Sensor Principles

Integrated Interface Circuits •Errors and Noise Jens Anders Institute for Theory of Electrical Engineering Department of Electrical Engineering and Computer Science University of Stuttgart
Integrated Interface Circuits •Introduction Jens Anders Institute of Smart Sensors Department of Engineering , Computer Science University of Stuttgart
? Lectures: •Mondays: 11:30 AM until 1 PM ? Seminar at the end of the lecture period/beginning of the lecture free period ? Participation in the seminar is mandatory for taking the exam ? The exam will be a written exam
? Introduction/Motivation •Why/where do we need sensors? •What are the challenges/problems in reading out the sensors? ? Noise and other sources of error ? Categorizing different types of sensor •Self-generating vs. modulating sensors •Electrical behavior ? Readout Concepts •Absolute vs. differential measurements •AM vs. FM detection •Resonant readouts •Phase sensitive-detection (Lock-in amplifiers) •Continuous-time vs. discrete time readout
? Readout Concepts (cont.) •Open-loop vs. Closed loop measurements ? Readout Circuit Implementations •Instrumentation amplifiers •Transimpedance amplifiers •Switched-capacitor readout circuits ? Data-converters for sensor readouts •A/D converters •D/A converters •T/D converters (if time permits)
? Medical applications (1/2): MRI, Ultrasound www.medical.siemens.com
http://www.magnet.fsu.edu/
www.sciencephoto.com
http://www.healthcare.philips.com
http://www.nibib.nih.gov/
http://www.gehealthcare.com/
? Medical applications (2/2): CT, PET/CT
http://www.toshiba-medical.eu/
http://www.healthcare.philips.com
http://www.cyberphysics.co.uk/
http://neuros.net/
http://www.uib.no http://www.siemens.com/
? Automotive applications
http://www.toyota.co.uk/
http://auto.howstuffworks.com
http://newsimages.motoring.co.uk/
http://www.eetimes.com/
http://i.telegraph.co.uk/
? Consumer electronics
http://www.arj.no/2007/01/14/iphone-sensing/
http://www.kinectingforwindows.com/
http://pertemi.wordpress.com/
http://www.touchuserinterface.com/
? Applications in Science/Metrology
http://www.bruker.com
http://simple.wikipedia.org
Source: Prof. Keller, Uni Graz
Array of Photodiodes Pixel A/D converter
? Sensors sense their environment ? Sensors can produce electrical or non-electrical signals transduction might be required ? Interface electronics typically, amplify, frequency convert, filter and A/D convert the sensed signal
REVIEW OPAMP BASICS
? Maximum input voltage in open loop configuration:
A ? 105, VDD ? ?VSS ? 10 V,V
? 18 V ==¿ V ? V
/ A ? 90 ?V
0 out,range in,max out,range 0 ? Opamps should be used in closed loop configuration ? Tradeoff between open loop gain and accuracy ? When using the opamp in feedback, stability becomes a concern! ? Stability criterion: Simplified Nyquist criterion (negative feedback) loop gain: ?? = ?? ? ????
phase margin: ??
= 1 ? PM = 180•+ ?
gain margin: ?
= ?180•? GM = 20 ? log10
? Assuming ???? ? ?
Vx ?
? ?Vout
? ? ? A ?? ? ? ?Vin
?Vx ? ?
? ? A ?? ? ? ?Vin
? ? ?Vout ?
?
? Very basic feedback theory •Ao(?) is the forward gain (open loop gain) •? is the feedback gain •?•Ao(?) is the loop gain •1 + ?? ? ????: feedback factor •Closed-loop TF:
Ao(?) Vin Vout
? There is a tradeoff between open loop gain and DC accuracy. ? Tradeoff of gain vs. bandwidth. ? Tradeoff of input and output resistance. (depending on the type of feedback) Buffer example of DC tradeoff: Open loop response Closed loop response (?? = 1) ? Placing the first non-dominant pole before or not to close behind the GBW results in peaking in the amplitude response of the closed loop system
? In the time-domain, placing the non dominant pole below or not sufficiently far beyond the GBW manifests itself as ringing in the step response ? Note: Depending on the application, the frequency and/or time-domain behavior is more important
Loop gain ?? ? ???? Closed loop gain ????/(1 + ?? ? ????) ? The worst case in terms of stability occurs for ?? = 1 because (assuming a passive feedback network) this choice maximizes the loop gain
? Assuming a finite value for ??out and a very large open loop gain ??0
? How is this condition ensured in the circuit? The opamp in the negative feedback loop adjusts ??out appropriately ? The potential at the opamp•s noninverting input is virtually copied to the inverting terminal (virtual short) ? Due to the virtual short between the inverting and noninverting opamp inputs, we have:
? The fact that typical opamps have large differential input impedances further attenuate the opamp•s input current
? Apply KCL to node X
? Feedback factor:
T ?? ?
? Vx? ? Vx
R1 ? A ?? ?
? Closed loop TF: ? ? •Either apply KCL at node X or use the finding of slide 16
? If negative feedback is applied around an opamp, the following rules apply:
? Important: The rules only apply if the opamp operates linearly (e.g. no clipping or oscillation at its output)
? Note: The opamp is used in positive feedback here (the output is fed back to the noninverting input) ? What do we know? ???? ? ? ? ?????? ? 0 for finite ???? ?
? Assume that initially ???? is positive and not too large (i.e. ?? VDD) and that the output is at zero volts
? ???? ¡
??out = ?? ? ???? ? ??out becomes positive as well the constraint ??in = ??FB enforces that ???? further increases ??out and ???? increase together until the opamp rails
? Virtual short (???? = ??out) and KCL at nodes X and Y
0 ? Vin
?Vx
? ?V
?V ? ? sC
? ?Vout
?Vx ?
? R out x 1 R 1 2
0 ? Vout
?Vx ? V
? sC
out 2 2
? Calculate the input impedance of the circuit above!
Zin
? vin i
in ? Hint: Assume an ideal opamp and a voltage drive
? Voltage at node 1: ????1 in ? Ideal opamp enforces virtual short: ??X3
= ??X1
= ??in
? Ideal opamp: Current through ??1 also flows through ??2:
??X2
= ??x3 ? ??1
= ??in ? ?? 1
? Ideal opamp: Current through ??conv is ??in
: ??in
= (??in???x2) ??conv
? The circuit should not be used with a current drive ? Voltage drive negative feedback ? Current drive positive feedback ? Intuitive explanation: For current drive there is unity gain feedback to the noninverting input and less than unity gain feedback to the inverting
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? Limit of detection (LOD) definition: The minimum level of the input quantity which can reproducibly be measured at a specified SNR (typically: ????NR = ???? ????B) ? Practical signals are specified by their dynamic range (DR): DR is the ratio between the maximum and minimum signal levels occurring within inaccuracy levels
? Two different types of error: •Deterministic errors e.g. source loading, offset, gain error •Random (stochastic) errors e.g. thermal noise, 1/f noise ? Errors can be quantified as absolute errors and relative errors
Absolute error: ??? =
???
? ??0
Relative error: =
where ??0 is the true value and
???
is the measured quantity/the estimate
? The maximum inaccuracy ???max should be specified such that the true value lies within the interval [??? ? ???max, ??? + ???max]
? Assumption: The output quantity ?? is affected by the ?? parameters ??????=1..?? according to y ? f ?x1, x2,•, xN ?
? Then, assuming small deterministic fluctuations in the ?????? the total error in ?? is given by
?y ?
? i ?1
?f ? ?x ?xi
? Consequently, if we denote by ???????,max the (small) maximum inaccuracy of each ?????? , then ??? is bounded by
?ymax
? ? i ?1
?f ?xi
? ?x
i ,max
? The partial derivative ???????? ?????????? is called sensitivity w.r.t. ??????
? If the quantity to be measured depends on the 3 parameters ??in, ??error,1 and ??error,2 according to
y ? G ? xin
? k1 ? xerror,1 ? k2 ? xerror,2
and the uncertainties in ??in, ??error,1 and ??error,2 are 0 (??in is the perfectly known input signal), ???error,1 and ???error,2, the uncertainty in y becomes
?y ?
? ?G ? xin
? k1 ? xerror,1 ? k2 ? xerror,2 ? ? ?x ?x
error,1 ?
? ?G ? xin
? k1 ? xerror,1 ? k2 ? xerror,2 ? ? ?x ?x
error,2
error,1 error,2 ? k1 ? ?xerror,1 ? k2 ? ?xerror,2 ? Typical sources of additive errors are: •Offset •Additive noise (cave: here rms values need to be considered) ? The uncertainty in the measurand due to additive errors is best specified as an absolute error
? Assume that the output ??(??) depends on the input Xin and the error source ??error according to Y ?? ? ? H ??, xerrror ? ? Xin ?? ? ? Then, the relative error in ??(??) becomes:
?Y ?? ?
? 1 ? ? ??H ??, xerror ? ? Xin ?? ??? ? ?x
Y ?? ?
Y ?? ?
?xerror
error
? Xin ?? ? ? ?H ??, xerror ? ? ?x
H ??, x ? ? X ?? ? ?x
error
error in error ? 1 ? ?H ??, xerror ? ? ?x
H ??, x ? ?x
error
error error
which is independent of Xin ? Therefore, the effect of multiplicative errors is best described as a relative error in the output signal
? Interference: •Interference is caused by an undesired coupling of external signals into the measurement setup •Example: 50 Hz hum ? Noise: •Noise is caused by random fluctuations originating in the measurement setup itself •Example: thermal noise ? Both noise and interference can usually be modeled as additive error signals they can be modeled by additional error sources in the system ? Cave: noise and interference should not be confused with signal distortion, which is caused by intrinsic system nonlinearities in either the amplitude or the frequency domain
Signal @ 1 kHz
? Total signal: ??
= 0.1 ? cos
+ 2 ? cos
+ ??(??)
? ??
has a varia nce of ???? = 0.01
? The signal is barely visible in the time domain, but easy to see in the frequency domain
? Errors are introduced at multiple points along the signal processing chain

