

SUGAR 3.0: A MEMS Simulation Program (User's Guide)

Document Authors - David Bindel, Jason Clark, Ningning Zhou
Revisions for Version 3.0 - David Garmire

Principal Investigators

Alice M. Agoginoaagogino@me.berkeley.edu
Zhaojun Baibai@cs.ucdavis.edu
James Demmeldemmel@eecs.berkeley.edu
Sanjay Govindjeesanjay@ce.berkeley.edu
Ming Gumgu@math.berkeley.edu
Kristofer S. J. Pisterpister@eecs.berkeley.edu

Graduated Students

Ningning Zhou.....nzhou@bsac.eecs.berkeley.edu

Graduate Students

David Bindeldbindel@cs.berkeley.edu
Jason V. Clarkjvclark@bsac.eecs.berkeley.edu
David Garmirestrive@cs.berkeley.edu
Raffi Kamalianraffi@me.berkeley.edu
Shyam Lakshminlakshmin@cs.berkeley.edu
Jiawang Nienjw@math.berkeley.edu

Undergraduate Students

Wayne Kaokaotao@usa.net
Ernest Zhu

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Chapter 1

Introducing SUGAR

1.1 What is SUGAR?

In less than a decade, the MEMS community has leveraged nearly all the integrated-circuit community's fabrication techniques, but little of the wealth of simulation capabilities. A wide range of student and professional circuit designers regularly use circuit simulation tools like SPICE, while MEMS designers often resort to back-of-the-envelope calculations. For three decades, development of IC CAD tools has gone hand-in-hand with the development of IC processes. Tools for simulation will play a similar role in future advances in the design of complicated micro-electromechanical systems.

SUGAR inherits its name and philosophy from SPICE. A MEMS designer can describe a device in a compact netlist format, and very quickly simulate the device's behavior. Using simple simulations in SUGAR, a designer can quickly find problems in a design or try out new ideas. Later in the design process, a designer might run more detailed simulations to check for subtle second-order effects; early in the design, a quick approximate solution is key. SUGAR provides that quick solution.

The main components of SUGAR are a netlist interpreter (based on a derivative of the Lua language), models written in MATLAB or C (possibly more languages in future revisions) describing the characteristics of the different components, a command-line and gui which allows interaction and visualization of the specified devices, and a SUGAR core that handles generated nodes and elements, mesh assembly, and analysis of devices.

1.2 A first example

Let's first look at a simple example of how SUGAR is used. Perhaps we have just designed a simple test structure in the MUMPS process, a long cantilever anchored at one end. We want to know how much it will deflect if we apply a small force to the free end.

First, we need an input file, called a *netlist*, that describes the device. We save this netlist in the file `cantilever.net`:

```
use("mumps.net")
use("stdlib.net")

A = node{0, 0, 0; name = "A"}
B = node{name = "B"}

anchor { A      ; material=p1, l=10u, w=10u }
beam3d { A, B   ; material=p1, l=100u, w=2u }
f3d    { B      ; F=50u, oz=90 }
```

The first line tells SUGAR that our device is made using the standard MUMPS process. The second and third line define two nodes to be used later in describing the *netlist*'s elements. The fourth and fifth lines tell SUGAR that the device is made of an anchor at node A, which is ten microns on a side; and a beam, two microns wide

and one hundred long, which goes from the anchored end point **A** to the free end **B**. Both the anchor and the beam are made of the poly1 layer, or **p1**. The sixth line describes a force of 50 micro-Newtons applied at a right angle to the free end of the beam.

Using SUGAR, we only need to write three commands to see the effect of the force on the beam:

```
> net = cho_load('cantilever.net');  
> q = cho_dc(net);  
> cho_display(net, q);
```

The first command tells SUGAR to process the netlist description in **cantilever.net**. The result is a data structure stored in the **net** variable that describes the device to other SUGAR routines. The **cho_dc** function does a static (DC) analysis of the device, and returns a vector representing the equilibrium position. Finally, the third line causes SUGAR to display the displaced device.

1.3 Installing SUGAR

All the SUGAR software is available from the SUGAR home page at

<http://bsac.berkeley.edu/cadtools/sugar>

We update the software frequently; if you encounter problems, you may want to download the latest version before devoting hours of your time (or ours!) to debugging.

There is also a web interface to SUGAR at:

<http://sugar.millennium.berkeley.edu/>

If you are building SUGAR for your particular system, note that you need to first make the **noweb** and Lua tools in the **sugar30/tools** directory of the source tree. **noweb** (refer to <http://www.eecs.harvard.edu/~nr/noweb/USA.html>) enables literate programming. The modified form of Lua (refer to <http://www.lua.org/>) is for the netlist and command-line interpreter.

1.3.1 System requirements

To require SUGAR, you will need MATLAB release 5.2 or later. Version 6.0 is recommended. Because the student edition of MATLAB 5 only handles matrices of a limited size, users of the student edition will only be able to simulate small devices.

SUGAR is regularly tested using MATLAB 5.3 on Windows, Sun, HP, and Alpha systems, and is tested using MATLAB 6.0 on Linux systems. We have not tested the software on other systems. If you would like to use SUGAR on a different system, you will need to compile the external routines for that system, as described later in this section.

