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A WORK-NOTE on OSCILLATORS - LEARNING by DOING

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Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Lindberg, E. (2005). A WORK-NOTE on OSCILLATORS - LEARNING by DOING.

A WORK-NOTE ON OSCILLATORS [1]

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Abstract

The aim of this work-note is to give insight in computer aided design of electronic oscillators by means of a study of a number of circuits given as figures - equivalent schemes - or as net-list files for electronic circuit analysis programs - "SPICE FILES". For each figure or net-list a number of questions and exercises are specified. The programs PSpice [1], APLAC [2], ANP3 [3] and WINLAP [4] are used as analysis tools.

I. Introduction

REAL OSCILLATORS are **nonlinear** circuits. By means of the *Barkhausen Criteria* a sinusoidal oscillator is normally designed as a linear amplifier with a frequency determining feed-back circuit so that the poles of the whole circuit are on the imaginary axis of the complex frequency plane, i.e. an ideal harmonic oscillator. In order to startup the oscillations some parameters of the circuit are adjusted so that the poles (eigenvalues) of the linearized circuit are in the right-half plane, RHP, i.e. in the dc bias point the circuit is unstable and signals will start to increase when the power supply is connected. It is obvious that if the poles are very close to the imaginary axis the time constant is very large and the transient time to steady state behavior is very large. Due to the nonlinearities, the physical nature of the circuit, the signals

(2'nd edt.),
Presented at a "SOCRATES/ERASMUS course" at Kaunas University of Technology, Lithuania, October , 2005

will always be limited in some way. The crucial point is whether there will be oscillations or just a transition to a new stable dc bias point. Very little is reported about how far out in RHP the poles should be placed initially. Also many authors assume that due to the nonlinearities the poles are fixed on the imaginary axis at a certain constant amplitude of the signals. This assumption is of course not true [5], [6]. The normal classification of oscillators in two groups "sinusoidal" and "relaxation" is questionable because the same oscillator topology may perform both "kinds" of oscillations depending on the parameter choice. Classification should be based on the mechanism behind the behavior.

At a certain instant you may investigate the linearized small signal model of the oscillator. The eigenvalues of the Jacobian of the linearized differential equations are the poles of the network functions. It is obvious that the signals will increase in amplitude if the poles are in RHP and decrease if the eigenvalues are in the left-half plane, LHP, of the complex frequency plane. If you assume that the poles are moving back and forth between RHP and LHP then the mechanism behind the behavior of an oscillator may be described as an act of balance between the energy you gain from the dc power supply when the poles are in RHP and the energy you loose when the poles are in LHP. The study of the movement of the eigenvalues of the Jacobian of the linearized differential equations as function of time is called *"the frozen eigenvalue approach"* [5], [7], [8].

Questions and exercises:

Please perform the following tasks: (1) Search the WWW for information concerning the *Barkhausen Criteria*. (2) Discuss the concept of *Loop Gain*. (3) If you have a circuit with only one nonlinear component then discuss the possibility of calculating the trajectories of the eigenvalues in the complex frequency plane. (4) Suggest your own questions and exercises.

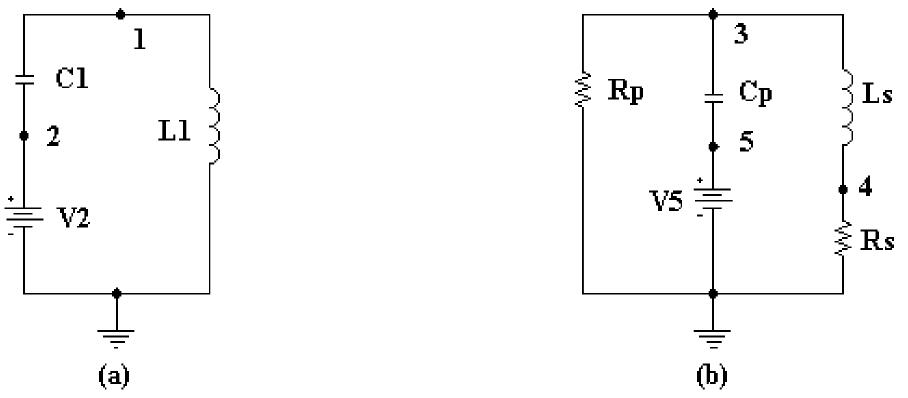

Fig. 1. Linear oscillators. (a) Ideal harmonic oscillator. (b) LC oscillator with losses.