? Examples of such error sources are offset, distortion, noise, crosstalk, cross sensitivity, gain error •? Question: What is the best way to assess their combined effect on the measured signal?
? General idea: We can only compare the effect of two different error sources when they are referred to the same point along the signal processing chain ? Two natural choices for the comparison points are the overall input and the overall output (input allows for an intuitive comparison with the measurand)
? For linear(ized) systems the superposition principle applies: Refer all error sources to the output and then refer them to the input by dividing by the overall signal gain ? Deterministic sources of error:
? Random uncorrelated sources of error:
? Output referred error: The effect of an error source on the overall output is called the output referred error ? Input referred error: The equivalent effect of an error source on the overall input is called the (equivalent) input referred error
? Example for finding the equivalent input and output referred noise: Error source: ????2 Find TF from ????2 to the output ??: ????,??2 ? ??out,??2 = ????,??2 ? ????2 Refer the result back to the input using the overall TF ????,??: ????2
= ??out,??2 ????,??
= ????,??2
? ????2 ????,??
? Fluctuations of a physical quantity can be mathematically modeled as a random or stochastic process ? A random process (r.p.) can be seen as a family of functions ?? where ??(?? = ??0) is a random variable with 1st-order probability density function (pdf) ????(??, ??)
? The instantaneous amplitude of the signal ?? only be predicted with probability ????(??, ??0) at time ??0 can therefore
? The mean or expected value ????(??) is obtained by averaging the amplitude ?? at time ?? over all possible realizations of ??(??) ?
mx (t) ? E ?x(t)?
? x ? px (x,t)dx ??
? The autocorrelation function (ACF) is a measure of the statistical
dependence between the random variables ?? epochs
and ??(??2) at two different
Rx (t1,t2) ? E[x(t1)x(t2)]
? ? ? ? ?? ??
x1 ? x2
? px (x1, x2,t1,t2)dx1dx2
where ????(??1, ??2, ??1, ??2) is the 2nd-order pdf of ??(??) ? The autocovariance is defined by
Cx (t1,t2) ? E ???x(t1) ? mx (t1)??x(t2) ? mx (t2)???
Rx (t1,t2) ? mx (t1) ? mx (t2)
? A random process is called wide sense stationary (WSS) if its mean is independent of ?? and its ACF only depends on the time difference ?? = ??2 ? ??1
mx (t) ? mx
? const.
Rx (t1,t2) ? Rx (t2 ? t1) ? Rx (?)
C (t ,t
) ? C (t ? t) ? C
(?) ? R (?) ? m2
x 1 2
x 2 1
x x x
? The normalized ACF (aka correlation coefficient) is defined as
? (?) ? Cx (?) , where ? 2 ? C
(? ? 0) is the so-called variance
x 2 x x x ? For real random processes one can show that:
Rx (?) ? Rx (??), Cx (?) ? Cx (??) C (0) ? ? 2, R (0) ? ? 2 ? m2, ? (0)=1 x x x x x x
? The Power Spectral Density (PSD) of a WSS r.p. x(t) is the Fourier transform of its ACF
Sx (f) ? F ?Rx
(?)? ?
? ? Rx ?? ?
(?) ? e? j 2?f? d?
R (?) ? F ?1?S
(f)? ?
? Sx ??
(f) ? e? j 2?f? df
? PSD has units of [V2] if ??(??) is a voltage and [A2]
if ??(??) is a current
Hz Hz ? The above definition defines the so-called double-sided PSD ? Most instruments display the so-called single-sided PSD which is related to the double-sided PSD according to
S? (f) ?
?2Sx (f) for f ? 0 ?
?Sx (f) for f ? 0
? The total power associated with the r.p. is given by ?
Px ?
? Sx (f) ? df ??
? Rx (0)
? Note: By definition the rms value is the square root of ???? ? For a noise voltage PSD ?
?
2 n,rms
? S (f) ? df ? n ?? 0
? (f) ? df n
? For a noise current PSD
? ?
2 n,rms
? S (f) ? df n ??
? S? (f) ? df n 0
Rx (?) x(t) Sx (f)
Impulse response ?(??)
Transfer function ??(??)
Rx (?) x(t) Sx (f)
? Assuming that the input ?? WSS with ACF
is WSS then the output ??(??) will also be ?
Ry (?) ? Rx (?) ? ?h (?) ? ? ?? ?
Rx (?
? t) ? ?h (?)dt
? (t) ? h(t) ? h?(?t) ?
? h(t ??
? t?) ? h?(t?)dt?
? The PSD Sy(f) is given by the Wiener-Khintchine theorem
Three main sources of noise ? Thermal noise •Due to thermal excitation of charge carriers •Appears as white spectral density ? Shot noise •Due to carriers randomly crossing a barrier •Dependent on DC bias current and is white ? Flicker noise •Due to traps in semiconductors •Has a 1/f spectral density •Significant in MOS transistors at low frequencies
? EPT: Every closed physical system at temperature T contains an average energy of kT/2 per degree of freedom ? Consider a gas of electrons having a Maxwellian velocity distribution ? mv 2 p(v) ? ? e 2kT
where ?? ?? ? d?? represents the probability of finding one electron in the velocity interval [??, ?? + d??] ? The average energy of the electron at equilibrium is given by
m m ? kT
W ? m
? ? v 2 ? ? ?v 2 ? p(v) ? dv ?
2 2 0 2
? In 3 dimensions, we have ? 2 2 2 2 v ? vx ? vy ? vz ==¿
? 2 ? 2 2 3
v ? v
? 3 ? vx
==¿ W ? m ? 2
? kT 2
A : cross section n : electron density J : current density
U ? R ? I
? R ? A ? J
? R ? A ? n ? q ? v
v ? 1 N
? i ?1
vi , with: N
? n ? A ? L
? The voltage ?? is then given by:
U ? q ? R
? ?v
? ?u , where: u
? q ? R ? v
i i i i i i
? If no current flows, then ¡ ?? ¿ = 0, ¡ ?? ¿ = 0 and ¡ ?? ¿ = 0. ? The variances on the other hand will be nonzero
v 2 ? v 2 ? 0 and U 2 ? U 2 ? 0
? The ACF of U is given by
R (?) ? ?R
(?) ? ? q ? R ? ? ?R
(?)
u ui ? L ? vi i ? ? i
where ???????? (??) is the ACF of ??????.
???????? ? ?
can be modeled as
R (?) ? R i i
(0) ? e
?0 , where ?
is the relaxation time and
R (0) ? 2 i
? If ?????? has a Maxwellian distribution we have:
kT ? q ? R ?2
? q ? R ?2 kT ? ?
R (0) ? v 2 ?
and R (?) ? ? R
(?) ? ? ? e ?0
vi i m
ui ? L ? vi
? L ? m
? ? ? ? ? The corresponding PSD is given by
? q ? R ?2 kT 2? ? q ? R ?2 kT 1
Su (f) ? n ?_A,? L ? ? ?
? ? 0
? n ? A ? L ? ? ? ? ? 2?0
for f •
N ? L ?
m 1? ?2? f?0 ?
? L ? m
2??0
? ? q ? ? ? n? ? ==¿ R
? L ? L ? m ==¿
? ? q ??0 ? m ?
? ? A A q2 ? n ??
? Langevin approach:
R C (noisy
R (noiseless)
Vn Vc
? Variance of thermal noise voltage across C:
? df ? ? 1
c ? 1? ?f / f ?2
2 c 2 2? RC
0 c ? The result also follows directly from the EPT: Average stored energy in C: W ? 1 C ?V 2 2 c
? Resistor R and capacitor C are in thermal equilibrium and there is only one degree of freedom Mean energy stored in C:
W ? kT
==¿ 1 CV 2
? 1 kT
==¿ V 2 ?
2 2 c 2 c
Z(j?) R1
Vn
RN
Z(j?)
Vn
? The PSD of noise voltage ???? is given by:
? The variance of voltage ???? is then given by:
? The variance of the noise voltage Vn can be obtained without computing the integral by using the Bode Theorem stating
where
C? C0
1 ? lim s ? Z(s) C? s??
1 ? li m
s ? Z (s) C0 s?0
? Noise PSD of a 1st-order RC circuit
Z(j?)
1 R R
?R2C
Z(j?) ? 1/ R ?
j?C
? 1? j?RC
? 1? ??RC ?
? j 1? ??RC ?
R Vn
Nyquist theorem ==¿
Sv (f) ? 4kT
? ??Z(j 2? f)? ?
4kT ? R 2
n 1? ??RC ?
? Noise variance of a 1st-order RC circuit from the Nyquist theorem
? 2 (f) ? df n
? 4kT
? ???Z ? j 2? f ??? df ?
0 0 ? df ? ? 1 kT
4kT
? R ? ? 1? ?f
/ fc ?
? 4kT
? R ?
2 ? fc
? 4kT
? R ?
? ? 2 2? RC C
? Noise variance of a 1st-order RC circuit (by Bode theorem) C? =C
1 ? lim s ? Z(s) ?
lim
s ? R ? 1
C? s??
s?? 1? s ? RC C
C0=?
1 ? lim s ? Z(s) ? lim
s ? R ? 0
C0 s?0
s?0 1? s ? RC
? From the Bode theorem we then have
V 2 ? kT ? 1 ? 1 ? ?
n ?C C ? ? ? 0 ?
? Let us consider the following simple mechanical system consisting of a proof mass ??, a linear spring with spring constant ?? and a linear damper with damping factor ??
? The deterministic equation of motion of this system in the absence of an external force is then given by:
d2x m ? dt 2
? b ? dx dt
? k ? x ? 0
? According to the dissipation-fluctuation theorem the damping (loss) is associated with noise we need to introduce a noise force to

model these statistical fluctuations according to
? Using the Equipartition Theorem (1 ? ??
? ?? = ??
) and a derivation
2 ??
spring
similar to the one on slide 23 using the equivalent model shown below shows that the PSD of the noise force ????(??) is independent of frequency and given by:
? In general, to model a noisy mechanical system, the system can be modeled by replacing every noisy damper by a noisefree damper and a noise force generator alongside the damper
? To analyze the noise behavior of the system shown below, the rule from the previous slide can be applied
Fn1 ?? ? ? Fn2 ?? ? ?
4kBT 4kBT
? b1 ? b2
? Equivalent model of a noisy resistor (Langevin approach)
R (noisy)
R (noiseless) R (nois eless) In Vn
S ? 4kT ? R n
? 4kT n
? G ?
4kT R
(single-sided) (single-sided)
? ?? is Boltzmann•s constant (?? = 1.38 •10?23 J/K) ? ?? is absolute temperature in K
? Equivalent model of a noisy forward biased diode (Langevin approach)
ID Rd noisy Gd In Vn
S ? 4kT n
? Rd 2
S ? 4kT n
? Gd 2
? 2q ? ID
(single-sided) ? Shot noise
(single-sided)
? ???? is the small-signal conductance of the diode ? Recall: Large signal current through a pn-diode
? Equivalent model of a noisy MOST (Langevin approach)
ID
noisy
InD
? Thermal noise:
GnD
? ?nD
? Gms
? ? nD
? Gm
? 1 WI ? 2
? ? n ? ?
?nD
? ? 2
? Flicker noise:

? Total input referred noise:
nD nD
? SI ??3
? Equivalent model of a noisy BJT (Langevin approach)
C
IC
B noisy B
E
C
?InC
E
? Equivalent model of a noisy opamp (Langevin approach)
noisy
? Requires 3 uncorrelated noise sources ? All 3 noise sources are needed to have a model independent of the generator impedance ? Current noise sources can be ignored for MOS input stages
? Noise is a small perturbation compared to ???? ? Analysis can use the small-signal equivalent circuit to which all the noise sources are added (Langevin approach) ? The total output referred noise PSD can be calculated as
Sn,out
(f) ? ? k ?1
H (f) 2 ? S
(f)
where it has been assumed that all the N sources are uncorrelated ? ????(????) are the transfer functions from each noise source k to the output ? The noise can then be referred to the input by dividing by the square of the magnitude of the transfer function from input to output ??(????), according to: SV ?f ?
S neq
?f ? ?
nout A ?f ? 2
?Vneq
ACL
? 1? R1 R2
Vout
V V
Vout
S 2 nR 1
S 2 nR 2
? 4kT R1 ? 4kT R2
? Equivalent input noise voltage PSD (assuming no correlation between the noise sources)
? The opamp noise current sources start to dominate at high source impedances
? How to calculate the input referred equivalent noise of an OTA?
Most general configuration Special case: Ideal voltage source drive
Vin
These two circuits must result in the same
Inout! noisy
Slide 39 Example •OTA Noise Analysis (2/5) ?
Langevin model of the OTA

Small signal equivalent model ?VG3
Inout
S 2 Ink
G
? 4kT
? ?
?Gnk ?G
for: k
? G2 ?
? 1•4 ?
for: k
? 1•4
nk nDk mk mk
W ? L ? f
k k ? ? KF 4kT n
? Small signal equivalent model ?VG3
Inout
S 2 Ink
? 4kT
?Gnk
for: k
? 1•4
G ? ? ?G ? G2
? ?
for: k
? 1•4
nk nDk mk mk
W ? L ? f
I k k ? ? KF
? Output noise
current:
4kT n
Gm3
? Gm 4
Inout
? Gm4 ? ?VG3
? In2
? In4 ? G G
I ? I
? ==¿ I
? m 4 ? I ? I
? m 4 ? I ? I
? I ? I ? I ? I
?V ? ?V
? n1 n3 ?
nout G
n1 n 2 G
n3 n 4
n1 n 2 n3 n 4
G3 G4
m 3
m 3 m3
? Transfer function from ???n to ??nout:
?Vn noiseless
H(?) ?
Inout ?Vn
? Gm1
? Calculating ????? :
?Vn
? ? ? ?
Gm 1

? Concept of equivalent noise resistance: •For a noisy resistor, we have: S ? 4kT ? R nR •Can express a noise voltage ?Vn as an equivalent noise resistance ??neq:
S 4kT Vn
?Req
? For our noisy OTA, this means:
S ? S ? S ? S ? S
? 4kT
? ?G ? G
? G ? G
? 4kT
?G2 ? R
?Inout In1
In 2
In 3
In 4
n1 n 2 n3 n 4
m1 nineq
? Input referred noise resistance in more detail:
Thermal noise: R
? 2? nD1 ? 2? nD3 ?Gm3
? 2? nD1 ? ? ? ? nD3 ? Gm3 ?
nineq-th
G G2
G ?1 ? G ?
m1 m1
m1 ? nD1 m1 ?
? ? G ? R
? 2?
? ? nD3
? Gm3 ? ==¿ I
? 4kT ? ? ?G
eq m1 nineq-th
nD1 ? ?1? ?
G ? nout
eq m1
1/f noise:
? 2? ? G ?2 2?
nD1 m1 ? 2? ? ? G ?2
W ? L ? ?
R ? n ? ? m3 ?
? p ? n ?1? ? m3 ?
? 1 1 ? p ?
nineq-f
W ? L ? f
? G ?
W ? L
? f W
? L ? f ?
? G ?
W ? L ? ?
1 1 m1 3 3 1 1 ? m1 3 3 n ? ? Assuming M1-M2 in weak inversion and M3-M4 in strong inversion:
? nD1 ?
n1 , 2
Gm1
? Ib , U
? nD3
? 2n3 , 3
Gm3
?

2 I b V
T P 3
Slide 43 Noise Example •1st-Order Low-pass Filter (1/5)
? Ideal OA (i.e. infinite DC gain and GBW and infinite input resistance) except for noise which is modeled by a simple input-referred noise voltage source ??nOA (the two current noise sources are neglected assuming the OA is MOS) ? Output noise voltage for ??in = 0:
V ? Z
? ?I
? I ? ? H ?V with Z ? R
and H
? 2 ? s ?c
nout 12
n1 n 2 nOA nOA 12
1? s ?
nOA
1? s ?
? Resulting output noise voltage PSD: c c
? with
S nout
?f ? ?
Z12
?f ? 2 ? ?S
? S n 2 ? ?
HnOA
?f ? 2 ? S
S ? S
? 4kT
and S
? 4kT ? ?
? ?1? fk ?
I I V ? ?
n1
n 2 R
nOA
? ? m ? ?
? Substituting into the output noise voltage yields: ? f ?2
8kT ? R
2 ? ? f ?
? ? f ?
S ? ? ? c ?
? 4kT
? ? ?1? k ?
Vnout
? f ?2 1?
? f ?2 1?
? ? m ? ?
? f ? ? f ? ? c ? ? c ? ? The input-referred noise voltage PSD is then given by:
? ? f ?2 ?
? ? f ?
SV ? 8kT
? R ? ? 2 ? ? ? ? ? 4kT
? ? ?1? k ?
nin
? fc ? ?
? ? m ? ?