1.3.2 Setting SUGAR paths

To use SUGAR, make sure that your MATLAB path is set correctly. In particular, make sure the analysis and model subdirectories are included in your MATLAB path. This can be done from within MATLAB, e.g.

```
addpath /home/eecs/dbindel/sugar30/src/matlab
```

or from the Unix shell, by setting the MATLABPATH environment variable. In **csh**, for instance, this might be

```
setenv MATLABPATH /home/eecs/dbindel/sugar30/src/matlab
```

In the Windows version of MATLAB, you can also set the path from the “File” menu.

1.3.3 Compiling external routines

You will need to compile the external routines *only* if pre-compiled versions are not already available on your system. To compile the routines, follow the directions in the included README file.

1.4 Getting (and giving) help

If you have concerns or difficulties using SUGAR which are not addressed in the manual sections, feel free to post to

`http://sourceforge.net/projects/mems`

We will try to respond promptly.

SUGAR *is* research software; let us know if you would like to contribute models, analysis routines, or examples to the SUGAR project.

Chapter 2

Describing Devices

Devices in SUGAR are described by input files called *netlists*. In this chapter, we describe the features of the netlist language which is a derivative of the Lua language.

2.1 Units and metric suffixes

By convention, the SUGAR model functions use the familiar MKS (meter-kilogram-second) system of units. This means that beam lengths, for example, are measured in meters instead of micrometers. In order to make it easier to type lengths of microns and pressures of gigapascals, we adopt a standard system of metric suffixes that can be appended to SUGAR numbers. For example, a hundred micron length in SUGAR could be represented as 100u as well as in scientific notation (100e-6) or as a simple decimal (0.0001). Similarly, a Young's modulus of 150 gigapascals might be written as 150G. Both suffixes and ordinary scientific notation can be used together, too; 0.1e7u is a perfectly legitimate (if somewhat silly) way of writing the number 1.

The standard suffixes are:

d	deci	10^{-1}			
c	centi	10^{-2}	h	hecto	10^2
m	milli	10^{-3}	k	kilo	10^3
u	micro	10^{-6}	M	mega	10^6
n	nano	10^{-9}	G	giga	10^9
p	pico	10^{-12}	T	tera	10^{12}
f	femto	10^{-15}	P	peta	10^{15}
a	atto	10^{-18}	E	exa	10^{18}

2.2 Expressions

It's often convenient to do simple calculations inside a netlist. For example, suppose I have defined a variable `beamL` for the length of a beam in a device. Then we can define the length of another beam in terms of `beamL`:

```
use("mumps.net")
use("stdlib.net")

beamL = 100u    -- Make a beam one hundred microns long

-- make a beamL by beamL/2 rectangle
A = node{0, 0, 0; name = "A"}
B = node{name = "B"}
C = node{name = "C"}
D = node{name = "D"}
```

```

beam3d{ A, B ; material=p1, w=2u, l=beamL }
beam3d{ C, D ; material=p1, w=2u, l=beamL }
beam3d{ A, C ; material=p1, w=2u, l=beamL/2, oz=90 }
beam3d{ B, D ; material=p1, w=2u, l=beamL/2, oz=90 }

```

SUGAR's treatment of expressions are similar to Lisp's treatment of expressions: we can add, subtract, multiply, divide, exponentiate, and negate numbers, and also evaluate functions. All functionality described in Lua is also available in SUGAR. All operations are left associative, so $a + b + c$ is evaluated as $(a + b) + c$ rather than as $a + (b + c)$. The order of operations, from highest precedence to lowest precedence, is

Level	Operators
7	(logical or)
6	& (logical and)
5	== (equality), != (inequality), > (greater), < (less), >= (greater or equal), <= (less or equal)
4	- (add), + (subtract)
3	* (multiply), / (divide)
2	- (negate), ! (logical not)
1	^ (exponentiate)

As in C and MATLAB, there is no separate logical type. Non-zero numbers are interpreted as “true,” and zero is interpreted as “false.” When a comparison or logical operation is true, it will evaluate to 1.

Besides numbers, SUGAR supports a string type. String literals are denoted by double quotes. Unlike C and MATLAB, the backslash does not quote characters in SUGAR expressions: “\t” is a backslash followed by a t, not a tab. Strings are values as well and can be used as operands to arithmetic or logical operations.

It is useful to note that a faster way of writing

```

if a then
  x = a
elseif b then
  x = b
else
  x = c
end

```

is to form it as

```

x = a or b or c

```

Lua for SUGAR also contains the primitives `addpath`, `node`, `material`, `element`, and `subnet`, which will be discussed more thoroughly later. `addpath` allows the inclusion of other directories for the `use` command. `node` defines a node in 3 space for use later in defining elements. `element` invokes a model defined on a set of nodal points with a set of parameters. `subnet` uses a function like declaration to parameterize netlists of sub-components.

2.3 Rotation angles

In order to orient structures in SUGAR, users specify how each piece is rotated from a model coordinate frame into its actual orientation in the structure. This specification can be done according to a global reference frame by specifying the exact positions of the nodes (and allowing SUGAR to figure out the internal rotations) or by specifying rotations of each component (may be done hierarchically in the case of subnets) and having SUGAR position the nodes. Rotations are specified by a sequence of rotations about the x , z , and y axes, respectively. The amount to rotate about each axis is given by angles `ox`, `oz`, and `oy`, given in degrees.

