
Medical Imaging

Example of successive approximation AD converter - AD7854 (cont.)

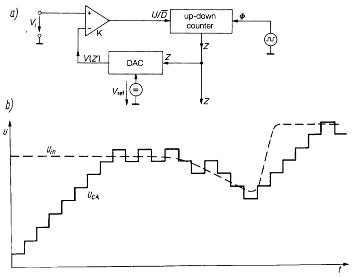


Tracking converter

(counting method conversion; „delta modulator”)

Features:

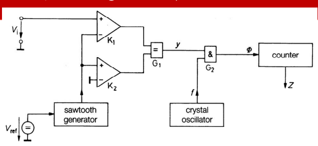
- one comparator
- high conversion time
- less popular

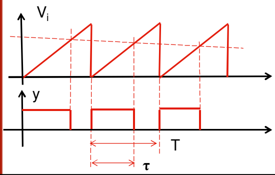


Compensation converter – single slop converter

(indirect, counting method)

$$N = 2^n \frac{\tau}{T} = 2^n \frac{u_{in}}{U_{REF}}$$

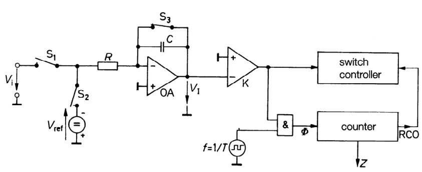




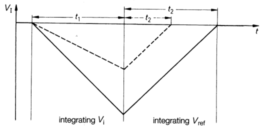
Features:
result depend on:

- comparator offset
- linearity of saw-tooth gen.
- clock (crystal)

Compensation converter (indirect) - dual slop converter



Compensation converter (indirect) - dual slop converter (cont.)

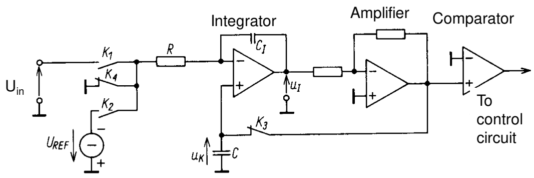


Advantages:

- result does not depend on:
  - linearity of the integrator,
  - time constant,
  - clock frequency,
  - comparator offset,
  - some noise is suppressed.

$$U_{in} = \frac{t_2}{t_1} U_{REF}$$

Auto-zero conversion (auto zero amplifier)



1. For K4 and K3 on, the capacitor C is charged to a voltage U_k equal to the integrator offset.
2. When K4 and K3 off the voltage U_k cancels the integrator offset.

Dual slope with auto-zero example ICL7106/7107

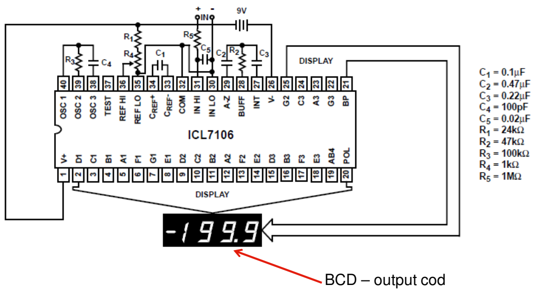
Features

- Guaranteed Zero Reading for 0V Input on All Scales
- True Polarity at Zero for Precise Null Detection
- 1pA Typical Input Current
- True Differential Input and Reference, Direct Display Drive
  - LCD ICL7106, LED ICL7107
- Low Noise - Less Than $15\mu V_{P-P}$
- On Chip Clock and Reference
- Low Power Dissipation - Typically Less Than 10mW
- No Additional Active Circuits Required
- Enhanced Display Stability
- Pb-Free Plus Anneal Available (RoHS Compliant)

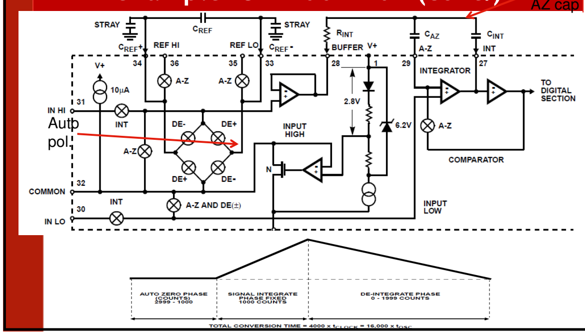
Dual slope with auto-zero example ICL7106/7107 (cont.)