II. "Linear" Oscillators

THE ideal linear harmonic oscillator - fig. 1 (a) - is mathematical fiction. Real linear oscillators are damped RLC circuits - fig. 1 (b). By means of a negative resistor RN in parallel with R_p the losses may be compensated.

Questions and exercises:

Please perform the following tasks: (1) Setup the differential equations for the circuit fig. 1 (b). (2) Find the Laplace transform of the equations. (3) Find the characteristic equation. (4) Find the eigenvalues. (5) Mark the eigenvalues in the complex frequency plane, s-plane, and discuss the performance of the circuit.

Statement: *"A resistor is a current controlled voltage source, CCVS"*.

(6) Discuss this statement. (7) How may other circuit elements (conductors, capacitors and coils) be interpreted as controlled sources ? (8) Discuss how to create a negative resistor by means of e.g. an operational amplifier or a transistor. (9) The component values for fig. 1 are as follows: $C_1 = C_p = 1\text{nF}$, $L_1 = L_s = 10\mu\text{H}$, $R_s = 10\Omega$, $R_p = 1\text{M}\Omega$. The initial conditions (charges on the capacitors at time zero) are modeled as dc sources $V_2 = V_5 = 1\text{Vdc}$. (10) Analyze the circuit by means of ANP3, Capture and PSpice, APLAC. (11) Make experiments with placing a negative resistor RN in parallel with R_p. (12) Find the value of RN (e.g. by means of ANP3) for which the parallel losses R_p and the series losses R_s are compensated. (13) Suggest your own questions and exercises.

III. Oscillators

An oscillator is a circuit which for constant input signal (dc power-supply, battery) produces an oscillating output signal (a steady state time varying signal). An old rule of thumb says that if you want to design an oscillator try to design an amplifier instead and if you want to design an amplifier try to design an oscillator (Murphy's Law).

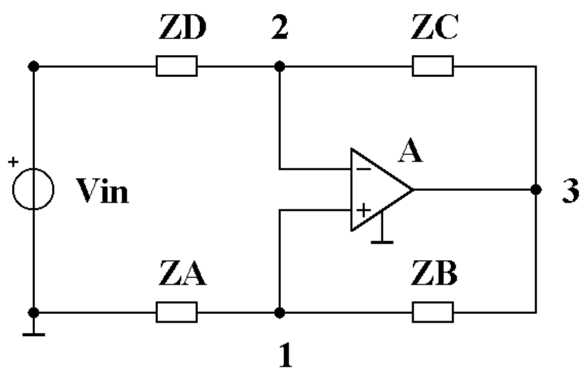

Fig. 2. An amplifier with positive and negative feed-back.

Figure 2 shows a perfect linear amplifier with positive and negative feed-back. The input impedance of the amplifier is assumed infinite and the gain of the amplifier is assumed constant, i.e. $V_3 = A \times (V_1 - V_2)$. If we introduce memory elements - capacitors, coils, hysteresis - in the four impedances various types of oscillators may be obtained [9], [10].

If we observe time varying signals for zero input signal $V_{in} = 0$ we have an oscillator. If the poles of the circuit are in the left half plane (LHP) of the complex frequency plane the signals are damped. If the poles are in RHP the signals are undamped. Only if the poles are on the imaginary axis the signals are steady state signals. This is of course impossible in a real world circuit. The ideal harmonic oscillator may be started with any initial condition and keep its amplitude and frequency constant. It is an impossible act of balance to place the poles exactly on the imaginary axis. Either the poles will be in RHP or in LHP and we have a very large time constant determining the steady state of the oscillator (unstable with infinite large signals or stable with zero signals).

If we want to build an oscillator we must introduce an amplifier with nonlinear gain so that for small signals the poles of the linearized circuit are in RHP and for large signals the poles are in LHP. In this case we may obtain steady state behavior based on balance between energy we obtain from the battery when the poles are in RHP and energy we loose when the poles are in LHP.