For many applications, most of the structure will lie initially in a single plane, and the only rotations used to describe the device will be rotations about the z axis. For example, the lines


```

beam3d{ A, B ; material=p1, w=2u, l=beamL }
beam3d{ C, D ; material=p1, w=2u, l=beamL }
beam3d{ A, C ; material=p1, w=2u, l=beamL/2, oz=90 }
beam3d{ B, D ; material=p1, w=2u, l=beamL/2, oz=90 }

```

describe a rectangle; the first two beams run parallel to the x axis, and the latter two beams are rotated ninety degrees in the plane to run parallel to the y axis.

For more complicated examples, it is important to remember that order matters. To go from local coordinates to global coordinates, first the rotation about the x axis is applied, then the z axis, and then the y axis. For instance, in the model coordinate system, a beam points in the direction $(1, 0, 0)$, along the x axis. If we rotate the beam first 90 degrees about the x axis and then 90 degrees about the z axis, it would point along the y axis, in the $(0, 1, 0)$ direction. If, however, we were to rotate the beam first about the z axis and then about the x axis, it would end up pointing along the z axis.

2.4 Lexical notes

SUGAR 3.0 netlists are “free form”; that is, white space characters like tabs and carriage returns are not significant.

A comment in a netlist begins with `--` and extends to the end of the line.

A SUGAR identifier (like a C identifier) consists of a letter followed by a string of letters, numbers, and underscores. The keywords `use`, `subnet`, `addpath`, `element`, and `node` are reserved (along with a slew of Lua commands), and cannot be used as identifiers. See Lua documentation for more details.

2.5 use statements

Netlists can contain `use` statements to include other files. A `use` statement has the form

```
use("filename")
```

For example, many netlists use the data for MUMPS process layers defined in `mumps.net`, and begin with the line

```
use("mumps.net")
```

Files included by a `use` statement are not particularly special. You can use `use` to include files of process parameters, libraries of frequently-used subnets, etc.

A file will only be used once in a netlist. For example, if the file `subnets.net` started with

```
use("mumps.net")
```

and a test netlist called `test.net` started with

```

use("subnets.net")
use("mumps.net")

```

then `test.net` would only include `mumps.net` once, and would not complain about the contents of `mumps.net` being defined multiple times.

2.6 addpath statements

Netlists can specify directories so the `use` statement does not need to specify the entire path, only a filename. For example,

```

use("src/lua/base/mumps.net")
use("src/lua/base/std.net")

```

could be rewritten as

```
addpath("src/lua/base")
use("mumps.net")
use("std.net")
```

2.7 node statements

Nodes are connection points which have associated variables shared by attached elements. Mechanical nodes also have positions.

An example of an absolute nodal declaration of node A at position (0,0,0) is

```
A = node{0, 0, 0; name = "A"}
```

An example of a relative nodal declaration of node B is

```
B = node{name = "B"}
```

When relative node positioning is used, SUGAR automatically ensures all of the node positions are generated for each of the elements.

The syntax

```
node "A"
```

is used to refer to a node named “A” in the current scope. If no such node exists yet, then a new one is created. For example, if we write

```
eground {node "ground"}
Vsrc    {node "ground", node "attach"; V=10}
```

the node “ground” is created in the first line, and the reference to `node "ground"` in the following line refers to the same node.

2.8 element statements

The basic unit of a SUGAR netlist is an element line. For example,

```
crossbeam = element{ A, B; model="beam2d", material=p1, l=100u, w=2u }
```

is an element line describing a beam. This line consists of several fields:

- Before the equals sign, one may optionally put a name for that element; in this case, the element is named `crossbeam`.
- Before the semicolon is a list of nodes. In this case, the specified beam connects nodes A and B. Elements are connected together by sharing a common node. For instance, to attach a wider 100 micron beam to the B end of the beam above, we might write

```
element { B, C; model="beam2d", material=p1, l=100u, w=5u }
```

Unlike in previous versions of SUGAR, node names in SUGAR 3.0 must begin with an alphabetic character.

- After the list of nodes comes a list of element parameters. Usually a process contains a model, a process, and a list of parameters.

The name of the model for the element is specified as `model="<model name>";` in this case, it is the two-dimensional beam model `beam2d`. There are models for beams, anchors, electrical devices, etc.; a complete list of models, along with information on how to build new models, can be found later in this document.

The process parameter structure for the element is specified as `material=<process name>;` in this case the beam is fabricated in the first layer of polysilicon in a MUMPS process, named `p1`. By specifying the

process layer `p1`, a user informs the model function of common material parameters such as the Young's modulus for polysilicon and the thickness of the deposited layer. For models which require no process information, such as models for external forces, the process field may be omitted.

In the example above, the model parameters consisted of the length and width of a beam; other models will require other parameters. A parameter specification always has the form `identifier = expression`. All permutations of arguments connected by commas are equivalent.

All the basic models in SUGAR have corresponding *subnet* wrappers. For example, these wrappers allow you to rewrite

```
element { B, C; model="beam2d", material=p1, l=100u, w=5u }
```

as

```
beam2d{ B, C; material=p1, l=100u, w=5u }
```

The preferred way to invoke elements is with the latter syntax.