? The variance of the output noise voltage can be calculated by integrating the output noise voltage PSD over frequency ? The contributions of the resistors are 1st-order low-pass filtered. The corresponding noise bandwidth is then simply B ? ? 1 1
n12 ?
2 ? fc
? ? ? 2 2? RC
4RC
? The variance of the output noise voltage due to ??1 and ??2 is then simply given by
V 2 ?
2 ? 4kT ? Z
?0? 2 ? B
? 8kT
? R2 ? B
? 8kT
? R ? 1
? 2kT
nout
R1,R2 R 12
n12
R
n12
4RC C
? The contribution of ??nOA to the output noise voltage PSD is not frequency bounded and hence its contribution to the output noise voltage variance is (in theory) infinite ? In order to evaluate the output noise voltage variance, we need to account for the amplifier finite bandwidth
? If the amplifier transfer function is assumed to be ??(??), then the transfer function ??nOA becomes:
H ?s ? ?
2 ? s ??
nOA
2 ? 1 ?
1? A ?s ? ? ?1? A ?s ? ? ? s ?? ? ? ? With ?? = ???? ? Note that for ?? ? ? , we recover the earlier result ? If ?? is simply approximated by ?? = ??0/?? where ??0 = ????/???? is the gain-bandwidth product with ???? being the compensation capacitance, the transfer function becomes
H ?s ? ?
2 ? s ??
nOA
? ? 2 ?
s2 ? ? ? ? ? ? ? ? s ? 1
?0 ? ?0 ?
? It can be shown that the noise bandwidth corresponding to the 2nd- order transfer function ??nOA is given by ?? ??
B ? 1
? H ?f ? 2 ? df ? 1 ? H
?? ? 2 ? d?
? ?0
? 4 ? ?0 ??
? ?0
for ?
?? •1
nOA
HnO A
?0? ?
nOA
8? ?
nOA
16 2 ? ?0 ?? 16
? The output noise voltage variance due to ??nOA is then given by
V 2 ? 4kT ? B ? R
? 4kT
? ?0
? ?
? kT ? Gm
? ?
? ? kT
nout Vn 3
nOA nOA
16 G
4C G 4C
m c m c
? The total output noise voltage variance then becomes
? Since the voltage gain in the passband is unity, this also corresponds to the total input-referred noise voltage variance
Fundamentals of LNA design for CT sensor interface CT LNA•S FOR RESISTIVE AND CAPACITIVE SENSORS
?nG
?1 WI saturation ? ? SI saturation ? 3
G ? ?2 ? ? qs ? ?CGS ? CGD ?
Gi 2n
?qs
? 1 L2
? ? ?UT ? 4 L2
WI saturation
? ? ?15
? ? ?VP
?Vs ?
SI saturation
? Drain noise current:
V ? VG ?VT0 P n
? Gate noise current: ? ?????????????????? is correlated w/ ??????????????D and most important at RF
? For an amplifier in saturation it makes sense to refer the drain noise to the gate
where ?????????? is given by
? 1 ? n
WI and saturation
RnG
? G nD G2
? ? nD G
? 2 Gm ? 2 n 1
m m ? ? ?
SI and saturation
??3 Gm Gm
? Two main sources of Flicker noise •Carrier number fluctuation ????N (Mc Worther model)
•Carrier mobility fluctuations ?????? (Hooge model) ? The PSD of the gate referred voltage fluctuations is:
where
S?V 2
?f ? ?
K?N 2
and
S?V 2
?f ? ?
K??
nG ?N
W ? L ?Cox ? f
nG ??
W ? L ?Cox ? f
? Inversely proportional to frequency and to gate area ? Note that ??????N and ???????? are slightly bias dependent
S?V 2
?f ? ? S?V 2
?f ?
? S 2
?f ?
nG nG ?N nG ??
? Usually carrier number fluctuations dominate over mobility fluctuations ? For design purposes, the gate referred noise PSD can be considered as bias independent
? PSD•s of noise currents ??????C and ??????B: I?F SI ?f ? ? 2q ? IC , SI ?f ? ? 2q ? IB ? Kf ? B
nC nB
m shot noise
_,f Flicker noise
? Thermal noise of resistances ????, ???? and ????:
S nRB
? 4kT , R
S nRC
? 4kT , R
S nRB
? 4kT R
B C E
? Base current is already at the base:
S n ,eq
? S ? nB
2q ? IB
? Collector current needs to be referred back to base:
S S ? nC ? S
? 2q ? Ic
? 4kT ? R
? 4kT ? ? 1
? R ?
Vn ,eq G2
VnR G2
B ? 2 ? G B ?
m B m ? m ?
Assumptions: •??????,B???????????? is sufficiently small •????????????????????????? is negligible
S nM1
S nM2
? 4kT
? 4kT
? 1 Gm1 ? 1 Gm2
? Total equivalent input referred voltage noise:
Assumptions:
•??????,B????????????M????/???? are sufficiently small
•??V????????????????????M????/???? are negligible
S nM1/2/3
? 4kT ? 1 G
? Total equivalent input referred voltage noise:
m1/2/3
sufficiently
negligible
S nM1/2/3
? 4kT ? 1 G
m1/2/3
? Total equivalent input referred voltage noise: M1 and M2 are assumed to be identical!
? Noise from distinct devices is uncorrelated
Total output referred current noise
S nout,tot
? S nM1
? S nM2
? S nM3
? S nM4
S ? 4kT n
?Gm
Referring it back to the input:
SVneq ?
1 2 m1/2
? S nout,tot
? Total input referred noise:
1 1 ? G ?
S neq
? G2
?2 ? SInM1/ 2
? 2 ? S nM3/4
? ? 2 ? 4kT
? ? ?1? m3/4 ? G G
m1/2
•_•m,1/2 ? S neqM1/ 2
m1/2 ?
? Voltage drive: ???? ? ???? ? Current drive: ???? ? ?
S ? R2 ? S
? Noise figure:
NF ?
s a ? 1? a ? 1? NF
? 1?
Vn,eq
s In,eq
N N ex
4kTR
? Voltage drive: NF???????? ?? ????/???? ? Current drive: NF???????? ?? ????
s s s
RB ? 10 ? ? ? 100
? For large source resistances ???? the input referred current noise becomes dominant ?
Optimum ???? exists for a given equivalent voltage and current noise
For sufficiently large A:
vx ? 0
vout vx
? ? Cin CFB
? Question: How to choose W and ??B???????????? for an optimum SNR?
? Circuit analysis: Compute ?????????? for the 2 circuits and equate them:
? C ? C ? C ?2 S ? ? FB GS in ? ? S
vneq
C ?G
ind
? in m ?Gms
? WI and saturation
S ? 4kT ? ? 2
inD
? ? ?G
SI and saturation
??3 ms
G ? n ?G ,
V ? VG ?VT0
ms m P n
2 G ? ? ?C
? ? W
??V
?V ? ? ?
2IIBIAS
C ? ?C
?W ? L
m ox ? L ? P S
n ?V ?V ?
GS 3 ox
••_•? ?
•,? P S
Simulation parameters:
L ? Lmin
? 180 nm,
tox
? Lmin
/ 50
? ? 400 cm2 / ?Vs?,
n ? 1.4
CFB
? 100 fF,
Cin
? 500 fF
Optimum transistor width:
? Total input referred voltage noise:
? C ? k? ?W ? C ?2
S neq
? 4kT ? n ? ? FB i n ? ? ?
? in ?
Simulation parameters:
L ? Lmin
? 180 nm,
tox
? Lmin
/ 50
? ? 400 cm2 / ?Vs?,
n ? 1.4

CFB
? 100 fF,
Cin
? 500 fF
Optimum transistor width:
? Total input referred voltage noise:
? C ? k? ?W ? C ?2 1 L 1 Sv ? 4kT ? n ? ? FB in ?
? ? ?
neq
C ? ?C W ?V ?V ?
? in ? ox P S
? Sensor: A device which converts information from one energy domain into the electrical domain ? In the electrical domain, (analog) signal conditioning, digitization and finally digital signal processing (DSP) and storage can take place
? Most sensors provide analog information at their outputs ? Analog-to-digital (A/D) conversion is required to benefit from DSP and convenient data displaying and storage ? There will be a lecture on A/D conversion for senor interfaces towards the end of the course
? Transduction: Converting a signal from one energy domain into another ? Both sensors and actuators are transducers ? Typical signal/energy domains: •Magnetic (Mag) •Mechanical (Mech) •Thermal (Therm) •Optical (Opt) •Chemical (Chem) and •Electrical (Elec) ? Sources of uncertainty (error): •Sensitivity to unintended electrical and nonelectrical quantities •Noise (thermal, 1/f, •) •Electromagnetic interference (EMI) •
? If we write the different signal domains (i.e. energy forms) as a column vector, the transduction action of a sensor can be written as a matrix with certain sensitivities acting on an input vector (sensor excitation) and producing an output vector (sensor output signal).
? E ?
? ?mag,mag ?mag,mech ?mag,therm ?mag,opt ?mag,chem ?mag,elec ? ? E
? ? E ?
mag
? ? ? ? ? ? ?
? ? mag ? ? mag,os
? Emech ?
? mech,mag mech,mech mech,therm mech,opt mech,chem mech,elec ?
? Emech ?
? Emech,os ?
? E ?
? therm,mag
?therm,mech
?therm,therm
?therm,opt
?therm,chem
? therm,elec E
? ? E ?
? therm ? ? ? ? ? ? therm ? ? ?
therm,os ?
? Eopt ? ? ?opt,mag ?opt,mech ?opt,therm ?opt,opt ?opt,chem ?opt,elec ? ? Eopt ?
? Eopt,os ?
? E ?
? ? ? ? ? ? ?
? ? E
? ? E ?
chem ? ?
? chem,mag chem,mech chem,therm chem,opt chem,chem chem,elec ? ?
chem ? ?
chem,os ?
? Eelec ?
? ? ? ? ? ? ? ? ? Eelec
? ? Eelec,os ?
? elec,mag elec,mech elec,therm elec,opt elec,chem elec,elec ?
? The additional additive vector models offsets which are often present in sensors
Slide 6 Example: Transduction from Emech to Emech ? Blue entries in the transduction matrix represent non-zero coefficients
? E ?
? ?mag,mag
?mag,mech
?mag,therm
?mag,opt
?mag,chem
?mag,elec ? ? E
? ? E ?
mag ? ? ?
? ? ? ?
? ? mag ? ?
mag,os
? Emech ?
? mech,mag
mech,mech
mech,therm mech,opt mech,chem mech,elec ?
? Emech ?
? Emech,os ?
? E ?
? therm,mag
?therm,mech
?therm,therm
?therm,opt
?therm,chem
? therm,elec E
? ? E ?
? therm ? ? ? ? ? ? therm ? ? ?
therm,os ?
? Eopt ? ? ?opt,mag ?opt,mech ?opt,therm ?opt,opt ?opt,chem ?opt,elec ? ? Eopt ?
? Eopt,os ?
? E ?
? ? ? ? ? ? ?
? ? E
? ? E ?
chem ? ?
? chem,mag chem,mech chem,therm chem,opt chem,chem chem,elec ? ?
chem ? ?
chem,os ?
? Eelec ?
? ? ? ? ? ? ? ? ? Eelec
? ? Eelec,os ?
? elec,mag elec,mech elec,therm elec,opt elec,chem elec,elec ?
? A simple spring with a proof mass attached to a stationary mass can detect accelerations as displacement mechanical energy (kinetic energy) is transformed into mechanical energy (spring potential energy) ? A mechanical offset energy can exist because the spring can e.g. be prestressed
? The transduction inside a sensing element can also take place via multiple transduction steps. Such a transducer is called a tandem transducer ? Example: an absorptive coating on a bimetal strip •In the 1st transduction step, optical energy (photons) is converted into thermal energy •In the 2nd transduction step, the thermal energy deflects the bimetallic strip, that is the optical energy is transduced into mechanical energy
? A tandem transducer can be modeled using two transduction matrices, representing the two successive transduction steps ? Note: Tandem transduction requires an intermediate non-electrical energy domain ? Example: •In the transducer on the right, acceleration (mechanical energy) is transduced into displacement (mechanical energy) •To readout the displacement signal one typically converts the displacement into a change in capacitance which can be processed by the readout electronics, i.e. there is a mechanical to electrical energy transduction Since there is no intermediate transduction step going to a non-electrical energy domain, the accelerometer on this slide is not a tandem transducer
? Consider a transduction to the electrical domain represented by the following transduction matrix
? E ?
? ?mag,mag ?mag,mech ?mag,therm ?mag,opt ?mag,chem ?mag,elec ? ? E
? ? E ?
mag
? ? ? ? ? ? ?
? ? mag ? ? mag,os
? Emech ?
? mech,mag mech,mech mech,therm mech,opt mech,chem mech,elec ?
? Emech ?
? Emech,os ?
? E ?
? therm,mag
?therm,mech
?therm,therm
?therm,opt
?therm,chem
? therm,elec E
? ? E ?
? therm ? ? ? ? ? ? therm ? ? ?
therm,os ?
? Eopt ? ? ?opt,mag ?opt,mech ?opt,therm ?opt,opt ?opt,chem ?opt,elec ? ? Eopt ?
? Eopt,os ?
? E ?
? ? ? ? ? ? ?
? ? E
? ? E ?
chem ? ?
? chem,mag chem,mech chem,therm chem,opt chem,chem chem,elec ? ?
chem ? ?
chem,os ?
? Eelec ?
? ? ?
? ? ? ?
? ? Eelec
? ? Eelec,os ?
? elec,mag elec,mech
elec,therm elec,opt elec,chem
elec,elec ?
? There is one (desired) sensitivity plus 2 cross-sensitivities and an offset ? This could be the transduction matrix of a photodiode •Desired sensitivity: ??elec,opt •Cross-sensitivities: ??elec,elec (e.g. electromagnetic interference), ??elec,therm(diode current strongly depends on temperature through ???? = ????/?? •Offset due to dark current
? Active sensors: Require an external source of excitation Examples: •Resistor-based sensors (AMRs, GMRs, thermistors, •) ? Passive or self-generating sensors: Generate their own electrical output signal without requiring external voltages or currents Examples: •Thermocouples (thermoelectric voltage generation) and photodiodes (photocurrent) ? Modulating sensors: Measure the desired quantity by modulating ? Analog vs. Digital sensors: •Analog sensors provide signals which are continuous in time and amplitude •Digital sensors provide discretized outputs
? Deflection mode sensors: •The sensor response to an input is a •deflection•or more general a deviation from its equilibrium position in the absence of an input. For an ideal sensor, this deviation is proportional to the measurand of interest ? Null mode sensors: •The sensors or instruments exert an influence on the measured system opposing the effect of the measurand. Ideally, the influence of the measurand and that by the sensor/instrument are precisely balanced in magnitude but opposite in sign, resulting in a null measurement. This nulling is typically achieved via feedback. ? Null mode instruments are very linear and can produce very accurate measurements, however, they are not as fast as deflection instruments (which are open loop systems)
? Self-generating sensors require no external power supply ? Due to the absence of an external source, there is no additional source of uncertainty/error ? A self-generating sensor draws all its required energy from the measurand (source loading) ? Example: Potentiometer for angle measurements
? Use an additional external source whose energy is modulated to produce the output signal ? The additional source introduces an additional source of error ? A modulating sensor takes less energy from the measurand ? Example: Non-contact displacement measurement
The code tracks on the rotating disc allow for a unique (digital) encoding of the current shaft angle
Illustrations courtesy TU Delft
? The resistance of a slab of conductive material can be expressed as:
where ?? is the bulk resistivity of the material ? Under mechanical stress (strain) the change in geometry produces an associated resistance change
?R ? L0
? ?? ?
?0 ? ?L ?
?0 ? L0
? ?A ==¿
2 0 0 0
?R ? ?? R0 ?0
? ?L L0
? ?A A0
? Assuming that the volume stays constant the expression can be simplified according to
Slide 15 Strain gauges with applied force (1/2)
? From previous slide:
?R ? ?? R0 ?0
? ?L L0
? ?A , A0
? A
?
?
? L
A 0
L 0
? For metal films the change in resistivity can be modeled according to:
?L ? 0 ==¿ ? ?R ? ? 0
? ? R0
? ?strain
? Bringing the 2 results together:
k: gauge factor
Slide 16 Strain gauges with applied force (2/2)
? From previous slide:
k: gauge factor ? For tensile stress we have
?L ? 0 ==¿ ? ?R ? ? 0
? For compressive stress the opposite is true
? ? R0
? ?strain
? The simple strain gauge structure on this and the previous slides is constructed to give a