In other words *an oscillator is a feed-back amplifier with an unstable dc bias point*. Due to the nonlinear components the linearized small signal model corresponding to the instant bias point will vary with time. The dominating behavior of the circuit is based on the instant placement of the poles of the linearized model. If the poles are in RHP the signals will increase in amplitude. If the poles are in LHP the signals will diminish in amplitude. The investigation of the movements of the eigenvalues of the linearized Jacobian of the differential equations is called *the frozen eigenvalue approach*.

Questions and exercises:

Please perform the following tasks: (1) Derive an expression for the load impedance of the source V_{in} in fig. 2. (2) Discuss the expression for variation of the gain A in the interval $[+\infty\ ,\ -\infty]$. (3) Discuss the concept of inverting/non-inverting amplifier for $A = \infty$. (4) Suggest your own questions and exercises.

IV. LC Oscillators

IF you introduce LC circuits in the impedances Z_A, Z_B, Z_C and Z_D of the feed-back amplifier in fig. 2 you may create a LC oscillator.

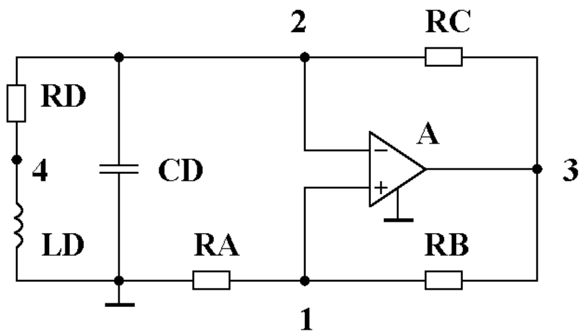

Fig. 3. A negative resistance oscillator

A. Negative Resistance Oscillator

If we replace one of the impedances e.g. Z_D in figure 2 with a passive LC circuit with losses and introduce resistors for the 3 other impedances Z_A, Z_B and Z_C we have a *negative resistance oscillator*, fig. 3.

Questions and exercises:

Please perform the following tasks: (1) Derive for all the 4 impedances in fig. 2 the expressions for the "negative" resistance in parallel to an impedance when the 3 other impedances are resistors (hint: [11]). (2) Show that the negative resistance in parallel with C_D is $R_p = -R_A R_C / R_B$ for $A = \infty$. (3) Discuss the expression for the "negative" resistance in parallel with C_D of fig. 3 for variation of the gain A in the interval $[+\infty\ ,\ -\infty]$. (4) Show that from the expression $2\ \alpha = \left(\frac{R_s}{L} + \frac{G_p}{C}\right) = 0$ where $R_s = RD$, we may calculate the value of the negative resistor needed for placing the poles on the imaginary axis as

$$R_p = \frac{1}{G_p} = -\left(\frac{1}{R_s}\right)\left(\frac{L}{C}\right) .$$

(5) With a given coil $L_D = 256$mH and $R_D = 14.8\Omega$ (the measured series resistance of the coil) design a 10kHz negative resistance oscillator. (6) Analyze the oscillator by means of ANP3, Capture and PSpice, APLAC. (7) Perform experiments with the placement of the poles in RHP for small signals. (8) Perform experiments with changing the sign of the gain A of the amplifier. (9) Discuss your results. (10) Suggest your own questions and exercises.