2.9 Variables

In order to allow users to experiment with variations on a simulation, or to do parameter sweeps, SUGAR allows users to define variables in the Lua environment at load time. For example, a user might write

```
> params.nfingers = 10;
> net = cho_load('comb.net', params);
```

to create an instance of `comb.net` with comb drives having ten fingers. To test inside the netlist whether a variable is defined, use the `if` statement

```
if not nfingers then
  nfingers = 10 -- default is ten fingers
end
```

a shorter way to write the code above would be as

```
nfingers = nfingers or 10
```

SUGAR netlists may also include definitions, such as

```
long_length = 200u
short_length = 100u
avg_length = (long_length + short_length)/2
```

Netlist variables are scoped, so that a definition declared with the keyword, `local`, made inside a subnet (see below) will not affect top-level element statements.

2.10 material statements - Process parameter structures

Physical parameters associated with a particular layer of a particular material are process parameters. An example of the baseline process information for the polysilicon layers in MUMPS (`default`) is provided below

```
default = material {
  Poisson = 0.3,           --Poisson's Ratio = 0.3
  thermcond = 2.33,        --Thermal conductivity Si = 2.33e-6/C
  viscosity = 1.78e-5,     --Viscosity (of air) = 1.78e-5
  fluid = 2e-6,            --Between the device and the substrate.
  density = 2300,          --Material density = 2300 kg/m^3
  Youngsmodulus = 165e9,   --Young's modulus = 1.65e11 N/m^2
  permittivity = 8.854e-12, --permittivity: C^2/(uN.um^2)=(C.s)^2/kg.um^3
  sheetresistance = 20     --Poly-Si sheet resistance [ohm/square]
}
```

In general a process definition has the form `name = material {...}`, where `material` is a keyword, `name` is the name to be given to the process information.

Process parameter structures may be derived from other process parameter structures. For example, a 2 micron poly layer named `p1` might be written

```
p1 = material {
    parent = default,
    h = 2u
}
```

This layer automatically includes all the definitions made in the default process parameter structure.

2.11 subnet statements

Subnets provide users with a means to extend the set of available models without leaving SUGAR. An example subnet for a single unit of a serpentine structure is shown below:

```
subnet serpent( A, F, material, unitwid, unitlen, beamw )
    beamw = beamw or 2u;
    len2 = unitlen/2
    beam2d{ A, node "b";          material=material, l=unitwid/2, w=beamw, oz=-90 }
    beam2d{ node "b", node "c"; material=material, l=len2,      w=beamw }
    beam2d{ node "c", node "d"; material=material, l=unitwid,   w=beamw, oz=90 }
    beam2d{ node "d", node "e"; material=material, l=len2,      w=beamw }
    beam2d{ node "e", F;          material=material, l=unitwid/2, w=beamw, oz=-90 }
end
```

Element lines using subnets are invoked in the same manner as element lines using model functions built in MATLAB

```
serp1 = serpent {X, Y; material=p1, unitwid=10u, unitlen=10u}
serpent {y, z ; material=p1, unitwid=10u, unitlen=10u, w=3u}
```

The `parent` process for a subnet is the process specified in creating an instance of that subnet. In the above example, the `p1` process information would be used for the beams in the `serpent` subnet.

In general, a subnet definition consists of the keyword `subnet`, a name for the subnet model, a set of arguments, and a code block followed by `end`. The code block may include definitions, element lines, and array structures (see below).

Sometimes it may be necessary to access variables attached to nodes internal to a netlist. For example, in the above example we might be interested in the version of node `b` for subnet instance `serp1`. In the analysis functions, that node would be referred to as `serp1.b`. It would not be valid to refer to node `x` as `serp1.A`, since `x` already has a name defined outside the subnet.

Subnet instances that are not explicitly named, like the second `serpent` element in the example above, are assigned names consisting of `anon` followed by some number. It is possible to use a name like `anon1.b` to refer to the `b` node in the second line, but it is not recommended since the internal naming schemes for anonymous elements are subject to future change.

2.12 Arrays

SUGAR supports arrays of structures through the same syntax as Lua. Arrays are built enclosed in braces and referenced using brackets. For example, the following code fragment creates a spring composed of twenty of the serpentine units from the subnet example and anchors it at one end:

```
link = { node {} };
anchor {p[1]; material=p1, l=5u, w=5u}
```

```

for k = 1,nlinks do
  link[k+1] = node {};
  serpent {link[k], link[k+1]; material=p1, unitwid=10u, unitlen=10u, w=2u}
end

```

Note that `link` needs to first be initialized. It is possible to have names with multiple indices as well (eg `link[i][j]`). The index variable is only valid within the loop body.

The general syntax of a for loop is

```

for index = lowerbound, upperbound [, increment] do
  ... code lines ...
end

```

where `index` is the name of the index variable, `lowerbound` is an expression for the lower bound of the loop, and `upperbound` is an expression for the upper bound of a loop.