large ??? in the up/down direction and a small ??? in the left/right direction!
? Ideally we have for the force applied on this slide: Applying a force in the insensitive direction:
? For commercially available sensors this is typically satisfied ? When designing your own sensors you need to ensure this by a proper geometry selection
? A simple resistive divider can be used to read out resistive sensors ? Features of a half-bridge: •Simple structure •The relationship between ??? and ??out is non-linear •For relatively small values of ??? the circuit tends to produce small changes in the output voltage with a large offset difficult to measure
? We can also make the bottom resistor the sensing element
? The features are virtually identical to the other half bridge configuration (but: sign reversal!)
? The offset present in the half-bridge can be removed using the differential structure shown on the right ? Features of the single-point full bridge •No intrinsic offset •Output does not change linearly with the change in resistance ??? ? Balance condition:
? Bridge configurations can be made more sensitive by incorporating two sensing elements
? Features: •No intrinsic offset, non-linear relation between ??? and ??diff •Two times better sensitivity than 1-point full-bridge ? Balance condition:
? The nonlinearity problem can be solved if a differential measurement becomes possible (i.e. one sensing element produces +??? resistance change and a second one produces ????)
? Features: •No offset and linear relation between ??? and ??diff ? Balance condition:
? If differential sensing elements are available we can also construct a full bridge where all sensing elements are varying
v ? 1 ? ?1?
?R ? ?V
1 2 ? R ? bias ? ? 1 ? ?R ?
v2 ?
2 ? ?1?
R ? ?Vbias
? ? ? Features: •No offset, intrinsically linear, highest sensitivity •Requires a differential sensing element ? Balance condition:
? Sensitivity: The bridge sensitivity ?? specifies the output voltage when the bridge is excited with 1 Volt and the sensor is at full scale Example: 1-point full-bridge with ??? ?? ????
= 20
vdiff Vbias
? 1 ? ?R ? 2 2R ? ?R
1 ? ?R R 2 2 ? ?R R
S ? 45 mV /V
? Accuracy: The bridge accuracy ?? measures the deviation of the bridge from an ideal bridge
v ? v
? ?R
? 0 ? ?
? ?R
diff,lin diff ? R ? R
? ?
v ? ?R ? ? v
?R ?0 R ? ?R ?
diff ? R ? diff,lin ? R ? A ? ? ? ? ?
v ? ?R ?
diff ? R ? ? ?
? Bridge resistance: The bridge resistance is the resistance of the bridge measured unloaded across the signal terminals Note: The bridge resistance determines the static power consumption of the bridge! ? Offset error: The bridge offset is the bridge output voltage which is produced when the measurement parameter is zero ? Drift: The drift of a bridge is the change in bridge output voltage with environmental condition over time. Here, typically temperature is the most critical source for drift
Readout w/ discrete electronics
On-chip readout electronics
? Signal conditioning takes care of: •Reading out the bridge circuit w/o significant loading effects •Amplification •Anti-aliasing filtering •Differential-to-single-ended conversion for discrete readout electronics
? Differential signal:
? Common-mode signal:
? The differential signal is most often much smaller than the common-
mode signal
? Example: ??bias
= 1 ??, ??? ??
= 1
vdiff
? ?R ?V R bias V
? 10 mV
50x
vCM
? bias 2
? 0.5 V
? The information carrying signal ??inDM is amplified by the differential gain ??DM
? The undesired common-mode signal ??inCM is amplified by the common mode gain ??CM
? In practice, ??CM is non-zero and the output depends on both ??inDM and ??inCM according to: ? Ideally, we would like ??CM to be zero or at least much smaller than ??DM
? The common-mode rejection ratio (CMRR) characterizes the ability of an amplifier to suppress common mode signals at its input w.r.t. differential signals (i.e. to •distinguish•DM from CM signals) ? From previous slide:
? The CMRR is then defined as:
? Note: the CMRR is most often expressed in dB! ? Example: If an amplifier has a CMRR of 60 dB and there is a differential signal of ???inDM = 0.5 mV and a common mode signal of ???inCM= 0.5 V at its input, the changes in output voltage due to ???inDM and ???inCM are equal!
? The simple opamp based difference amplifier can be used to amplify voltage differences at its input
? Let•s calculate ??DM, ACM and the CMRR!
? 1st assume ??
= ?, ??2 = ??? = ?? ? ??1 = ?? ? ???
2 1
? 2nd assume ?? ?? = ?, ??2 = ?? ? ??1,
??? =
? ??? , ??? = ??1 + ??????
2 1 1 ? Note: ??DM, ??CM and CMRR are independent of ??? and scale positively with ???. Numerical Example: ??? = 1
? 3rd assume ??
= ??DC
/(1 + ?? ? ??DC) GBW
? Note: The finite opamp gain and GBW affect ??DM and ??CM in the same way and therefore, the CMRR remains unaltered! ? Apart from the finite CMRR due to resistor mismatch, the difference amplifier suffers from source loading due to the finite value of ??1 (this is particularly true for IC realizations where large resistor values require large areas) we will address these problems by introducing so-called instrumentation amplifiers later in the course
? A bridge structure can also be used to measure reactive sensors (i.e. capacitive and inductive sensors) •Replace the resistors by generalized impedances •Replace the DC excitation by an AC source ? The balance condition is:
? This complex balance equation can be written as 2 real valued equations:
Z1 ? Z2 ? ?
R1 ?
jX1
? R2 ?
jX2
Z4 Z3
R4 ?
jX4
R3 ?
jX3
? For the capacitive bridge according to Wien, the balance condition is:
R1 ? R2
R4 ?
j ? ?
? ? ?C ?
Rx ?
j ? ?
? ? ?C ?
? 4 ? ? x ?
? For the inductive bridge according to Maxwell, the balance condition is:
R ? ? 1
? ? R3 ? R1
4 ? j?C ?
R ? j?L
? ? x x
Integrated Interface Circuits •Chapter 2: Sensor types
? The virtual short of an opamp can be used to enforce a zero bridge voltage. Note: The balance conditions from the previous slides are not satisfied! Why? ? For a resistive bridge with ??1 = ??2 = ??4 = ?? and Z3 = ???? we obtain for the required feedback voltage ???? ileft ? iright ==¿
Vex
? ?Vex
? vx ?
2 ? R R ? Rx
? Setting as usual ???? = ?? + ???, we find
? All bridge configurations are typically read out with a low offset, high input impedance differential amplifier. The amplifier is then typically followed by an LPF (anti-aliasing filter) and an ADC
MAGNETIC FIELD SENSORS
? Magnetic field sensors are mostly distinguished by their dynamic range and frequency range (i.e. bandwidth)
Min. B field Max. B field Frequency range
Induction coils 100 fT unlimited 0.1 mHz •1MHz Hall sensors 10 nT 20 T 0 •100 MHz Magnetoresistive sensors 100 pT 100 mT 0 •100 MHz Fluxgates 10 pT 1 mT 0 •100 MHz SQUIDs 5 fT 1 •T 0 •100 kHz ? Therefore, different applications clearly require different magnetic field sensors ? In this course we will focus on Hall sensors because: •they can nicely be integrated in CMOS technologies •They have an enormous market share (Asahi Kasei Co. sells over 100 million Hall elements per month)
? As ingredients, we need the Lorentz force (which in general relates the electromagnetic world (Maxwell equations) to the mechanical world (Newton•s laws of motion) ? Next, we need to introduce scattering into Newton•s law of motion
where
???
is the drift velocity and ?? the mean free time collisions
? Combining these two equations yields: ? Assumptions: We apply an electric field in the ???? direction with a resulting current flow and no current flows in the y- and z-directions:
? On the previous slide we found:
? Writing this equation in component form
? And substituting: ? Yields:
? From the previous slide:
? Assume that according to the drawing on this slide ???? ? 0, ???? = 0, then the Hall voltage ??hall becomes:
Vhall
d /2 ? ? ?d /2
Ey dy
? vx ? Bz ? d
? ? ? Ex ? Bz ? d
? ? ? ? ? Jx ? Bz ? d ?
? ? ? h
? I ? Bz
? Recall: The resistivity is given by:
? ? 1 ?
? 1 e ? n ? ?
? Jx ? h ? d
? Note: To maximize ??hall, we need minimum ?, maximum ?? and low doping (small ??), also ??hall is independent of the sensor surface ?? ? ??
? The effectively measurable Hall voltage depends on the geometry of the specific Hall device. This is modeled by the geometry factor ??
? The most important noise sources for Hall devices are: •Thermal noise (eventually determining the limit of detection (LOD)) •1/f noise •Noise of the signal conditioning electronics, EMI ? The intrinsic thermal noise of a Hall device originates in the resistance between the two voltage terminals of the Hall device ? Noise power:
? Signal Power:
? Resolution: ? Example (Si): ?? = 1016 cm?3, ? = 2 •m, ?? = 1 ?cm, ?? = 300 K, ?? = 15 k?, ????? =
0 V A?T
, ?? = 0.5 mA
? From the previous slide: ? To achieve a good resolution we need: •materials with a high mobility (large ??) •low doping levels (small ??) •thin devices (small ?) •large currents ?? ? BUT: ??, n and ? are limited by •heating •available power (e.g. in battery operated devices) •Carrier velocity saturation
Stress (e.g. due to packaging)
? In the absence of a magnetic field ?? = 0, the Hall plate can be modeled as a simple Wheatstone bridge ? Non-uniform stress inside Hall devices leads to intrinsic offsets in this Wheatstone bridge ? This offset is superimposed on the actual Hall voltage resulting in an (unknown) offset ? Typical (equivalent) offset values are between 5 and 30 mT
? According to the above figure, we can couple two Hall sensors, which are rotated by 90•(i.e. the bias current port and the voltage sense port are swapped), to cancel the intrinsic offset ? Key idea: The offset voltages due to doping gradients, temperature gradients and mechanical stress gradients are 180•out of