B. Colpitts Oscillator

The following file is an input file for the APLAC program [2] describing an analysis of a Colpitts oscillator. The file is available from: http://www.es.oersted.dtu.dk/~el/colpitts.txt

```
$ colpts2.i, colpitts oscillator, APLAC input file

$ Transistor model with package parasitics
  DefModel Transistor 3 c b e
  Ind Lc  c  c1 0.2n
  Ind Lb  b  b1 1n
  Ind Le  e  e1 0.9n
  Cap Cbc c1 b1 0.5p
  Cap Cce c1 e1 0.3p
  Cap Cbe b1 e1 0.5p
  Model BJTRF1   IS=0.89f BF=105 IKF=200m NF=1.01  ISE=54f   TF=23p
  +     NE=1.55  VAF=45   BR=13  IKR=20m  NR=1.01  ISC=50f
  +     NC=2.12  VAR=5    RE=0.7 RC=2.2   RB=10    CJC=0.74p
  +     CJE=2.1p VJC=0.60 TR=2n  VJE=0.60 MJC=0.51 MJE=0.36
  BJT q1 c1 b1 e1 MODEL=BJTRF1
EndModel

$ Simple Transistor model without package parasitics
  DefModel TransX  3 cc bb ee
  Model BJTRF1   IS=0.89f BF=105
$ + IKF=200m NF=1.01  ISE=54f   TF=23p
$ + NE=1.55 AF=45 BR=13 IKR=20m  NR=1.01  ISC=50f
$ + NC=2.12  VAR=5 RE=0.7 RC=2.2   RB=10 CJC=0.74p
$ + CJE=2.1p VJC=0.60 TR=2n VJE=0.60 MJC=0.51 MJE=0.36
  BJT q1 cc bb ee MODEL=BJTRF1
EndModel
```

```
$ Common-emitter amplifier stage
  Res RB1  0  2   21k
  Res RB2  2  4   100k
  Res RC   1  4   1.4k
  Res RE   0  3   100
$ Transistor Q1 1 2 3
  TransX     Q1 1 2 3
  Cap CB1  2  5   100n
  Cap CB2  1 10   1u
  Cap CE   0  3   10u

$ Phase-shift network
  Cap C1  5 0   1u
  Cap C2  1 0   1u
  Ind L   5 6   500u   I=bOsc

$ Load,  V_{out} = V(10)
  Res RL 10 0 1k

  Short s 1 6

  Volt Vcc 4 0 DC=10 R=1
  Curr Inject 0 10 TRAN=10m*sin(2*pi*10k*t)*(t<100u)

Sweep "Transient Analysis"
  + LOOP 2001 TIME LIN 0 5m
  + WINDOW 0
  + Y "V_{out}" "V" -5 5 MULTX=m
  +   BIGSCREEN
  + EPS="colpts2a.eps"
  + WINDOW 1
  + X "t" "s" 4.6m 5.0m MULTX=m
  + Y "u" "V" -5 5
  + Y2 "i" "A" -260m 260m MULTY2=m
  + EPS="colpts2b.eps"

  Show WINDOW 0 Y Vtran(10)

  Display WINDOW 1
  + Y "v_{out}" Vtran(10)
  + Y2 "i" Itran(bOsc) MARKER=1
EndSweep

$ end of file EOF
```

.

Questions and exercises:

Please perform the following tasks: (1) Draw the equivalent scheme for the circuit. (2) Discuss the transistor models. (3) Discuss the Sweep statement. (4) Transfer the circuit to PSpice by (4a) changing the net-list directly (PSpice A/D) and (4b) by means of the equivalent scheme (Capture). (5) Perform the simulation by means of APLAC and PSpice. Compare the results and discuss the use of the programs. (6) Import the PSpice net-list into APLAC and compare with the original APLAC net-list. (7) Determine the small signal model for the circuit in the dc bias point for the case with the simple transistor model. Calculate the eigenvalues by means of ANP3 and WINLAP. Discuss the result. (8) Assume ideal and/or perfect amplifier and calculate the oscillation frequency. Compare with the simulations. (9) Investigate the amplifier alone by means of APLAC and PSpice simulations e.g. dc and ac transfer characteristics. Setup a simple nonlinear model for the amplifier which include input impedance, output impedance, nonlinear gain and dominating pole. Repeat the calculations from (5) with the simple amplifier model and discuss the results. (10) If the transistor operates as an almost ideal switch we have a situation where the capacitors CE, C2 and CB2 abruptly should distribute their charges. Almost a short-circuit of the series connection of CE and C2 will occur. This mechanism may give rise to chaotic performance. Please make simulations with different transistor models in order to provoke chaos. Study the voltages and the currents of the capacitors as functions of time. Study the instant charge ($q = C \times v$) or the instant energy ($p = i \times v$) of the capacitors as functions of time. (11) Suggest your own questions and exercises.