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
SYSTEM PERFORMANCE					
Zero Input Reading	V_{IN} = 0.0V, Full Scale = 200mV	-000.0	±000.0	+000.0	Digital Reading
Stability (Last Digit) (ICL7106S, ICL7107S Only)	Fixed Input Voltage (Note 6)	-000.0	±000.0	+000.0	Digital Reading
Ratiometric Reading	V_{IN} = V_{REF}, V_{REF} = 100mV	999	999/1000	1000	Digital Reading
Rollover Error	$-V_{IN}$ = $+V_{IN}$ ≅ 200mV Difference in Reading for Equal Positive and Negative Inputs Near Full Scale	-	±0.2	±1	Counts
Linearity	Full Scale = 200mV or Full Scale = 2V Maximum Deviation from Best Straight Line Fit (Note 5)	-	±0.2	±1	Counts
Common Mode Rejection Ratio	V_{CM} = 1V, V_{IN} = 0V, Full Scale = 200mV (Note 5)	-	50	-	μV/V
Noise	V_{IN} = 0V, Full Scale = 200mV (Peak-To-Peak Value Not Exceeded 95% of Time)	-	15	-	μV
Leakage Current Input	V_{IN} = 0 (Note 5)	-	1	10	pA
Zero Reading Drift	V_{IN} = 0, 0°C To 70°C (Note 5)	-	0.2	1	μV/°C
Scale Factor Temperature Coefficient	V_{IN} = 199mV, 0°C To 70°C, (Ext. Ref. 0ppm/×°C) (Note 5)	-	1	5	ppm/°C
End Power Supply Character V+ Supply Current	V_{IN} = 0 (Does Not Include LED Current for ICL7107)	-	1.0	1.8	mA
End Power Supply Character V- Supply Current	ICL7107 Only	-	0.6	1.8	mA
COMMON Pin Analog Common Voltage	25kΩ Between Common and Positive Supply (With Respect to + Supply)	2.4	3.0	3.2	V
Temperature Coefficient of Analog Common	25kΩ Between Common and Positive Supply (With Respect to + Supply)	-	80	-	ppm/°C

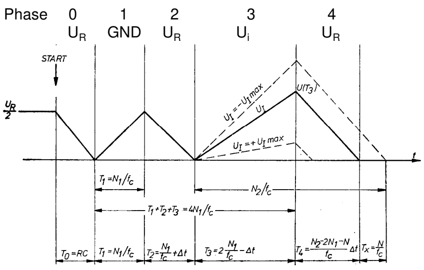
Dual slope with auto-zero example ICL7106/7107 (cont.)



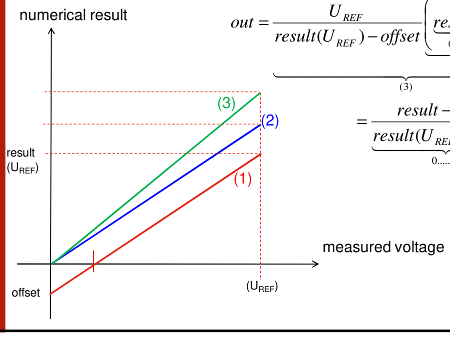
Dual slope with auto-zero example ICL7106/7107 (cont.)



Indirect converter ---four - slope



Four slope converter - „principle" of correction



$$out = \underbrace{\frac{U_{REF}}{result(U_{REF}) - offset}\underbrace{\left(\underbrace{result - offset}_{(1)}\right)}_{(2)}}_{(3)} =$$

$$= \underbrace{\frac{result - offset}{result(U_{REF}) - offset}}_{0.......1} U_{REF}$$

Indirect, integrating converters - dual and four slope

- Result is independent on:
  - time constant of the integrator
  - integrator nonlinearity,
  - comparator offset (integrate and de-intergrate phase)
  - clock frequency (result = ratio of pulse number)
  - high frequency noise (averaging effect)
  - gain error
  - temperature drifts