phase while the generated Hall voltages are in phase
? : Hooge parameter (1/f noise model) GF: geometry parameter Rsheet : sheet resistance n: doping concentration
? A typical (asymptotic) noise PSD of a Hall sensor is shown above ? The lower frequency noise is dominated by the sensor•s 1/f-noise ? The white noise part of the spectrum is determined by the thermal noise associated with the loss of the Hall element ? Typical corner frequencies are in the range of 1 to 100 kHz
? Offset and 1/f noise can be greatly reduced by the so-called spinning current or switched Hall technique ? Intuitive explanation: Assume ??? ¿ 0
furthermore
Slide 56
CL K ph as e
? The spinning current method implemented above produces an output voltage with a DC component equal to the offset and a frequency component proportional to the Hall voltage at the clock frequency (Fourier expansion of a square wave!) ? How is this useful? Answer: The amplifier in the circuit above also possesses an offset and 1/f-noise. By •modulating•the information to the clock frequency we can greatly mitigate the effects of both noise and offset
? A complete •switched Hall system•consists of •The switched Hall plate together with an amplifier •The demodulation switches to translate the signal from the switching frequency back to DC •A final low-pass stage to remove the signal around the 2nd harmonic Conventional Hall readout Low-power Hall readout
? In a conventional implementation of the spinning current technique, the Hall element and the amplifier are biased with separate dedicated bias currents
? In the low-power configuration, the bias current for the Hall element is reused to bias the amplifier
Source: Kejik et al., •Integrated Hall Microsystem with current re-use•, Sensor Letters, vol. 5, 1-3, 2007
? Spinning current technique applied to 4 Hall elements ? Demodulation is achieved by commuting the input differential pair in the switching box ? Amplification is properly defined by feedback resistors feeding the output signal back to a dedicated feedback differential pair
? Technology: 0.8 •m standard CMOS technology ? Total current consumption of 2.4 mA •80 •20 ? DDA configuration: •Simple demodulation implementation •Small silicon area ? Spinning current technique: •1/f noise suppression ? Features: •Low-power, small size •High performance (resolution: 500 nT)
Source: Kejik et al., •Integrated Hall Microsystem with current re-use•, Sensor Letters, vol. 5, 1-3, 2007
? The so-called •Seebeck effect•refers to the conversion of temperature difference into an electromotive force (emf)
? Any emf ??emf modifies ohm•s law according to:
J ? ?
? ???V
? Eemf ?
where ?? is the electric potential and ?? is the electric conductivity
? The Seebeck effect produces an emf ??emf according to:
Eemf
? ?S(T) ? ?T
Sou rce: http ://e n.wi kip edi a.or g/wi ki/F ile: The rmo elec tric _Ge ner ator _Di agr
where ??(??) is the Seebeck coefficient
am.svg
(material property) and ??? is the temperature gradient ? For •standard•materials, the Seebeck coefficient takes on values from ? 100 ?V/K to 1 mV/K
? Thermocouples make use of the Seebeck effect to measure the temperature difference between two objects
? For ??? = 0, the emf induced by the Seebeck effect can be directly measured as a voltage difference ? The measured voltage can be calculated by integrating (•summing up•) all emfs due to material differences inside the sensor shown below
? From the previous slide: ? Clearly, to maximize the emf, one should use materials with very distinct Seebeck coefficients (e.g. chromel and alumel) ? Note: To compute ??sense one does not need to invert the above equation for every measurement ? Instead, we use the following •trick•:
Define:
? From previous slide: ? Typically, ??standard is chosen as 0 •C ? The so-called characteristic function of the thermocouple ??(??) is provided by thermocouple manufacturers and metrology standards organization over a range of temperatures for different specific thermocouple types ? Note: To extract the temperature ??sense from the above equation, the reference temperature needs to be known typically evaluated by two different methods ••Ice bath•method: Immerse the reference junction in a semi-frozen bath of distilled water at atmospheric pressure ? ??ref = 0 •C (not so practical) •Reference junction thermometer (thermocouples are still useful, because their leads can be exposed to extreme environmental conditions)
? The table lists some commonly used materials for thermocouples:
material stack sensitivity (at 0•C) [•V/K] range [•C] iron/constantan 45 0..760 copper/constantan 35 -100..370 chromel/alumel 40 0..1260 platinum/Pt+Rd 5 0..1500 ? Thermocouples give quite small output voltages, however, they are intrinsically offset free because they always measure a temperature difference which results in ??emf = 0 for ??? = 0 K ? The small output voltage is problematic due to the non-zero offset of real-world voltage amplifiers ? Solution idea: We could increase the emf, by connecting many thermocouples in series •
? According to the previous slide, one can increase the output voltage of a thermocouple by connecting many of them in series resulting in a so- called thermopile
? While the problems associated with the small output voltage are solved, a new problem arises: •There is increased thermal conduction between cold and hot parts increased source loading and more heat flux required to build up a temperature difference
? Transistors are natural temperature sensors ? However, manufacturing tolerances cause temperature errors of up to 3•C
? Key idea: Producing a temperature stable reference which cancels a positive temperature coefficient with a negative one with
VREF ?T ? ? VCTA T ?T ? ? K ?VPTA T ?T ?
??PTAT ?? a voltage which is proportional to absolute temperature ??CTAT(??) a voltage which is complimentary to absolute temperature
?? a temperature independent constant which makes ??REF temperature ? This type of reference is known as bandgap reference independent of
? Collector current of a BJT as a function of its base emitter voltage and emitter area for ??BC = 0 (diode connected device)
? VEB
? VEB •kT q
VEB
I ? I? ? A
? ?ekT q
? 1? ? I? ? A
? ekT q
C VBC ?0 S E ? ? S E
? Conversely, the base emitter voltage can be expressed as a function of the collector current
VEB
? kT q
? ln ? IC I? ? A
? kT ? 1? ? q
? ln ? IC ? I? ? A
? S E ? ? S E ?
? A PTAT voltage can be generated using 2 diode connected BJTs
VPTAT
? ?VEB
? VEB1 ?VEB2
? kT
? ln ? Iq
? ? kT
? ln ? Iq ?
q ?I? ? A ? q ?I? ? A ? ? S E1 ? ? S E 2 ?
? kT ? ln ?Iq ? IS?
? AE 2 ? ? kT
? ln ? AE 2 ?
q ? I? ? A
? I ? q
? A ?
?? S E1
q ??
? E1 ?
? Numerical example: ??E2 = 10 ? ??E1
? 1.381?10?23 J/K 199 ?V
VEB ?
1.6 ?10?19 C
? ln?10? ?T ?
K ?T
? Note: A true CTAT voltage does not exist! ? Best approximation: Start from the current through a pn diode: VEB
I ? I
? ekT q
? I? ? e
, E : bandga p energy, E
? 1.13 eV (Si)
D S S g g
I? ? K
?T ? ,
? ? 3, I
? I?
?Eg ? e kT
Eg •kT ==¿ I? •I ,
I? ? I
S 1 S S s s s D
kT ? I? ? ? K
?T ? ?
VEB
? Eg / q ? ? ln? s ? ?? VG
? UT ? ln? 1 ?
m mq
? ID ? ? ID ?
V G UT
VG ? VG0
? a ?T
(good from 200 K to
400 K)
? The terms ????
and ? ???? ??
provide the desired CTAT
voltage while the temperature dependence in the argument of the natural logarithm is undesired results in curvature of the CTAT voltage and therefore in an error in the •temperature independent curvature correction (not covered
? Basic structures:
? Series form: ??
= ??
? ??
+ ??
= ??2 ? ??
+ ??
REF
PTAT 2
CTAT
??1
PTAT
CTAT
? Parallel form: ?? =
? ?? = ??3 ? ??
+ ??3
? ??
REF
3 ??1
PTAT
??2
CTAT
? To achieve temperature independence, the resistor ratios and other parameters must be adjusted to result in ??????????? = 0 ??????
? Simple realization of the series bandgap form: ? Assume ???????? = 0 and an ideal opamp V ? VEB1 ?VEB2
? U ? ln? I1 ? ? U
? ln? I2 ?
T ? A ? I? ? T ? A ? I? ? ? E1 S ? ? E 2 S ?
? U ? ln? I1 ? AE 2 ? ? U
? ln? R1 ? AE 2 ?
T ? A ? I ? T ? R ? A ? ? E1 2 ? ? 3 E1 ? ? The opamp ensures that the voltage drops across ??3 and ??1 are equal, i.e. ??1 ? ??3 = ??2 ? ??1 ==¿ V ? V ? I ? R ? V ? V ? R1 ? V ? R1 ?U
? ln? R1 ? AE 2 ? ? V
? R1 ?U
? ln? R1 ? AE 2 ?
REF EB1 1 3 EB1
R2 R
EB1 R
T ? R ? A ?
CTAT R
T ? R ? A ?
2 2 ? 3 E1 ?
2 ? 3
E1 ?
? Differentiating w.r.t. to ?? and equating the result to zero yields
R1 ? ln? R1 ? AE 2 ? ? VG0 ?VCTAT ? ?
?
? UT
R ? R ? A ? U 2 ? 3 E1 ? T
? For ??OS ? 0, ??REF becomes:
? R ? R
? R ? A ? V ? ?
V ? V
? ?1? 1 ? ?V ? 1 ?U
? ln? 1 E 2 ?1? OS ? ?
REF BE1
R2 ? R2
? R3
? AE1 ? I

2 ? R1 ? ?
?
? Recap: A temperature independent voltage can be obtained by adding the PTAT and CTAT voltages ??REF: temperature independent (bandgap) voltage ??EB: CTAT voltage ?? ? ???EB: PTAT voltage ? New: The ratio of the PTAT and reference voltage ??REF can be used as a measure of temperature
? Using a current mirror ratio of ??, an emitter area ratio of ?? = ????2/????1 and an amplifier gain of ?? results in
VPTAT
? K ? kT q
? ln?p ? r ?
? The CTAT voltage is obtained from ??EB2, the ADC computes the ratio of ??PTAT and ??REF to obtain ??
? Why don•t we just measure ??PTAT because it is already proportional to absolute temperature? We could certainly do that. However, we want a digital output and every ADC needs a reference voltage The smartness of the sensor comes from the fact that we use a temperature independent quantity (the bandgap voltage) as reference for the sensor Moreover, when choosing the (digital) ADC offset (??) and gain (??) correctly, the digital codeword is directly a digital temperature reading
Pertijs et al., JSSC, Dec. •05
? CMOS process use substrate PNPs ? Spread in ???? use one room temperature trim to obtain an absolute temperature measurement ? Inaccuracy ¡ •0.1 •C (3??) from ?55 •C to 125 •C (military range)
? Capacitive sensors are very suitable for displacement measurements
? Parallel plate capacitance approximation
C ? ?
? ? ? A ? ? ? A , ? ? 1 for air
0 r h h r
1 2 3
C ? ?
? w ?x0
? ?x ?
C ? ?
? A
C
? ?
? A
?C ? C ? C0
h ? ? ? w h
? ?x
C0 ? ?
h ? ?z ? A h
top
Cbot
? ? ?
h ? ?z A
h ? ?z
Linear Nonlinear Reduced nonlinearity due to differential measurement 3
Charge amplifier
vout
? Csense CFB
? vex
Voltage amplifier
vout
? Av ? C
Csense ? C
vex
sense ref
Transimpedance amplifier
vout ? s ? RFBCsense ? vex
? The node ??sense has no DC connection to gnd (it is a •floating node•) The DC potential is not well defined •The node is very sensitive to leakage currents charging/discharging the node ? A bias resistor provides a well-defined DC bias point The value of ??BIAS needs to be large because ??BIAS together with the capacitors forms a high pass whose corner frequency needs to be sufficiently low compared to the excitation frequency to avoid signal attenuation and discharge during the periods where the excitation voltages stay constant •The large RC-time constant associated w/ large values of ??BIAS causes a slow discharge of the node against drifts ? We can also use a periodic reset using a switch (reset requires introduction of reset phase, where ??p+ = ??p? = 0)
A. Burstein and W.J. Kaiser, •Mixed analog-digital highly sensitive sensor interface circuit for low-cost microsensors•, Intl. Conf. On solid-State Sensors and Actuators, June 1995 ? The circuit uses correlated double sampling to reduce offset, charge injection and 1/f noise ? During ????1 the excitation voltage is applied to the bridge ??sense changes its value according to the change in capacitance of ??sense1,2 the corresponding voltage is sampled on ??1 Note: ??sense also contains errors due to charge injection, amplifier offset and amplifier 1/f noise ? During ????2 zero volts are applied as excitation voltage to the bridge ??sense now contains only changes due to errors (charge injection etc.) This voltage is stored on ??2 and subtracted from the voltage on ??1
? When using a voltage amplifier to readout the capacitive difference between ????1 = ?????? + ???/2 and ????2 = ?????? ? ???/2, ??out becomes very sensitive to parasitic capacitances at the center node v ? ?C ? A ? v out
2C ? C ? C
v in
s0 p1 p2 ? Parasitic capacitances associates with interconnects can be bootstrapped out by using a voltage buffer driving the shield potential ??shield
v ? ?C
? A ? v
out 2C ? C ? C
v in
s0 p1 p2
? Intrinsic sensor parasitics can typically not be bootstrapped out (e.g. the capacitance associated with the anchor area of a released MEMS)
? In the TIA (transimpedance amplifier) readout circuit the effect of ??p is attenuated by the gain of the opamp ??(??)
v ? 1 ?
s ? Csense ? RFB
x 1? A ?s ? ?C ? C ?R
ierror
1 ? s ?
? s ?Cp ? vx
sense p FB 1? A ?s ?
? Also in the charge amplifier, the virtual gnd node introduced by the opamp mitigates the effect of ??p
vx ?
?C CFB
? 1 1 ?
? C
?
C p
?
A
? s
?
C F B
ierror
? s ?Cp ? vx
? Assuming an ideal opamp
?vin,op
? 0,
iin,OP
? 0 ==¿
iin ?
j ? ? ?Cin ? vin ?? ?
iFB
? ? j ? ? ?CFB ? vout ?? ? ? iin
? ??in can be the sensing capacitance of a capacitive sensor ? Then, for lateral displacement sensing ??in = ???? = ???? + ???, ??? ?? ???
? For vertical displacement sensing ???? = ???? + ???, ??? ?? ???/(1 + ???)
? For an ideal opamp:
? In practice: •The opamp is non ideal (finite DC gain, finite GBW and finite input impedance) •The opamp can have a nonzero DC bias current to avoid opamp saturation a discharge of ??FB is required (continuous or discontinuous)
? Frequency response of the charge amplifier with finite gain and GBW opamp
? In a typical charge amplifier, the excitation voltage ??in is attenuated, i.e. ??out ¡ ??in because ??in ? ??FB Features ? Excitation voltages up to the opamp•s GBW are possible
? The negative opamp input is a virtual gnd and can thus be used for adding currents in a differential sensor structure
? The differential readout topology shown above is frequently used to read out MEMS structures such as accelerometers and gyroscopes
? The output signal is proportional to the half-bridge excitation voltage •??ex any error in •??ex will directly translate into an output error Accuracy is particularly important when sensing small values of ??? Mismatch (or drift) of the two amplitudes will introduce errors ? For sinewave excitation the signals •?????? can be generated using a center-tapped transformer or an active balun. This configuration is called a Blumlein bridge
? For rectangular excitation signals and switched excitation schemes, the signals can be generated using the scheme below
? Assuming ideal opamps (??op ? ?)
==¿ v x2
? v x1,
v x3 ? 0
? The part of the circuit highlighted in red is a simple inverting amplifier with input voltage ??outn and output voltage ??outp ? The part of the circuit highlighted in blue is a simple non-inverting amplifier with input voltage ????1 and with its reference potential pulled to ??outp ? The part of the circuit highlighted in green is a voltage divider between ??in and ??outp
? From the inverting amplifier subcircuit it directly follows
? The noninverting amplifier subcircuit enforces the following relations
voutn
? vx1
? vx1 ? ??voutn ? ==¿
R R vx1 ? 0
? The resistive divider finally enforces the following relation between ??in and ??outp
v ? v
vx1 ? 0 x1 outp
in x1 ? ==¿ R R
A. Burstein and W.J. Kaiser, •Mixed analog-digital highly sensitive sensor interface circuit for low-cost microsensors•, Intl. Conf. On solid-State Sensors and Actuators, June 1995 ? Idea: Introduce FB to regulate either the positive (shown) or the negative supply to provide a truly balanced excitation ? Working principle: Use a pair of reference capacitors ????1, ????2 (matched to ????1 and ????2) to measure the mismatch between the positive and negative excitation voltage ? The FB loop enforces ??ref = 0 by adjusting the magnitude of the positive excitation voltage
? Capacitance to displacement relation for
? Linearization for small displacements
Output is approximately proportional to displacement!
? For open loop readouts typically a lock-in detection scheme is used to maximize SNR ? For large excitation signals the sensor non-linearity becomes an important issue ? This is true for all open loop sensor readout systems
Integrated Interface Circuits •Chapter 2: Sensor types
? Using an inductor, we can embed any capacitive sensor into a resonant circuit w/ resonant frequency ????res (Note: The self resonant frequency of the sensor has to be significantly larger than ????res)
Q ? Rcoil ? Rloss ? ? 1 ? ? ?
res 2 LC
?LC ?
M. Lemkin and B. Boser, •A three-axis micromachined accelerometer with a CMOS position-sense interface and digital offset-trim electronics, JSSC, pp- 456-468, April 1999
? Differential readout topologies greatly suppress common mode interferences (power supply noise, charge injection, substrate noise)
? Using the differential charge integrator on the top right with the drive signal applied to the proof mass, only one excitation source is required ? The output signal of this structure is given by ? ?
? ?C ?
C ? ?C
? ?C C ?
?V ? ??V
? ? s ? ?1? s ? ? i p ? s ?
out ex ? C
? C ? C ? C ?
C C ? C ? C ?
? i ?
••s
_•i
••,p ?
••i
••_•s
••i
•,p ?
? gain error
offset error ?
? ?
M. Lemkin and B. Boser, •A three-axis micromachined accelerometer with a CMOS position-sense interface and digital offset-trim electronics, JSSC, pp- 456-468, April 1999
? W/o the input common mode feedback (ICMFB), the opamp•s input common mode voltage would make steps ???iCM in response to the steps in ???? The opamp needs a large input CMR and CMRR ? The CM feedback amplifier senses the input common mode voltage of the main opamp, compares it against a reference and applies the required voltage at the foot point of the bridge formed