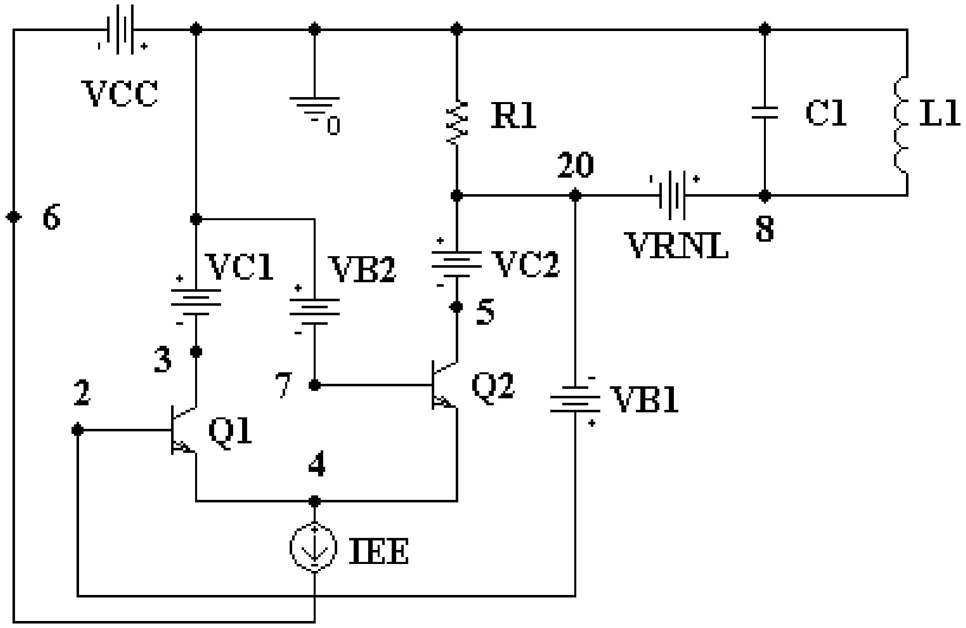

Fig. 4. Emitter coupled pair oscillator "Sony1".

C. Emitter Coupled LC oscillators

C.1 Sony1

Figure 4 shows a LC oscillator based on an amplifier made from a pair of emitter coupled transistors ([9] page 316).

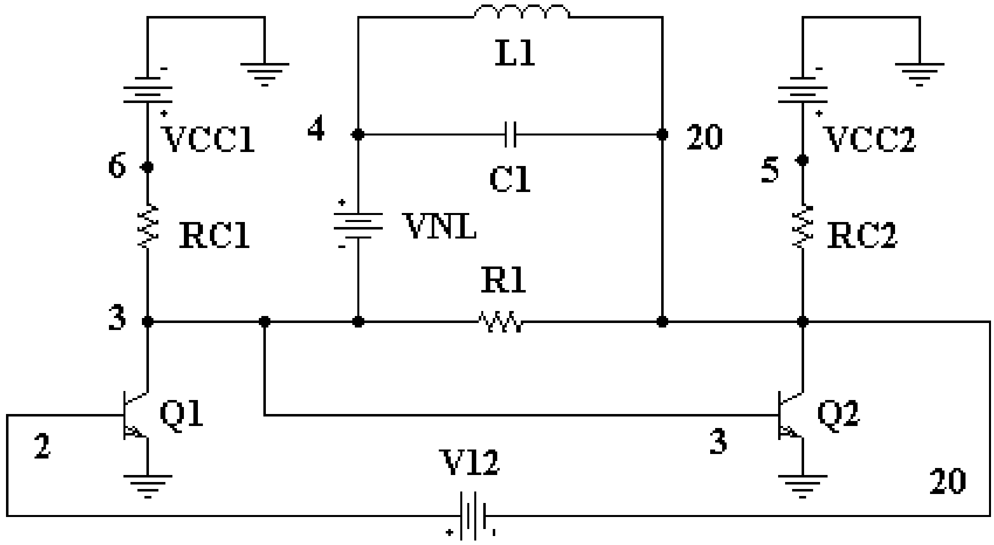

Fig. 5. Emitter coupled pair oscillator "Sony2".

The components of the "Sony1" oscillator are chosen as: $C1 = 106$pF, $L1 = 2.39\mu$H, $R1 = 5$kΩ, $VCC = 5$V, $IEE = 0.2$mA. The dc sources $VC1, VC2, VB1, VB2$ and $VRNL$ are zero valued sources inserted for measurement of currents. The transistor models may be specified as simple Ebers-Moll transport models with $\beta_f = 100$, $I_s = 0.1$fA, and $R_b = 50\Omega$.