2.13 Conditionals

SUGAR supports `if` statements of the form

```

if expression then
  ... code lines ...
end

```

and

```

if expression then
  ... code lines ...
else
  ... code lines ...
end

```

The main purpose of `if` statements is to give some flexibility to subnet writers. For example, suppose I wanted a beam that would automatically compute its electrical resistance if one was not provided. I could do that with the following subnet:

```

subnet mybeam( A, B, l, w, h, R, resistivity )
  -- If R is nil, then the user didn't specify anything to override
  -- the default, so we'll help calculate the resistance.
  if not R then
    resistance = resistivity * l/(w*h)
    beam3de {A, B; material=parent, l=l, w=w, h=h, R=resistance}

    -- Otherwise, we'll just accept whatever the user wrote in
  else
    beam3de {A, B; material=parent, l=l, w=w, h=h, R=R}
  end
end

```

There are a few caveats that go with this example:

1. Usually, `resistivity` would be defined in the process information when an instance of `mybeam` was created.
2. A briefer way to write this example would be

```

subnet mybeam(A, B, l, w, h, R, resistivity)
  beam3de{A, B; material=parent, l=l, w=w, h=h,
    R=( R or (resistivity * l/(w*h)) )}
end

```

The `local` statement restricts the variable to the given scope.

3. The SUGAR netlist language is designed to be extensible, yet it is limited. By using the `if` statement, it is possible to write arbitrarily complicated netlists, with constructs like recursive subnets or even more subtle beasts. Exercise good taste when you write netlists, and try to relegate any subtle and complicated coding tasks to MATLAB instead of to the SUGAR netlist language.

Chapter 3

Analyzing Devices

3.1 Types of analysis

SUGAR supports three basic styles of analysis:

Static analysis : In static analysis, we find the equilibrium state of a device. Static analysis is sometimes called DC analysis by analogy to the equilibrium analysis for direct current circuits.

Linearized analysis : A linearized approximation to a system near equilibrium can provide valuable information about the stability of the system and the nature of small oscillations about equilibrium. SUGAR provides two flavors of linearized analysis:

- In *modal analysis*, the characteristic modes of the system (and their corresponding frequencies) are determined. SUGAR can display the shapes of the displacements corresponding to various modes.
- In *steady-state analysis*, SUGAR computes the frequency response of a user-specified variable when another user-specified variable is sinusoidally excited. The output of steady state analysis is Bode plots.

Transient analysis : In transient analysis (or dynamic analysis), the motion of the system is integrated forward in time. Transient analysis in SUGAR is still somewhat unreliable; we hope to have better support for it soon.

3.2 Static analysis

In static analysis, we attempt to find an equilibrium state for a MEMS device. In the most general case, the equilibrium may not be unique; in this case, SUGAR will usually find the equilibrium position closest to where it starts looking (which, by default, is the undisplaced position).

The equilibrium state is characterized by a collection of force and moment balance equations (and their electrical and thermal analogues):

$$F(x) = 0$$

where x is a vector of displacements from the original positions (and voltages, temperatures, etc) of the device. We solve these equations using a standard Newton-Raphson iteration. For linear problems, a Newton-Raphson iteration will converge in one steps; for nonlinear problems, the iteration may never converge. Currently, SUGAR assumes the iteration has converged when the size of the change between iterations is sufficiently small in an appropriately scaled norm. If convergence has not set in after 40 iterations, the routine exits with a diagnostic message.

The function to perform static analysis is `cho_dc`:

```
res = cho_dc(net, q0, is_sp)
```

The first argument, `net`, is the netlist structure returned from `cho_load`. The other arguments are optional. The starting value for the iteration is given by `q0`; by default, the iteration starts at the undisplaced position (`q0 = 0`). The flag `is_sp` tells the routine whether it should use sparse solvers or not; by default, the flag is true (sparse solvers are used). The function returns a vector of displacements to reach the computed equilibrium (`res.q`), and a flag that indicates whether the iteration converged (`res.converged`).

In some cases, it is possible to find tricky equilibrium positions by approaching them step-by-step. For example, suppose we wanted to determine the equilibrium position of a device near a pull-in voltage. As we approach the critical voltage, it becomes more difficult to find the equilibrium position, and past the critical voltage, no equilibrium exists. If the commands

```
params.V = Vfinal;
net = cho_load('device.net', params);
q = cho_dc(net)
```

fail, we could try

```
q = [];
for V = 0:.5:Vfinal
    params.V = V
    net = cho_load('device.net', params);
    q = cho_dc(net, q);
end
```

Even if we were still unable to find the equilibrium position, we might get useful information from seeing how nearly we were able to approach the final voltage, and what the equilibrium was at the last point where we were able to find it.

There are two ways to view the results of a static analysis:

1. We can view individual components of the displacement vector using the command `cho_dq_view`:

```
% Find displacement of the y coordinate at node 'tip'
tipy = cho_dq_view(q, net, 'tip', 'y');
```

Alternately, we could look up the index of the tip *y* coordinate, and then look at the corresponding entry of the `q` vector:

```
% Find displacement of the y coordinate at node 'tip'
tipy_index = lookup_coord(net, 'tip', 'y');
tipy = q(tipy_index);
```

2. We can display the shape of the displaced structure using the `cho_display` routine:

```
% Display the undisplaced structure in figure 1,
% and the displaced structure in figure 2.
q = cho_dc(net);
figure(1); cho_display(net);
figure(2); cho_display(net, q);
```

3.3 Steady-state and Modal Analysis

We determine system behavior near equilibrium by analyzing the linearized system. In modal analysis, we find the resonant behavior of the structure, assuming no damping, by solving the eigenproblem

$$\det(\lambda^2 M - K) = 0$$

The eigenvalues give the resonant frequencies, and the corresponding eigenvectors give the resonant modes. The routine `cho_mode` returns selected frequencies and mode shapes for a structure, along with the operating point

at which linearization took place. Mode shapes can be viewed graphically using the `cho_modeshape` commands. For small problems, the default dense solvers are adequate; for larger problems, users should select the number of modes they want, and those modes will be computed using a less expensive iterative method.