by ????1, ????2, ????????1 and ????????2 required to bring the input common mode voltage back to its nominal value after every jump
Parallel plate capacitor Comb finger capacitor
C ? ?
? A
?C ?x ? ? ?
? ? A
N :
f i n g e r s h :
f i n g e r
h e i g h t C ? x ? ? N ? ? ? h ? ?L ? x ?
?C ?x ?
? ?N ? ? ? h
x0 ? x
?x ?x0
? x ?2
g ?x g
Capacitive structures can be used for both sensing and actuation. We can use this to form feedback systems around a capacitive sensors!
? In a capacitive sensor with comb structure, we typically exploit the possibility of realizing differential capacitances ? We either need dedicated electrodes to apply the force or we can use the same electrodes for sensing and actuation by time multiplexing the electrodes (in this case ??s1 = ??a1, ??s2 = ??a2) ? ??FB is the voltage applied to generate the electrostatic feedback. For ??FB = 0 the net force is zero and the plate moves back to the center position ? In contrast to the single-ended case, here the voltage-force relation is linear
? Modeling the mechanical resonator
C0 : static capacitance
Index •m•identifies motional quantities
? Assuming a parallel plate structure for the sensor, we obtain:
Fmech : mechanical force (e.g. gravity) Vn : noise in the voltage across the capacitor
Vn ?t ? ?Vn ?t ? ? ?
? 2 ? kBT ? R ? ? ?? ?
Fn : mechanical force noise
Fn ?t ? ? Fn ?t ? ? ?
? 2 ? kBT ?? ? ? ?? ?
? Nonlinear dynamics (nonlinear in the voltage only) ? Coupling between electrical and mechanical noise ? In a nonlinear system, the superposition principle does not apply ? To obtain the intrinsic sensor SNR, we only have to consider the force noise ???? and compute its effect on the sensor output quantity!
? The transfer function from the mechanical noise to the displacement ?? is
? The displacement noise PSD due to the force noise ???? const. then becomes:
= 2?????????? =
? Displacement noise due to mechanical force noise at ????:
? Displacement noise due to mechanical force noise at ?? = 0:
? Low frequency noise decreases by increasing the quality factor ???? (i.e. by decreasing friction) here vacuum encapsulation helps ? BUT: Noise at the resonance frequency increases with ????!
? Signal (i.e. displacement in response to an applied force)
? Signal is shaped in the same way as the noise
? Synchronous demodulation delivers magnitude, phase, real part and imaginary part of the frequency response in one frequency sweep!
? Why feedback?
Y ? A ? X
Y ? A ? X
1? ? A ? 1 ? X ?
For large loop gains ?? ? ??
? In a feedback system with sufficiently large loop gain, sensitivity and linearity are NOT determined by the sensor ?? but rather by the feedback network. This is typically easier to achieve!
? Feedback around the sensor can be used to enhance the bandwidth ? Feedback (FB) does not improve the SNR per se ? However, it allows for the use of very high-Q structures thereby FB indirectly helps to lower the Brownian motion noise (the random motion of the structure)
? Typical open loop response of the sensor is a resonant 2nd order system ? What type of controller should you use for the FB?
•P-controller alone not a good idea because of insufficient phase margin (PM) •PD-controller (lead compensation) introduces additional PM
KP ? 50,
K ? 5 ?10?3
•Could add an I-controller part (full PID-controller) to null steady state errors
? The feedback signal is used to keep the comb structure at nearly zero displacement minimum effect of nonlinearity ? The same electrode is used for sensing and applying the feedback signal. How is this possible? Frequency domain separation of the feedback and the sense signal (synchronous demodulation)
? For a single-ended capacitive structure, the voltage-force relationship is non-linear (cf. slide 98)
? However, we would like to have a linear voltage-force relationship to obtain an overall linear feedback loop we could either use a nonlinear controller which cancels the nonlinearity (i.e. a square root controller) Or we can use a force feedback with two values only •The connection between two points is always a straight line (only gain error and offset possible) •Can apply a two point force feedback by exploiting the sigma-delta modulation technique •Pulse-density modulation rather than amplitude modulation C. Lu, M. Lemkin, and B.Boser, •A monolithic surface micromachined accelerometer with digital output•, JSSC, pp. 1367-1373, Dec. 1995
? The compensation block is required for system stability (essentially a digital lead compensation) ? Also, the compensation block can be used to optimize the noise shaping performance of the closed system
Analog feedback ? Continuous feedback minimizes ??in ? ??FB ? The output is an analog signal Digital feedback ? ?? minimizes mean of ??in ? ??FB ? Mean of ??FB and ??out track ??in ? ??in can be recovered by low pass filtering ??out ? The digital feedback system is clocked
? Measuring the capacitance value using the charge redistribution method •Step1: S3 closed, S1 to ??ref, S2 to gnd, DAC output is set to 0 ???? forced to gnd by the amplifier in feedback, ???? is charged to ?????? = ??ref ? ???? •Step2: S3 opened, S1 to gnd, S2 to ??ref, ??DAC = 0 S3 open freezes charge on node ????, total charge on node ????:
Q ? v ?C ? ?v ?V ? ?C ? v ?C ? ?Q ? ?V ?C ==¿ v ? V ?
CS ? CR
x x R x ref S x C R ref R x ref
C ? C ? C
•Step3: Adjust ??DAC until ???? = 0
S R C
Qx ? vx ?CR ? ?vx ?Vref ? ?CS ? ?vx
? vDAC ? ?CC
? ?QR
? ?Vref
?CR
Integrated Interface Circuits •Chapter 2: Sensor types
? Embed a differential capacitive sensor into a relaxation oscillator
v1 ?t ? ? sgn ??vc ?t ???
vc ?t ? ? v1
?t ? ? ??v
2 ?t ? ? v1
?t ??? R ? R
7 8
v ?t ? ? ? 1 ? v ?? ?d? ?
1 ? v
?? ?d?
2 RC ? 1
RC ?
out
3 1 1 1 R dv2 ?t ? v4 ?t ? ? ? 2 ? v1 ?t ? ? R2C2 ? R4 dt R vout ?t ? ? ? 6 ? v4 ?t ? R5
? Embed a differential capacitive sensor into a relaxation oscillator
Integrated Interface Circuits •Differential Measurements
Jens Anders Institute for Theory of Electrical Engineering Department of Electrical Engineering and Computer Science University of Stuttgart
? Differential signaling has many advantages compared to single-ended signaling •Inherent rejection to common-mode interference and noise •Wider signal swing for a given supply voltage •Minimum effect of even order distortion including DC offset •Can lead to improved sensor linearity
? BUT most practical amplifiers also respond to some degree to common-mode signals at their inputs •The relevant figure is the common-mode rejection ratio (CMRR) •Good amplifiers for high-end sensing applications have CMRRs better than 120 dB
? A simple diff amp consists of a differential pair with resistive load ? Its output voltage can be written as ? Assuming ideal components (i.e. no mismatch and an ideal current source) this structure provides: •No offset •An infinite CMRR and PSRR ? Differential pairs can be easily built using both MOS and bipolar transistors ? Definition of CMRR
? Definition of PSRR
? In practical differential amplifiers component mismatch (??1 ? ??2, ??1 ? ??2) and imperfect current sources (??out? ?) lead to •Offset •Finite CMRR and PSRR ? Mismatch is mainly due to process variation lithographic errors
? Intuitive interpretation: the input referred offset voltage is the voltage, which needs to be applied to obtain zero volts differential output voltage
v ? ? R
? ?RL ? ? ? I
? ?ID ? ? ? R
? ?RL ? ? ? I ? ?ID ?
?
out ? Lav 2 ? ? Dav 2 ? ? Lav 2 ? ? Dav 2 ? ? ? ? ? ? ? ? ?
? Next, we need to approximate ????? = ????1 ? ????2
?I ?
?1 ? ?V ?V
? nV
?2 ? ?2
? ?V ?V
? nV ?2
D 2n
G1 T01
S 2n
G 2 T02 S
? Same idea as before: Introduce
?? ?
? ? , ?
?1 ? ?2 , ?V V
?V , V
VT01 ? VT02 , ?V V
?V , V
VG1 ? VG2
1 2 av 2
T0 T01 T02 T0av 2
G G1 G2 Gav 2
?av
? ?? ? ?
?V ? ?
?V ? ?2
?I ? 2 ? V
? G ? V
? T0
? nV
D 2n
? ??
Gav
2 ??
?? T0av
2 ?? S ?
? ?
?av
? ?? ? ?
?V ? ?
?V ? ?2
? 2 ? V
? G ? V
? T0
? nV
2n ? ??
Gav
2 ??
?? T0av
2 ?? S ?
? ?
?ID
? ?ID ?? ?0,?V ?0,?V ?0 ? ? 0
?? ?0,?VT0 ?0,?VG ?0
? ?? ?
?? ?0,?VT0 ?0,?VG ?0
? ?VT0 ?
?? ?0,?VT0 ?0,?VG ?0
? ?VG
? Evaluating the expression from the previous slide, we find:
?ID ?
1 ? ??
? Gmav
? ?V
? Gmav
? ?V , G
? ?IDav
I ? I
T0 I
G mav ?V
Dav av Dav Dav Gav
! vout ? 0 ==¿ 0 ? R ? I
? ? ??
? Gmav
? ?V
? Gmav
? ?V
? ? I
? ?R
Lav Dav ? ? I
T0 I
G ? Dav L