Questions and exercises:

Please perform the following tasks: (1) Redraw the circuit according to fig. 2 and identify the impedances. (2) Redraw the circuit according to the Barkhausen criteria [12]. (3) Suggest your own questions and exercises.

C.2 Sony2

Figure 5 shows a LC oscillator based on an amplifier made from a pair of emitter coupled transistors ([9] page 321).

The components of the "Sony2" oscillator are chosen as: $C1 = 106$pF, $L1 = 2.39\mu$H, $R1 = 1$kΩ, $RC1 = RC2 = 50$kΩ, $VCC1 = VCC2 = 5$V, $IEE = 1$. The dc sources $V12$ and $VRNL$ are zero valued sources inserted for measurement of currents. The transistor models may be specified as simple Ebers-Moll transport models with $\beta_f = 100$, $I_s = 0.1$fA, and $R_b = 50\Omega$.

Questions and exercises:

Please perform the following tasks: (1) Redraw the circuit according to fig. 2 and identify the impedances. (2) Redraw the circuit according to the Barkhausen criteria [12]. (3) Suggest your own questions and exercises.

D. Transformer Coupled Oscillator

The following file is an input file for the PSpice program [1] describing an analysis of a transformer coupled oscillator. The file is available from: http://www.es.oersted.dtu.dk/~el/squeg.txt

```
title SQUEG.CIR, transformer coupled oscillator
*
* ref. Fig. 10.6, page 344 in
*      D.O. Pederson and K. Mayaram,
*      "Analog Integrated Circuits for Communication -
*      Principles, Simulation and Design",
*      Kluwer 1991.
*
  R1   1   0       1
*
  Q1   7   1   3   mod1
* Q1   7   1   3   qnideal
* Q1   7   1   3   bc107
* Q1   7   1   3   q2n2222
*
  VC   2   7       0
  VCC  4   0       10
*
* tank circuit
*
  RL   4   2       750
* RL   4   2       2.6k
  CT   4   2       450pF
  L1   4   2       5uH
*
* transformer
*
  L2   0   5       50nF
  K1  L1  L2       1
*
* feed-back
*
  CE   5   3       5.0n  ; 5.5n  ; 6n ; 10n ; 5.0nF
* vary CE in order to observe squegging
*
  RE   3   6       4.65k
  VEE  6   0       -10   ;   pulse -15 -10  0 0  0 1s
*
.tran  15e-9  100e-6  0   15n  UIC  ; 9.3u   15n
.probe
.options nopage opts itl5=0
+  RELTOL =    1.0000E-05   ; 03
+  ABSTOL =    1.0000E-12
+   VNTOL =    1.0000E-08   ; 12  06
+    GMIN =    1.0000E-12
```

```
+    ITL4 =   10
+  CHGTOL =   10.0000E-15
+  NUMDGT =    4
* .width out=80
* ----- models -------------
.model mod1 npn is=1e-16
+               bf=100  rc=10
*
.MODEL Qnideal NPN (
+ Is=1e-16A BF=49 BR=960m Rb=0ohm Re=0ohm
+ Rc=0ohm Cjs=0F Cje=0F Cjc=0F Vje=750mV
+ Vjc=750mV Tf=0s Tr=0s mje=0 mjc=0
+ VA=50V ISE=0A IKF=0A Ne=0)
*
.MODEL BC107 NPN (
+ Is=1.16pA BF=364 BR=4 Rb=42.6ohm Re=10.6ohm
+ Rc=4.26ohm Cjs=0F Cje=36.8pF Cjc=10.8pF Vje=750mV
+ Vjc=750mV Tf=530ps Tr=87.4ns mje=333m mjc=333m
+ VA=120V ISE=42.2pA IKF=120mA Ne=2)
*
.model Q2N2222  NPN (
+ Is=14.34f Xti=3 Eg=1.11 Vaf=74.03 Bf=255.9 Ne=1.307
+ Ise=14.34f Ikf=.2847 Xtb=1.5 Br=6.092 Nc=2 Isc=0 Ikr=0 Rc=1
+ Cjc=7.306p Mjc=.3416 Vjc=.75 Fc=.5 Cje=22.01p Mje=.377
+ Vje=.75 Tr=46.91n Tf=411.1p Itf=.6 Vtf=1.7 Xtf=3 Rb=10)
*               National        pid=19          case=TO18
*               88-09-07 bam    creation
* ---------------------------------------------------------------
.end
```