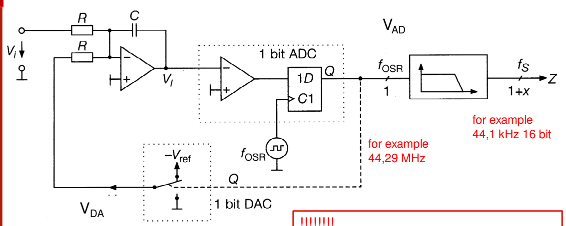
dual slope: time constant of the integrator, integrator nonlinearity, comparator offset, clock frequency, high frequency noise

four slope: all of the above, plus gain error and temperature drifts

Types of AD converters

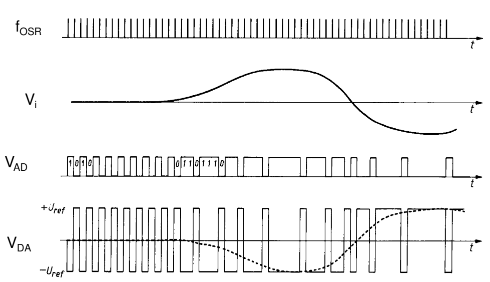
- Direct (voltage comparison)
  - parallel „flash” converter,
  - serial or „pipeline” (2-step, 3-step,….),
  - successive approximation.
- Indirect (voltage – time - counter)
  - tracking converter,
  - compensation converters (singe-,dual-, four-slop converter),
  - oversampling converter (Σ-Δ converters),
  - U/F converters.