? av Dav Dav ?
? Now, we need to solve this equation for ???G = ??OS, resulting in
? Finding from previous slide
? ??mav/??Dav is an important parameter which largely varies vs. the operating point of a MOSFET ? Moreover, the above derivation also holds true for BJTs with the difference that ???????
? 0 for BJTs (????
= ???? ??
is equal for both devices)
? The achievable offset voltages can thus be summarized as follows:
10 mV ? 2 ??ov
1 ? 100 mV
MOS (SI)
1 mV
120 ?V
1 ? ? 1/26 mV ?? no change
BJT
With offset trimming (Laser, fusible links)
? In a real-world differential pair mismatch and finite output impedance of the current source also lead to finite CMRR ? As before, decompose all quantities according to
?G G
? G , G
Gm1 ? Gm2
m m1 m2 mav 2
?R R
? R , R
RL1 ? RL2
L L1 L2 Lav 2 ? Then, performing a simple nodal analysis yields
? Using the result from the previous slide, the CMRR of a diff pair becomes
CMRR 20 ? log? A
ADM ? ?
ADM
?
? ?Gmav ? RLav
CM-to-DM ?
ACM-to-DM
? ? ?Gmav ? ?RL 2G
? RLav ? ?Gm ? ? r
mav out
? ?
? Relating ???m/??mav to physical parameters, we obtain:
G ? , I
? ?av
? ?V ?V
? nV ?2
?G ?
?Gm
? ??
? ?Gm ?
?ID ?V
mav
Dav 2n
G T0 S
m ??
?I ?V T0
D T0
? Note:
Question: Is there any link between CMRR and offset?
? Expression for ??OS assuming random fluctuations in ?????, ? ?? and ??????? the signs of the individual terms do not matter (worst case all are added)
? Expression for (linear) CMRR assuming random fluctuations in ?????, ? ?? and ??????? (again worst case all are added)
? These two expressions look quite similar, ignoring the little difference
caused by the factor of 1 2
and multiplying the two expressions, we find:
? From previous slide ? Note: ??mav ? ??ov = ??BIAS
? Recall: ??out
= ???? (??BIAS/2)
where ????
is the modulation voltage (modeling channel length modulation) ? Note: Our derivation actually also holds true for BJTs and MOSFETs in weak inversion
? The power supply rejection ratio(s) is/are defined as:
Slide 16 PSRRVDD calculation ? First let us calculate the PSRR for the positive supply, PSRRVDD ? As long as the finite output conductance of ??1 and ??2 are neglected, mismatch in ??L1,2 and ??1,2 result in no differential output voltage, i.e. infinite PSRRVDD ? Assuming:
RL1 ? RLav
? ?RL,
RL2
? RLav
? ?RL
Gm1 ? Gmav
? ?Gm,
Gm2
? Gmav
? ?Gm
and finite output conductances of ??1,2 of ??outM1,2, the resulting PSRR becomes resulting in a PSRRVDD of
Slide 17 P????RRV??????? calculation ? Assuming:
RL1 ? RLav
? ?RL,
RL2
? RLav
? ?RL
Gm1 ? Gmav
? ?Gm,
Gm2
? Gmav
? ?Gm
and finite output conductances of the current source ??out, the resulting PSRR becomes
? Recall from the previous slide:
Integrated Interface Circuits •Modulation techniques to improve low frequency performance
Jens Anders Institute of Smart Sensors Department of Electrical Engineering and Computer Science University of Stuttgart
? Synonyms: coherent detection, synchronous demodulation, lock-in amplification, chopping
? These are all modulation techniques that are used to improve the low frequency performance of measurement systems ? When square-wave modulation is employed the technique is referred to as chopping ? Chopping leads to improved low-frequency specifications e.g. reduced offset and 1/???? noise, better CMRR and PSRR
? Characterized by •Offset, gain error •Drift, 1/???? noise •PSRR, CMRR ? Offset, gain error and 1/???? noise are caused by component mismatch and non-idealities they are a part of life ? But we can reduce their effects by •Static techniques like calibration and trimming •Dynamic techniques such as chopping, auto-zeroing and dynamic element matching
? Involves measuring a static error of a system (e.g. offset or gain error) and then adjusting the value of a component in order to reduce the error to zero + Low complexity + No bandwidth limitation - Requires measurement equipment ? Also requires a memory element to store the trimmed value e.g. a potentiometer or a PROM C
Vin
Vout
? Techniques which continuously attempt to cancel the effect of system non-idealities to zero. + (Usually) do not require measurement equipment + Also compensate for drift and 1/???? noise and improve CMRR and PSRR - Requires more complex circuitry - Reduce bandwidth
? Two main Dynamic Offset Cancellation (DOC) techniques are: Chopping and Auto-zeroing
? Time domain: Auto-zeroing periodically measure the offset (the noise) and subtract it from the input signal ? Frequency domain: Chopping modulating the input signal above the 1/???? noise
? Signal is modulated, amplified and then demodulated ? DC offset is modulated once and the resulting AC signal can be removed by a low-pass filter ? The modulators are usually implemented as polarity reversing switches, known as choppers ? The technique is known as chopping
? Easily generated modulating signal ? Modulator is a simple polarity-reversing switch
? Switches are easily realized in CMOS
? Output chopper converts offset into a square-wave ? To avoid residual offset, the duty-cycle of the square-wave should be exactly 50? Non-ideal LPF residual ripple
? Complete suppression of 1/???? noise if ????ch ¿ 1/???? corner frequency
but harmonics slightly (??2 8
? 1.23) higher noise power
because noise from higher harmonics folds into baseband ? Up-modulated offset must be filtered out loss of signal bandwidth and residual chopper •ripple•
xsquare ?t ? ?
4 ? ? k ?1
sin?2? ?2k 2k
? 1?? fch ? 1
? t ?
? Turning off/on the switch injects charge in ??L ? How much of the charge is added to ??L? •Usual assumption: The charge splits half-half •In reality the amount of charge is a complex function of the impedance at each terminal and the transition time of the clock ? ???? is linear (proportional) w.r.t the transistor area ???? ? ?? and nonlinear w.r.t. ??in
Q ? W
? L ?C ? ?V
?Vin
?VT0 ? ??
? ? ? ??out can be decomposed into a term linear w.r.t ??in and a 2nd term nonlinear w.r.t ??in Distortion ? ?
V ? V
?1? W
? L ?Cox
? ? W
? L ?Cox
? ?V ?V
? ??
out
in ?
2C ? 2C
? ? T0 ?
•_L•, ? gain error ?
••L •••_•••••, offset , dostortion
? Capacitive coupling due to ??OV capacitive divider between ??OV and ??L
? Clock transition couples to ??out and creates an error
? ???out is independent of ???in
? ???out is linear w.r.t capacitive divider ratio constant offset
? Clock asymmetry (non-50? Spikes at the amplifier•s output due to clock feedthrough and charge injection ? Demodulation of these spikes back to DC by the output chopper residual offset (in the range of millivolts) ? Residual offset is proportional to the chopping frequency
? Limited amplifier bandwidth results in an output signal which is not a perfect square-wave less power at the harmonic less gain ? Chopping reduces DC gain
? Chopping is a powerful technique that can be used to reduce offset and 1/???? noise in amplifiers and systems
? Main drawback: the need for a LPF to remove the up-modulated offset bandwidth limitation
? Main non-idealities are caused by: bandwidth, clock asymmetry and chopper spikes
? Offsets as low as a few nV can be achieved
? Three-stage amplifier, first two stages are chopped ? 1 mHz 1/???? corner frequency, 5 •V offset voltage, CMRR , PSRR ¿ 120 dB
R. Wu, K.A.A. Makinwa and J.H. Huijsing, ”A Chopper Current-Feedback Instrumentation Amplifier With a 1 mHz Noise Corner and an AC-Coupled Ripple Reduction Loop,” Solid-State Circuits, IEEE Journal of , vol. 44, no. 12, pp. 3232-3243, Dec. 2009
Analog Storage Digital Storage
Vin
Vo ut
Vin
?2 S ?1
A 1
N Vn CLK
V o u t A2
SAR = Successive Approximation Register DAC ? Sampling the unwanted signal (noise and offset) during ?1 ? Storing this value (analog or digital) ? Subtracting the stored value from the input signal during ?2 ? Amplifier is disconnected from signal path during ?1 ? An auxiliary port N can be used to apply the stored value offset and low-frequency noise can be greatly reduced
Vref
? S1 and S2 are closed ??out = ??OS ? The amplifier•s offset is stored on ??az
? S3 is closed output signal is available ? For an amplifier with finite DC gain ??, the residual offset is given by ??OS/(?? + 1)
? Clock feedthrough and charge injection errors in stored offset
? Stored offset on ??az will slowly leak away
? In practice, ??az is made as large as possible
? Use minimum size switches (subject to noise , speed requirements)
? Use differential topologies for 1st order cancellation
? Use complementary switches
? Use dummy switches
? Use bottom plate sampling
? The error in the differential output signal can be written as:
?Q2
? ?Q1 ? W ? L ?Cox ???Vinp
?Vinn ? ? ?VT02 ?VT01 ???
? W ? L ?Cox ??Vinp
?Vinn ? ? ? ? 2?F
? VT02 ?
2?F
? VT01 ??

? ? perfect cancelation is only achieved for zero differential input signal (??inp = ??inn)
? BUT: The constant offset as well as the nonlinearity due to the square root term are reduced compared to a single-ended switch
? Use an NMOS and a PMOS switch in parallel we can achieve a first order cancelation of the opposite charge packets. To this end we need: Consequently, the drain source cancelation can only occur for one input level ??in ? Also for clock feedthrough, there is not a perfect cancelation due to the different overlap capacitances of NMOS and PMOS
? Assuming the charge injection due to ??1 is:
? Then, since the charge injection of ??2is for ??2 = ??1 and ????2 = 0.5 ? ????1 the two charge packages cancel ? Unfortunately, the assumption of equal charge splitting of ??1 is in general not valid ? Fortunately, the above choice of ??2 also mitigates clock feedthrough
? Switch ??2 opens slightly earlier than ??1 the charge injected by the opening of ??2 is constant and can be eliminated by using differential sampling ? Since the bottom plate of ??az is floating when ??1 is opened, no charge is injected on ??az ? This scheme works very well but requires an additional clock signal
Slide 29 Effect of Autozeroing on Noise VC R
VN
When switch S is open:
VAZ
VAZ
? VN
?VC
for: RC
•TAZ
? Each time the switch ?? is closed, the output voltage ??AZ is reset to zero and the noise source voltage ??N appears across resistor ?? and capacitor ?? ? Assuming ???? ? ??AZ at the end of the sampling phase (when switch ?? opens) the noise voltage is sampled onto capacitor ?? ? The output voltage ??AZ becomes equal to the difference between the instantaneous voltage ???? and the voltage ???? stored on ?? DC component of ???? is eliminated but HF is passed
? If the source voltage ????(??) corresponds to a stationary random noise with PSD ??????(????), the PSD of the autozero voltage ????????(??) across the switch can be decomposed into two components: •One caused by the baseband noise (which is reduced by the autozeroing process) •And the other one created by the foldover components introduced by aliasing:
S ?f ? ? H
?f ? 2 ? S
?f ? ? S
?f ?
VAZ
0••_•VN•, baseband
•fo_ld •, foldover
where:
Sfold ?f ? ?
??
n??? n?0
2 Hn ?f ? ? S ? ?
n ? ? ? Ts ?
? The baseband transfer function is given by:
2 ? ?
sin?2? ? f ?T ??2
?
cos?2? ? f ?T ??2 ?
H ?f ? ? d 2 ? ? ?1?
h ? ? ?1?
h ? ? ? ? ? f ?T for ? ? f ?T •1
0 ? 2? ? f
?Th ? ?
2? ? f
?Th ? ?
where ?? = ???/???? is the duty cycle (???? = ??? + ???????)
S ?f ? ? H
?f ? 2 ? S
?f ? ? S
?f ?
VAZ
0••_•VN•, baseband
•fo_ld •, foldover
Sfold ?f ? ?
??
n??? n?0
2 Hn ?f ? ? S ? ?
n ? ? ? Ts ?
? The baseband transfer function imposes a zero at ???? = 0, which cancels out any DC component present in ????(??) ? The transfer functions for ?? ? 0 are given by: ? sin?? ? f ?T ??2
H ?f ? ? ?d ?
h ? for
n ? 0 and T •T
n ? ? ? f
?Th ?
AZ h
S f ? AZ
H ?f ? 2 ? S
?f ? ? Sfold
?f ?
with:
SV ?
?f ? ?
S0
1? ?f fc ?
? In order to use the previous analysis, we simply have to replace the voltage source ???? by the noise at the output of the AZ amplifier
? The baseband signal is autozeroed by ??0 2 while the PSD of the autozeroed signal is dominated by the foldover component
S ?f ? ? sinc2 ?? ? f ?T ? ? S
? f ?
n ? ? sinc2 ?? ? f
?T ? ? ?? ? f
?T ? 1? ? S
fold
s ? n ? ? ? n ? 0
VN? ? ?
? Ts ?
c
s
c
0
Reference: C. Enz and G.C. Temes, Proc. IEEE, Nov. 1996
S f ? AZ
H ?f ? 2 ? S
?f ? ? Sfold
?f ?
with:
SV ?
?f ? ? ?
1
1? ?f fc ?
? The baseband 1/f is eliminated by the high-pass filtering action of
??0 2
? An additional foldover component is present in the autozeroed output
S ?f ? ? sinc2 ?? ? f ?T ? ? S
? f ?
n ? ? sinc2 ?? ? f
?T ?
2 f T ?
? 2 ? f
?T ?? ? S
fold
s ? VN? ? T ?
c s ? ? k ?
s ? ?1? In? 3
c s ?? 0
n??? ? s ? n?0
? ? ??
Reference: C.C. Enz and G.C. Temes, Proc. IEEE, Nov. 1996
? Auto-Zeroing is a powerful offset and 1/f noise reduction technique for amplifiers and systems ? Unlike chopping, it does not suffer from ripples, but its noise performance is worse due to aliasing ? Main non-idealities are caused by switching spikes, leakage currents and (sometimes) by finite gain ? Offsets of a few microvolts can be reached
? CDS is a special case of AZ frequently used in SC circuits ? SC circuits are sampled data systems clock available •Phase 1: calibration phase: ??1 = ??(??1) = ?? ? •Phase 2: operation phase: ??2 = ??(??2) = ?? ? (??2 ? ??1) = ?? ? ??in
? To maximize suppression of 1/f noise, the interval ??1 ? ??2 should be as short as possible
? For small signals, offset dominates (can use AZ, CHS, •) ? For large signals, gain error dominates
? Both gain error and offset are static errors, which can be removed by calibration and/or trimming ? It can also be removed by dynamic element matching (DEM)
? If ?? ? ?? ? 1 ??CL ? 1/??
? For moderate 1/??, DC-gain of op-amp is large enough
? ??: Resistor/Capacitor ratio •Resistors: 0.01•Capacitors: 1
? So feedback allows us to replace the inaccurate gain of open loop amplifiers by well defined ratios of passive components Can we do better?
? Idea: In a sensor system we would like to know ??in but we do not know (precisely) ?? and ??OS for 3 unknowns, we need 3 equations
? 3 Phases are required for a measurement: •Phase 1: ??1 = ?? ? •Phase 2: ??2 = ?? ? •Phase 1: ??3 = ?? ? ??OS ??, ??OS and ??in can be found Accuracy is limited by ADC resolution and noise
? Gain errors can be further reduced by using Dynamic Element Matching (DEM) ? DEM involves swapping the position of nominally identical elements within a circuit ? The average error is significantly reduced ? Gain of 2 ? 2 identical resistors i.e. ??1 = ??2 ? DEM can be applied by using switches to swap the position of mismatched resistors in the circuit ? Accuracy is limited by mismatch of switch resistance
? Accurate gain 2 amplifier with DEM ? Average value of ??out ? 2??in ? ??out contains AC components which must be removed by a LPF (like in chopping) ? Chopping and DEM can be easily combined
? Mismatch is shifted to the harmonics of ????DEM ? To avoid unwanted intermodulation, keep ????in ¡ ????DEM/2
? Pro •Gain (ratio) error can be reduced to ppm levels ? Cons •Switches are required to swap components extra circuit complexity, switching transients •Result must be averaged BW reduction •Input signal must be band-limited (????in ¡ ????DEM/2) to prevent inter-modulation products
? Precise gain can be achieved by feedback •discrete resistors: 0.01•on-chip: 0.1? Better performance can be achieved by using DEM, but like chopping, this is at the expense of BW
? If the signal is digitized, the 3-signal method is also effective, but accuracy is limited by ADC resolution
Chapter 5
Coherent Detection
Jens Anders Institute of Smart Sensors Department of Electrical Engineering and Computer Science University of Stuttgart
? Review: •Synonyms: coherent detection, synchronous demodulation, lock-in amplification, chopping •These are all modulation techniques that are used to improve the low frequency performance of measurement systems •When square-wave modulation is employed, the technique is referred to as chopping ? Today we talk about coherent detection/lock-in amplification ? This technique is very similar to chopping except that one uses a sine wave instead of a rectangular waveform for modulation
? When to use it? •When measuring low-bandwidth or quasi-static signals in the presence of high noise or disturbance levels •If a high dynamic range is required ? Therefore it is often used to readout sensors such as: •(MEMS) Accelerometers (fF of capacitance change) •Optical (infrared) detectors (detecting fA•s of current change) •Magnetic sensors (detecting mV•s of voltage change) •Strain gauges (detecting mV•s of voltage change) ? A coherent detector behaves like a band-pass filter
? Setup:
? ??oM = ??Amp ? ??mult?
??????? ? sin
? ????? sin
? ??oM
= ??Amp
? ??mult
? ????????????? ? 2
cos
? cos
? For ???? = ?????? (?????? is derived from ???? ? coherent signals):
??oM
= ??Amp
? ??mult
? ????????????? ? 2
1 ? cos
? ??oM
= ??Amp
? ??mult
? ????????????? ? 2
1 ? cos
(????
= ??
????)
? LPF to remove the sum frequency:
??oF
= ??LPF
? ??Amp
? ??mult
? ??????? ????? 2
? A coherent detector directly extracts the amplitude of the input signal ?????? if ??i and ??ref are in phase (Synchronous detection) ? What if they are not in-phase?
? ??oM = ??Amp ? ??mult ?
??????? ? sin ?????? ?? + ?? ? ?????? sin ??????
= ??Amp