To use the steady-state analysis routine, a user specifies a single input degree of freedom and a single output degree of freedom, usually by naming a nodal variable. SUGAR then draws a Bode plot illustrating the amplitude gain and phase shift between a harmonic excitation at the input and a measured harmonic at the output. Note that, unlike the modal analysis routine, the steady state routine does not discard damping terms.

3.4 Transient Analysis

Note: Note yet in SUGAR 3.0

Chapter 4

Examples

This section describes how to use SUGAR 3.0 by examples. The netlists, commands for running analysis, and output are shown. For convenience, all netlist files given here are available in the SUGAR demo directory (converted from 2.0). Netlist format is defined in chapter 2.

4.1 Examples with explanations

4.1.1 cantilever example (demo_dc1)

This demo shows how to simulate the deflection of a beam due to an external force, where the beam is fixed at one end. It shows to make the netlist, how run static analysis, and obtain graphical output.

To model the beam a 3D linear beam model called beam3d will be used. If a planar beam is desired, simply replace the model b3dm with beam2d in line 2 of following netlist.

Netlist

The following netlist is created by opening a text editor, entering the 3 lines of netlist text shown below, and saved as cantilever.net. The 3 text lines represent an anchor, beam, and force.

```
-- 'cantilever.net'  
use("mumps.net")  
use("stdlib.net")  
  
anchor {node "substrate"; material=p1, l=10u, w=10u, h=10u}  
beam3d {node "substrate", node "tip"; material=p1, l=100u, w=2u, h=2u}  
f3d {node "tip"; F=2u, oz=90}
```

The first line in the netlist includes a process file “mumps.net”. All process information such as layer thickness, Young’s modulus etc. are defined in “mumps.net”. The second line includes the standard library file “stdlib.net”.

The first line in the netlist represents the anchor element. Anchors are the MEMS components that mechanically ground flexible structures to the substrate. Without anchors, structures would be statically indeterminate.

The material properties of the anchor are given in process file “mumps.net”. The fabrication layer of this process is p1.

The anchor is attached to the substrate by the node labeled substrate. Notice that both the anchor element and beam element (described below) contain the node labeled substrate. The anchor is coupled to the beam through node substrate.

The parameters section of this line of text provides the geometry and orientation, where the length, width are 10 microns.

The second element is a flexible beam. The model used for this beam is called beam3d, which is described in appendix. The fabrication layer with which this beam is composed of is the p1 layer (i.e. the first layer of

polysilicon). It is fixed on one end due to its connection to the anchor through the node labeled substrate. The opposite end of the beam, labeled tip, is free to move.

The last section of this line provides geometry and orientation. The beam extends to the right, from node substrate to node tip.

The final line is a force applied at the free end of the beam (node tip). The magnitude of the force is given as 2 microNewtons. The orientation of the force vector is in the y- direction since it was rotated from its default position along the positive x-axis.

Command

Once the netlist text file is created, load it into Matlab with the `cho.load` command. Then static analysis may be performed, which finds a final equilibrium state of the system. Running static analysis on the above netlist requires 3 commands. Within the Matlab workspace:

1. load the netlist,
2. perform static analysis on it, and
3. display the results:

```
net = cho_load('cantilever.net');
dq = cho_dc(net);
cho_display(net,dq);
```

The first command loads the text file called `cantilever.net` into a variable called `net`. The `net` variable contains all of the important information in the netlist file.

The second line performs the static analysis. The `cho_dc` command takes `net` as its input. Using the parameter values given in the netlist and the parameterized element models described in appendix, it calculates the deflection of the structure. The displacement vector `dq` is the output of `cho_dc`.

Incidentally, `cho` stands for the basic building blocks of sugar (i.e. carbon, hydrogen, oxygen).

Using geometries and orientations from `net` and node displacements from `dq` as input to `cho_display`, SUGAR can graphically display the deflected structure in Matlab.

To display original, non-deflected structure, simply type

```
cho_display(net);
```

After the structure is displayed, left clicking and dragging within the display window may adjust the view. The magnification buttons in the display window may be used to zoom in and out by first clicking on, say the zoom-in (+), followed by pointing and clicking on the display window at the precise position that is to be magnified.