„Σ-Δ” converter oversampling converter

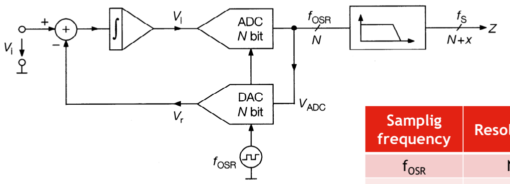


!!!!!!!
Sampling frequency f_{OSR} is much greater than reading frequency f_S

„Σ-Δ” converter - principle of operation

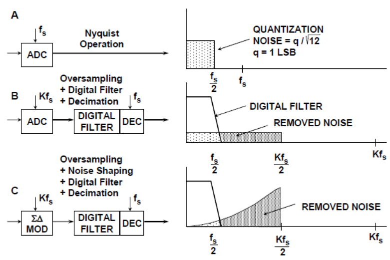


Oversampling „Σ-Δ” converter - general principle

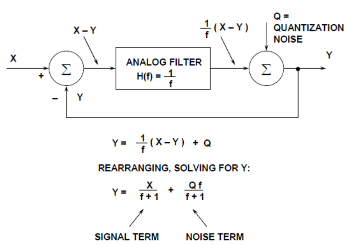


Samplig frequency	Resolution
f_{OSR}	N
$f_S << f_{OSR}$	N+x

Noise shaping in „Σ-Δ” converter



„Σ-Δ” converter - linear model



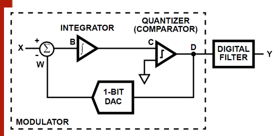
Conventional converter

$$U_{Nout} \propto \frac{1}{\sqrt{f_{OS}/f_S}}$$

$$N_{bits} = \frac{20\log\sqrt{f_{OS}/f_S}}{6dB/bit}$$

f_{OS}/f_S	bit
2	0.5
4	1
256	4

First order „Δ-Σ” converter

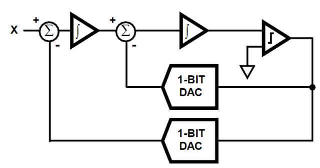


$$U_{Nout} \propto \left(\frac{1}{\sqrt{f_{OS}/f_S}}\right)^3$$

$$N_{bits} = \frac{20\log\left(\sqrt{f_{OS}/f_S}\right)^3}{6dB/bit}$$

f_{OS}/f_S	bit
2	1.5
4	3
256	12

3dr order „Δ-Σ” converter

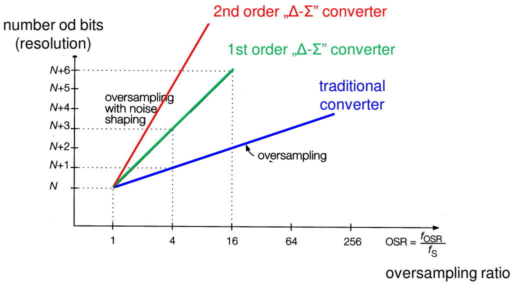


$$U_{Nout} \propto \left(\frac{1}{\sqrt{f_{OS}/f_S}}\right)^5$$

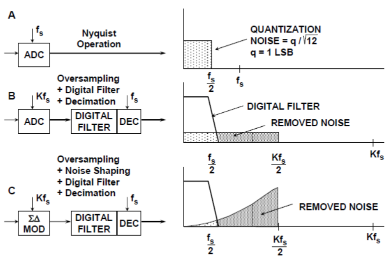
$$N_{bits} = \frac{20\log\left(\sqrt{f_{OS}/f_S}\right)^5}{6dB/bit}$$

f_{OS}/f_S	bit
2	2.5
4	5
256	20

Oversampling



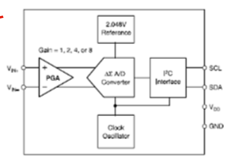
Noise shaping in „Δ-Σ” converter

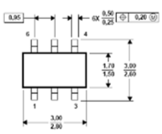


Example of „Δ-Σ” converter ADS1110

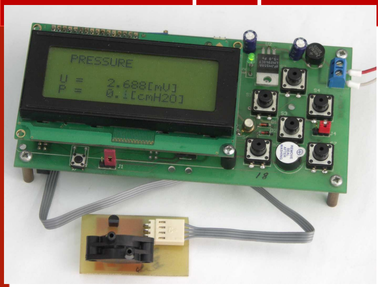
FEATURES

- COMPLETE DATA ACQUISITION SYSTEM IN A TINY SOT23-6 PACKAGE
- ONBOARD REFERENCE:
  Accuracy: 2.048V ±0.05%
  Drift: 5ppm/°C
- ONBOARD PGA
- ONBOARD OSCILLATOR
- 16-BITS NO MISSING CODES
- INL: 0.01% of FSR max
- CONTINUOUS SELF-CALIBRATION
- SINGLE-CYCLE CONVERSION
- PROGRAMMABLE DATA RATE: 15SPS TO 240SPS
- I²C™INTERFACE—EIGHT AVAILABLE ADDRESSES
- POWER SUPPLY: 2.7V to 5.5V
- LOW CURRENT CONSUMPTION: 240μA

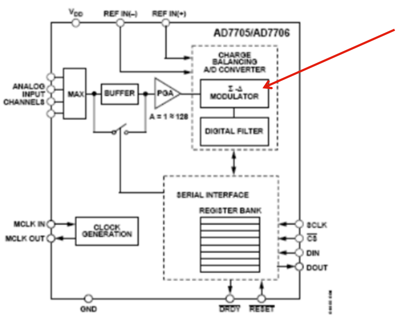




Lab setup of pressure sensor



Example of „Δ-Σ” converter AD7705/7706



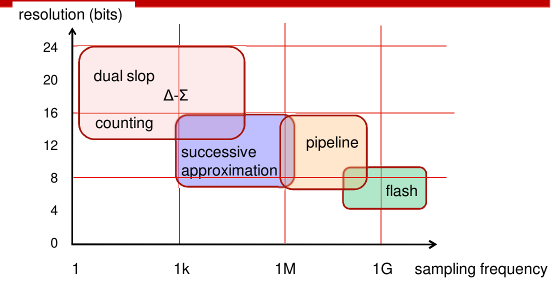
„Δ-Σ” summary

- Inherently Excellent Linearity
- High Resolution Possible (24-Bits)
- Oversampling Relaxes Analog Antialiasing Filter Requirements
- Ideal for CMOS Processes, no Trimming
- No SHA Required
- Added Functionality: On-Chip PGAs, Analog Filters, Autocalibration
- On-Chip Programmable Digital Filters (AD7725: Lowpass, Highpass, Bandpass, Bandstop)
- Upper Sampling Rate Currently Limits Applications to Measurement, Voiceband, and Audio, except for Bandpass Sigma-Delta ADCs
- Analog Multiplexer Switching Speed Limited by Internal Filter Settling Time.