??mult
??????? ???
2
cos
? cos [????
+??????
]?? + ??
? ??oF
= ??LPF
? ??Amp
? ??mult
? ???????????? 2
=0 LPF ? cos
? Phase sensitive coherent detector
? What would be the SNR of ? an oscilloscope (wideband, LPF) ? a coherent detector (narrowband, BPF)
? Some numbers: ? What would be the detection limit of the coherent detector if the white noise spectral density is 10nV/?Hz and fLPF = 1Hz?
????????
????V ?
= ???????? ????V
ui ? u•i
? cos ??r t
? ? ?
? Use a quadrature LO to obtain both the phase and the amplitude information
? Linear operation of an analog multiplier circuit, working over a large range of input signals is difficult to realize. ? A much simpler realization is a switching detector aka a chopper ? Chopper realization in CMOS: •Easy: just 4 Transistors •Accurate: no offset introduced •But: switching spikes can cause problems (residual offset)
? An ideal coherent detector is only sensitive to frequency components in a narrow band around a reference signal ??ref ? The LPF determines the signal bandwidth
A practical example •ESR DETECTION
Analyzing the structure and dynamics of •biomolecules•Source: SREP (http://sites.univ-provence.fr/srep/index.html)
Food industry: Quality control
Biomedical Imaging •Sensor Fusion
Source: S. Liu et al., Applications of in vivo EPR in brain research: Monitoring tissue oxygenation, blood flow, and oxidative stress
In-vivo ESR Dosimetry
Source: EPR Center Dartmouth College
? What is •spin•? ? A property of some particles like mass and charge
? What do we need to know to detect them?
? A spin
???
always comes along with an angular momentum
???
and a magnetic
dipole moment
???
I•?: reduced Planck constant ????: gyromagnetic ratio
Parameters: Free electron
???? ???????
? ?????????.024 GHz/T
?????? = ???????? ???????? ?????? = ????????
????T ? ??RF = ???? for ?????? = ????. ???? T
Circulator operation: Non-reciprocal 3-port w/ S-parameter matrix:
? 0 0 1? S ? ? 1 0 0 ? ? 0 1 0 ?
Incident power at one port is transferred to the next port
? Sample absorption is a (resonant) function of the static ??????-field ? Resonator containing the sample is critically coupled at Larmor frequency (critically coupled resonator ? no reflected power) ? Static ??????-field is swept through the resonance field Resonant sample absorption changes cavity Q factor Reflected power at circulator output varies as function of ?????? CW -ESR spectrum is the reflected power vs. ??????
ESR •DC•spectrum Parameters: Free electron
???? ???????
? ?????????.024 GHz/T
?????? = ???????? ???????? ?????? = ????????
????T ? ??RF = ???? for ?????? = ????. ???? T
? ESR signal inherits the absorption shape (associated w/ sample loss) ? Resonance condition: ??RF = ??L = ???????????
? When sweeping ??
????
, the peak occurs at ??
????
= ???RF ????
ESR signal generation in the presence of field modulation
Resulting ESR signal for small modulation fields
? The •DC•ESR spectrum is relatively noisy due to low frequency disturbances (e.g. 1/f noise and drift) ? The signal is modulated to an IF by modulating the ??????-field ? In this way, a lock-in amplifier can be used to extract the signal
Chapter 6 Integrated Interface Circuits •DACs
Jens Anders Institute of Smart Sensors Department of Electrical Engineering and Computer Science University of Stuttgart
? Recap: digitization •Time discretization (sampling) •Value discretization (quantization)
? Digital-to-analog conversion ? Analog-to-digital conversion
Integrated Interface Circuits •Chapter 6: DACs
? Sampling is the conversion of a time-continuous signal into a value equivalent, time-discrete signal ? Prerequisite: Nyquist sampling theorem: To be able to perfectly reconstruct a band limited signal ????max = ?????? from an equidistantly sampled version (sampling frequency ?????? = 1/????) of it, the sampling frequency must satisfy ?????? ?
?????? = 2 ? ??????
? Quantization: •Value discretization in steps of one LSB •Infinite set of values ? finite set of values •E.g., rounding
? Sample: S is closed, ??out = ??in ? Hold: S is open, C holds ??out
? IC1 with small Zout for fast charging of C ? IC2 with high Zin for slow discharge of C ? Switch: Transmission gate or single FET with small Ron
? Aperture time: time required for the switch to open ? Droop: discharge of capacitor ? Acquisition time: time to switch and charge the capacitor ? Switching transients: voltage buffer ringing ? How to design C? •Large enough for small droop, small enough for fast charging •Fast charging depends on ??on of the switch and ??out or ??out,max of IC1 •Sufficiently large for sufficiently small kT noise C
? Analog multiplexer use transmission gates which are bi-directional: MUX , DEMUX
? Functionality ? Static DAC errors •Gain , offset error •Differential non-linearity (DNL) •Integral non-linearity (INL) ? Dynamic DAC errors •Jitter, Glitches ? Types of DACs
? Convert transient digital input signal to a transient analog output signal ? Output voltage variation upon the variation of 1 LSB at the input ??LSB ? Maximum (full scale) input voltage ??FS
VLSB
? Vref 2N
VFS
? Vref
2N ? 1 2N
? Gain error: Offset error:
? Gain and offset errors do not affect linearity!
? If needed, they are easy to compensate •e.g., by pre-processing: scaling, shifting
? Differential nonlinearity (DNL) is a measure of (non-) uniformity ? The vector DNL(k) quantifies for each code k the deviation of the step size from the ideal (or average, in case of gain error) step size of 1 LSB
k DNL(k) 000 N/D 001 -0.4 010 0.2 011 0.9 100 -0.7 101 0.9 110 -0.2 111 -0.7
Note: no gain and offset error in this example!
? What if DNL(??) is smaller than ?1?
•The output value ?? is smaller than the previous sample ??(?? ? 1)
•Characteristic is non-monotonic! ? Critical for feedback structures since non-monotonicity turns negative into positive feedback ? Occurs most often when switching the MSB
? Integral nonlinearity INL(k) is the deviation from the output value V(k) from the ideal output value Videal(k)
? If
????NL
? ????. ???? then
DNL
? ???? (mo noto nicit y)
Note: no gain and offset error in this example!
? Clock frequency/phase varies slightly •Clock edges affected by jitter •Uncertainity of the position of the clock edge ? Rough estimation: •Sinusoidal signal:
•Maximum change rate:
•Maximum jitter for error below one LSB:
? 10-bit DAC with 10 MSamples/s requires 30 ps accurate clock edges!
? Glitches occur when turn-off and turn-on times are not precisely synchronized ? S2 represents the MSB output signal ? S1 represents the (?? ? 1) ? LSB output signal ? Example: transition S1 = 0111 to S2 = 1000
? Resistor string DAC ? Binary weighted resistive voltage divider DAC ? Binary weighted current source DAC ? Thermometer weighted DAC ? R-2R ladder DAC ? Pulse width modulation
? Simple voltage divider
? Inherently monotonic
? Amount of resistors proportional to 2N •3 bit ? 8 resistors •8 bit ? 256 resistors •Resistors are large
Slide 19 Binary Weighted Resistive Voltage Divider DAC (1/2) ? Inverting summing amplifier configuration
? Each bit ???? produces an output voltage according to
? Combined output:
? Impractical for large N: •Area ?? ?? W?? ? ???? ? 2??+1 •Resistors need to be very precise, RMSB must have the highest precision
? Current mirror realization of the current sources:
? Few number of resistors / current sources and switches ? Large ratios of resistors, currents and switches (2N) •Monotonicity not guaranteed •5bit: 1uA, 2uA 4uA, 8uA, 16uA •15uA ? 16uA means switch 4 sources off and 1 source on •Assume statistical variations of 10•1u+2u+4u+8u ¡ 16u is not guaranteed •Linearity •Accuracy •Matching ? Prone to glitches •Large portions of the output are switched on/off
? Current steering DAC:
? Reduced glitches
? Inherently monotonic
? 2N current sources
? Binary to thermometer decoder needed:
? Reduced area: ?? ?? W?? ? ????(3 ? ?? + 2) ? The current ?? in every branch is given by:
? Looking from node ?????? to the left or right one sees a resistance of 2?? The current flowing through each resistor splits half half
? The current in the branch corresponding to bit ???? times split half half
is ???? + 1
? R-2R ladder DAC: switches change from GND to -Vref ? Solution: inverse R-2R network
•Switches change from GND to virtual GND ?
Working principle:
•??left
•??MSB
= 2?? ? ??left
= ? ??re?? 2???
= ? ???????????? 2???
?????????????? •??MSB?1 = ? 2???
LSB MSB
?????????????? •?? = ? 2??? 2???1
I M S B AN-1 AN- 2 A0 Z l e f t
? From previous slide:
Vout,i
? ?di
? Vref
??2R ? ? R 2i
? Vref
? di
?
1
2 i
? 1
LSB MSB
AN-1 AN-2
IMSB A0 Zleft
? Summing amplifier with weighted inputs:
out
C in1 C
in2
f f
? Transfer function from bit ???? to the output voltage:
cf. slide 19!
? Combined output voltage:
? For N bit ? (2N - 1) + 2N unit capacitors ??unit = ??0/2?? •4 bit ? 15 + 16 = 31 unit capacitors ??0/16 ? Impractical for large N: •Area ?? ?? 2 ? A??unit ? 2?? with ????unit being the area of a unit capacitor •Capacitors need to be very precise, CMSB must have the highest precision
MSB-Group
? Example: 8 bit ? 15 + 1 + 15 + 16 = 47 unit capacitors
? Phase 1: reset
Right hand side for 10000000:
Right hand side in general:
? MSB group all caps shorted between gnd and virtual gnd do not matter (i.e. do not store any charge) ? From node ??2 to the output the circuit is a simple SC voltage amplifier with a gain of
??out ??A2
????0 = ? 16 ??0
= ? 1 16
? Question? What is the voltage at node ??2?
Slide 34 Realization with less Capacitors •LSB Group (2/4)
V ? ? Vref V V 2 ? Vref 1
2 A 2
out ? ? ? 4
Slide 35 Realization with less Capacitors •LSB Group (3/4)

V ? ?
V ? ? 1V
A2 C 4 ? 3C
4 ref 4 ref
0 0
V V 2 Vref 1
out
? ? ? ? 16 4 24
Left hand side in general:
? Pulse width modulated bitstream ? Pulse width corresponds to the desired analog output voltage ? RC low pass filter averages the PWM signal
? Combination of various architectures •optimize speed, linearity, •glitches, matching ? Commonly used for high performance DACs ? Course DAC (MSBs) •feeds•fine DAC (LSBs) ? Each source supposed to have Iref •Assume particular source has only 90? Calibration Phase •VGS1 settles so that Q1 draws 10? Operation Phase •Q1 still calibrates so that Id1 = Iref