4.1.2 multiple beam example (demo_dc2)

This demo is similar to above demo with the exception that it uses multiple beams and it is deflected by a moment. Netlist is as following:

Netlist

```
-- 'multibeam.net'
use("mumps.net")
use("stdlib.net")

anchor {node "substrate"; material=p1, l=10u, w=10u, oz=180}
beam3d {node "substrate", node "A"; material=p1, l=100u, w=10u}
beam3d {node "A", node "B"; material=p1, l=50u, w=4u, oz=45}
beam3d {node "A", node "C"; material=p1, l=50u, w=4u, oz=-45}
beam3d {node "C", node "D"; material=p1, l=50u, w=4u, oy=-45}
f3d {node "D"; M=1n}
```

As before, each element is connected at shared nodes. The commands to load the netlist, do the analysis, and display the non-deflected and deflected figures are

```
net = cho_load('multibeam.net');
dq = cho_dc(net);
figure(1); cho_display(net);
figure(2); cho_display(net,dq);
```

4.1.3 Beam gap structure (demo_beamgap)

This is a 2D coupled electrical and mechanical domain analysis. It contains electrical voltage source, electrical ground, electro-mechanical anchors, beam and gap. The netlist and structure of this demo are as following:

Netlist

```
-- 'beamgap2e.net'
use "mumps.net"
use "stdlib.net"

Vsrc    {node "A", node "f"; V = 10}
eground {node "f"}
anchor  {node "A", p1; l=5u, w=10u, oz=180}
beam2de {node "A", node "b", p1;
        l=100u, w=2u, h=2u, R=100}
gap2de  {node "b", node "c", node "D", node "E", p1;
        l=100u, w1=10u, w2=5u, gap=2u, R1=100, R2=100}
eground {node "D"}
eground {node "E"}
anchor  {node "D", p1; l=5u, w=10u, oz=-90}
anchor  {node "E", p1; l=5u, w=10u, oz=-90}
```

Equilibrium displacements have been calculated at an input voltage 10v. The deflected structure is shown as following:

4.1.4 Modal analysis (demo_mirror)

This is a 3D mechanical modal analysis for a mirror structure. 3D mechanical anchors and beams are included. Resonant frequencies have been calculated and the first to fourth mode shapes are displayed. Below are the netlist and demo pictures

Netlist

```
-- 'mirror.net'
use "mumps.net"
use "stdlib.net"

anchor {node "b";          material=p1, l=10u, w=10u, oz= 90, h=8u}
beam3d {node "b", node "c"; material=p1, l=80u, w=2u, oz=-90, h=2u}
beam3d {node "d", node "e"; material=p1, l=80u, w=2u, oz=-90, h=2u}
anchor {node "e";          material=p1, l=10u, w=10u, oz=-90, h=8u}

-- outer frame:
beam3d {node "c", node "f"; material=p1, l=100u, w=20u, oz=-90, h=4u}
beam3d {node "f", node "d"; material=p1, l=100u, w=20u, oz=-90, h=4u}
beam3d {node "c1", node "f1"; material=p1, l=100u, w=20u, oz=-90, h=4u}
```

```

beam3d {node "f1", node "d1"; material=p1, l=100u, w=20u, oz=-90, h=4u}
beam3d {node "c", node "c1"; material=p1, l=200u, w=20u, oz= 0, h=4u}
beam3d {node "d", node "d1"; material=p1, l=200u, w=20u, oz= 0, h=4u}

-- inner torsion hinges:
beam3d {node "g3", node "f1"; material=p1, l=40u, w=2u, oz=0, h=2u}
beam3d {node "f", node "g6"; material=p1, l=40u, w=2u, oz=0, h=2u}

-- inner solid "plate":
beam3d {node "g6", node "g3"; material=p1, l=120u, w=140u, oz=0, h=4u}

-- rear lever:
beam3d {node "h", node "f"; material=p1, l=75u, w=80u, oz=0, h=4u}

```

4.1.5 Steady state analysis (demo_ss)

This is a 2D steady state analysis for a resonator as following:

Netlist

```

-- 'multimode_m.net'
use("mumps.net")
use("stdlib.net")

anchor {node "A"; material=p1, l=5u, oz=0, w=10u }
beam2d {node "A", node "D"; material=p1, l=150u, oz=180, w=2u }
anchor {node "B"; material=p1, l=5u, oz=0, w=10u }
beam2d {node "B", node "E"; material=p1, l=150u, oz=180, w=2u }
beam2d {node "D", node "F"; material=p1, l=50u, oz=90, w=5u }
beam2d {node "D", node "E"; material=p1, l=50u, oz=-90, w=5u }
beam2d {node "E", node "G"; material=p1, l=50u, oz=-90, w=5u }
beam2d {node "F", node "H"; material=p1, l=50u, oz=0, w=2u }
beam2d {node "G", node "L"; material=p1, l=150u, oz=0, w=2u }
beam2d {node "H", node "I"; material=p1, l=50u, oz=0, w=20u }
beam2d {node "I", node "O"; material=p1, l=50u, oz=0, w=20u }
beam2d {node "I", node "J"; material=p1, l=75u, oz=-90, w=20u }
beam2d {node "J", node "K"; material=p1, l=75u, oz=-90, w=20u }
beam2d {node "L", node "K"; material=p1, l=50u, oz=0, w=20u }
beam2d {node "K", node "P"; material=p1, l=50u, oz=0, w=20u }
beam2d {node "J", node "M"; material=p1, l=300u, oz=0, w=2u }
beam2d {node "M", node "N"; material=p1, l=196u, oz=0, w=116u }

```

4.1.6 Transient analysis (demo_talgap)

Note: This demo has not yet been converted to SUGAR 3.0

This is a 3D electromechanical transient analysis for a gap-closing actuator. A piecewise linear voltage $V(t)$ is applied across the page. The voltage $V(t)$ ramps from 5V at $t=10\mu\text{sec}$ to 12V at $t=500\mu\text{sec}$, and then drops to 0V. The displacement component of node C in the direction of force is observed below. The initial voltage step causes the device to oscillate. At the voltage increases at a linear rate, the gap decreases at a nonlinear rate due to the electrostatic force increasing proportionally to $1/\text{gap}(q)^2$. This force also causes the period of oscillation to increase. Once the voltage is removed, the actuator exponentially decays back to equilibrium due to viscous Couette air damping between the beams and the substrate.