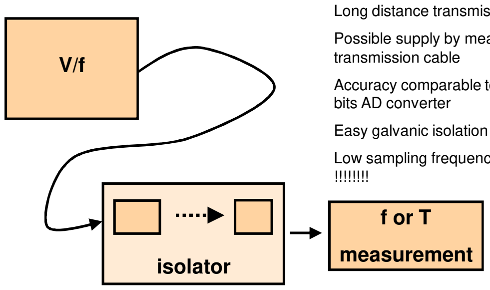
Example of „Δ-Σ” converter AD7705/7706 (cont.)

Parameter	B Version[1]	Unit	Conditions/Comments
STATIC PERFORMANCE			
No Missing Codes	16	Bits min	Guaranteed by design, filter notch < 60 Hz
Output Noise	See Table 5 and Table 7		Depends on filter cutoffs and selected gain
Integral Nonlinearity[2]	±0.003	% of FSR max	Filter notch < 60 Hz, typically ±0.0003%
Unipolar Offset Error[3]			
Unipolar Offset Drift[4]	0.5	μV/°C typ	
Bipolar Zero Error[3]			
Bipolar Zero Drift[4]	0.5	μV/°C typ	For gains 1, 2, and 4
	0.1	μV/°C typ	For gains 8, 16, 32, 64, and 128
Positive Full-Scale Error[3, 5]			
Full-Scale Drift[4, 6]	0.5	μV/°C typ	
Gain Error[3, 7]			
Gain Drift[4, 8]	0.5	ppm of FSR/°C typ	
Bipolar Negative Full-Scale Error[2]	±0.003	% of FSR typ	Typically ±0.001%
Bipolar Negative Full-Scale Drift[4]	1	μV/°C typ	For gains of 1 to 4
	0.6	μV/°C typ	For gains of 8 to 128

General comparison of AD converters



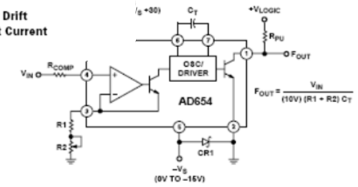
Voltage-frequency transducers -features



- Long distance transmission
- Possible supply by means of transmission cable
- Accuracy comparable to 14 bits AD converter
- Easy galvanic isolation
- Low sampling frequency !!!!!!!!

Voltage-frequency transducers AD654

FEATURES
Low Cost
Single or Dual Supply, 5 V to 36 V, ±5 V to ±18 V
Full-Scale Frequency Up to 500 kHz
Minimum Number of External Components Needed
Versatile Input Amplifier
  Positive or Negative Voltage Modes
  Negative Current Mode
  High Input Impedance, Low Drift
Low Power: 2.0 mA Quiescent Current
Low Offset: 1 mV

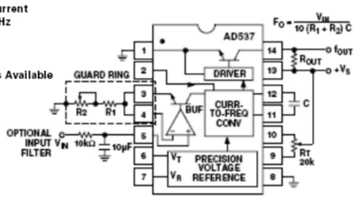


Voltage-frequency transducers AD654 (cont.)

Model	AD654JN/JR Min	Typ	Max	Units
CURRENT-TO-FREQUENCY CONVERTER				
Frequency Range	0		500	kHz
Nonlinearity[1]				
f_{MAX} = 250 kHz		0.06	0.1	%
f_{MAX} = 500 kHz		0.20	0.4	%
Full-Scale Calibration Error				
C = 390 pF, I_{IN} = 1.000 mA	–10		+10	%
vs. Supply (f_{MAX} ≤ 250 kHz)				
V_S = +4.75 V to +5.25 V		0.20	0.40	%/V
V_S = +5.25 V to +16.5 V		0.05	0.10	%/V
vs. Temp (0°C to +70°C)		50		ppm/°C
ANALOG INPUT AMPLIFIER				
(Voltage-to-Current Converter)				
Voltage Input Range				
Single Supply	0		$(+V_S - 4)$	V
Dual Supply	$-V_S$		$(+V_S - 4)$	V
Input Bias Current				
(Either Input)		30	50	nA
Input Offset Current		5		nA
Input Resistance (Noninverting)		250		MΩ
Input Offset Voltage		0.5	1.0	mV
vs. Supply				
V_S = +4.75 V to +5.25 V		0.1	0.25	mV/V
V_S = +5.25 V to +16.5 V		0.03	0.1	mV/V
vs. Temp (0°C to +70°C)		4		μV/°C