Questions and exercises:

Please perform the following tasks: (1) Draw the equivalent scheme for the circuit. (2) Discuss the transistor models. (3) Discuss the .tran statement. (4) Transfer the circuit to PSpice A/D by means of the equivalent scheme (Capture). (5) Perform the simulation by means of PSpice A/D directly from the squeg.cir file and via Capture. Compare the results and discuss the use of PSpice A/D via Capture and directly. (6) Import the PSpice net-list into APLAC and compare simulations. (7) Determine the small signal model for the circuit in the dc bias point for the case with the simple transistor model. Calculate the eigenvalues by means of ANP3 and WINLAP. Discuss the result. (8) Assume ideal and/or perfect amplifier and calculate the oscillation frequency. Compare with the simulations. (9) Suggest your own questions and exercises. (4) Search the literature for other kinds or types of LC oscillators and enlarge these work-notes.

V. RC oscillators

IF you introduce RC circuits in the impedances Z_A, Z_B, Z_C and Z_D of the feed-back amplifier in fig. 2 you may create a RC oscillator.

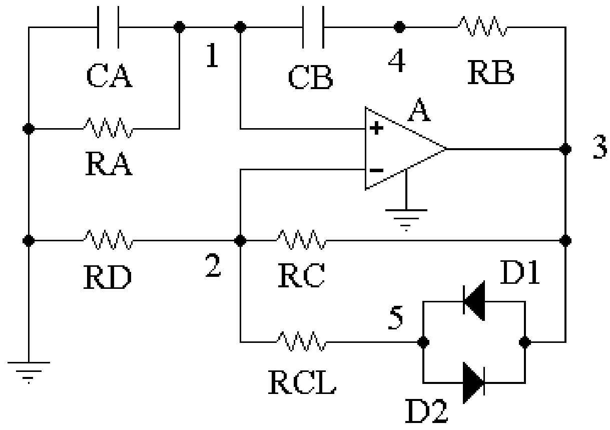

Fig. 6. Wien Bridge Oscillator

A. Wien Bridge Oscillator

Figure 6 shows a Wien Bridge Oscillator for which the components are chosen as: $CA = CB = 1\text{nF}$, $RA = RB = 15.91549431\text{k}\Omega$, $RD = 10\text{k}\Omega$, $RC = 24.6\text{k}\Omega$, $RCL = 99\text{k}\Omega$, $A = 100\text{k}$.

Questions and exercises:

Please perform the following tasks: (1) Redraw the circuit according to fig. 2 and identify the impedances. (2) Redraw the circuit according to the Barkhausen criteria [12]. (3) Suggest your own questions and exercises. (4) Search the literature for other kinds or types of RC oscillators and enlarge these work-notes. (5) Search the literature for other kinds or types of oscillators e.g. mechanical or chemical oscillators and enlarge these work-notes.

VI. Work-Note Comments

PROVOKING REMARKS concerning ***the idea of work-notes***. When the universities emerged some 800 years ago it was a process where *the students* searched and found proper persons with knowledge - *the professors* - to cooperate with concerning the work with the increase of knowledge among everybody. There were few students for each professor. To-day we see a pattern emerging on some universities where the BS and MS students are considered pupils guided by the teachers and only the PhD students are considered proper students. There are many pupils for each teacher. The teachers give lectures for the students i.e. the students are learning by listening and learning by seeing - ***"passive entertainment"***. The teacher enjoy the fun by creating exercises and lecture notes - books. The teacher is learning a lot. We all know that the best way to learn and master a subject is to teach the subject. It is more fun to create an exercise than to solve an exercise. By means of work-notes the student is offered the possibility for making his own lecture notes ("papers", "reports") to be shared with his fellow students and the supervisor ("teacher", "professor") i.e. we are back in the old pattern with learning by doing and learning by reading and writing - ***"active working"***. In short:

Learning by listening and learning by seeing imply passive entertainment.

Learning by doing and learning by reading and writing imply active working.

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