Voltage-frequency transducers AD537

FEATURES
Low Cost A–D Conversion
Versatile Input Amplifier
  Positive or Negative Voltage Modes
  Negative Current Mode
  High Input Impedance, Low Drift
Single Supply, 5 V to 36 V
Linearity: ±0.05% FS
Low Power: 1.2 mA Quiescent Current
Full-Scale Frequency up to 100 kHz
1.00 V Reference
Thermometer Output (1 mV/K)
F-V Applications
MIL-STD-883 Compliant Versions Available



Przetworniki U/f
AD537

Model	AD537JH	AD537JD	AD537KD AD537KH
CURRENT-TO-FREQUENCY CONVERTER			
Frequency Range	0 kHz to 150 kHz	*	*
Nonlinearity[1]			
f_{MAX} = 10 kHz	0.15% max (0.1% typ)	*	0.07% max
f_{MAX} = 100 kHz	0.25% max (0.15% typ)	*	0.1% max
Full-Scale Calibration Error			
C = 0.01 µF, I_{IN} = 1.000 mA	±10% max	±7% max	±5% max
vs. Supply (f_{MAX} < 100 kHz)	±0.1%/V max (0.01% typ)	*	*
vs. Temp (T_{MIN} to T_{MAX})	±150 ppm/°C max (50 ppm typ)	*	50 ppm/°C max (30 ppm typ)[2]
ANALOG INPUT AMPLIFIER			
(Voltage-to-Current Converter)			
Voltage Input Range			
Single Supply	0 to ($+V_S$ – 4) Volts (min)	*	*
Dual Supply	$-V_S$ to ($+V_S$ – 4) Volts (min)	*	*
Input Bias Current			
(Either Input)	100 nA	*	*
Input Resistance (Noninverting)	250 MΩ	*	*
Input Offset Voltage			
(Trimmable in "D" Package Only)	5 mV max	*	2 mV max
vs. Supply	200 µV/V max	100 µV/V max	100 µV/V max
vs. Temp (T_{MIN} to T_{MAX})	5 µV/°C	*	1 µV/°C
Safe Input Voltage[3]	$\pm V_S$	*	*

Summary of AD converters

- Direct (voltage comparison)
  - parallel „flash" converter,
  - serial or „pipeline" (2-step, ...),
  - successive approximation.
- Indirect (voltage – time - counter)
  - tracking converter,
  - compensation converters (singe-,dual-, four-slop converter),
  - oversampling converter (Δ-Σ converters),
  - U/F converters.
- AD converters comparison

Summary of AD converters (cont).

Parameters of ADC:

- resolution,
- offset,
- scale error,
- integrated nonlinearity,
- differential nonlinearity,
- sampling rate,

From previous lecture: "DA converters"

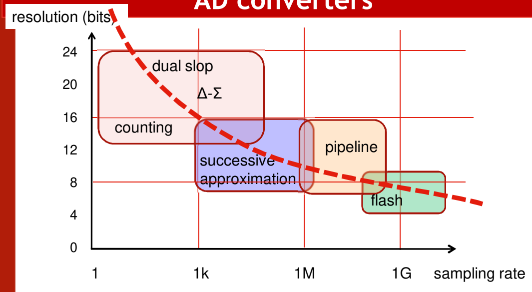
Flow rate sampling frequency vs. resolution

$$FR[bits/s] \approx \underbrace{\frac{SNR[dB]\cdot B[Hz]}{3}}_{\text{flow rate of a channel}} \approx \frac{6n\cdot {f_S}/{2}}{3} = n\cdot f_S$$

high resolution – low sampling rate
high sampling rate – low resolution

!!!!!!!!!!!!!!!!!

General comparison of AD converters



References

1. W. Tietze, Ch. Schenk, „*Electronic circuits. Handbook for Design and Applications*", Springer 2002.
2. P. Horowitz, H. Hill, „*The Art of Electronics*", Cambridge Univ. Press 1989.
3. Application notes:
   - Analog Device Inc.,
   - Texas Instrument Inc.

Test questions:

- Name types of AD converters, describe the typical speed and resolution.
- What is the principle of oversampling ?