Netlist

```
use("mumps.net")
a = node{0, 0, 0; name = "a"}
b = node{name = "b"}
c = node{name = "c"}
d = node{name = "d"}
e = node{name = "e"}

-- beam and it's anchor:
anchor {a; material=p1, l=5u, w=10u, oz=180, ox=0, oy=0, h=10u}
beam2de {a, b; material=p1, l=100u, w=4u, oz=0, ox=0, oy=0, h=4u}

-- electrostatic
gapV2 {b, c, d, e; material=p1, V1=5, t1=10u, V2=12, t2=500u,
      l=100u, w1=4u, w2=4u, oz=0, ox=0, oy=0, h=4u, gap=2u}

-- gap anchors
anchor {d; material=p1, l=5u, w=10u, oz=-90, ox=0, oy=0, h=10u}
anchor {e; material=p1, l=5u, w=10u, oz=-90, ox=0, oy=0, h=10u}
```

Chapter 5

Available Models

5.1 Available models

Note that some of these models are implemented using subnets in stdlib.net.

beam2d planar mechanical beam

beam2de planar mechanical beam and electric resistor

beam3d 3D mechanical beam

beam3de 3D mechanical beam and electronic resistor

anchor 0D mechanical fixed node

f2d planar force or moment

f3d 3D force or moment

gap2de two planar electrostatic mechanical beams, resistors

gap3de two electrostatic 3D mechanical beams, resistors

Vsrc Voltage source

eground Electronic ground

comb2d N-finger electrostatic comb, 2D mechanical

R constant resistor

Isrc constant current source

nmos nmos model

pmos pmos model

5.2 Model descriptions and interfaces

5.2.1 beam2d

Describes an in-plane beam connecting two nodes.

Example:

```
beam2d { A, B; material=p1, l=100u, w=5u, oz=10 }
```

Nodal variables:

{x, y, rz} at both nodes

Parameters

l beam length in meters (required)

w beam width in meters (required)

h thickness of beam in meters (optional; supplied in process info)

oz initial rotation about beam's z-axis (required if not 0)

5.2.2 beam2de

Similar to beam2d but adds electronic resistance to the beam.

Example

```
beam2de { A, B; material=p1, l=100u, w=5u, oz=10, R=100 }
```

Nodal variables

{x, y, rz, e} at both nodes

Parameters

l beam length meters (required)

w beam width in meters (required)

R beam resistance in ohms (required)

h thickness of beam in meters (optional; supplied in process info)

oz initial rotation about beam's z -axis (required if not 0)

5.2.3 beam3d

Similar to beam2d but can be rotated out-of-plane.

Example

```
beam3d { A, B; material=p1, l=100u, w=5u, oy=20, oz=10, ox=45 }
```

Nodal variables

{x, y, z, rx, ry, rz} at both nodes

Parameters

l beam length meters (required)

w beam width in meters (required)

h thickness of beam in meters (optional; supplied in process info)

oy initial rotation about y-axis (required if not 0)

oz initial rotation about beam's z -axis (required if not 0)

ox initial twist about the beam's x-axis (required if not 0)

5.2.4 beam3de

Similar to beam3d but adds electronic resistance to the beam.

Example

```
beam3de { A, B; material=p1, l=100u, w=5u, oy=20, oz=10, ox=45, R=100 }
```

Nodal variables

{x, y, z, rx, ry, rz, e} at both nodes

Parameters

l beam length meters (required)

w beam width in meters (required)

R beam resistance in ohms (required)

h thickness of beam in meters (optional; supplied in process info)

oy initial rotation about y-axis (required if not 0)

oz initial rotation about beam's z -axis (required if not 0)

ox initial twist about the beam's x-axis (required if not 0)

5.2.5 anchor

Describes a mechanically fixed node. 3D or 2D.

Example

```
anchor { A, B; material=p1, l=10u, w=10u, h=10u }
```

Nodal variables

{x, y, z, rx, ry, rz} at both nodes

Parameters

l beam length meters (required)

w beam width in meters (required)

h thickness of beam in meters (optional; supplied in process info)

oy initial rotation about y-axis (required if not 0)

oz initial rotation about beam's z -axis (required if not 0)

ox initial twist about the beam's x-axis (required if not 0)

5.2.6 f2d

Describes an in-plane external force at a node.

Example

```
f2d { A; F=10u, oz=45 }
f2d { A; M=1u, oz=45 }
```

Nodal variables

{x, y, rz} at node

Parameters

F force in Newtons (required if M is not used)

M moment in Newton-meters (required if F is not used)

oy initial rotation about y-axis (required if not 0)

oz initial rotation about the vectors's z -axis (required if not 0)

5.2.7 f3d

Describes a 3D external force at a node.

Example

```
f3d { A; F=10u, oy=35, oz=45 }
f3d { A; M=1u, oy=35, oz=45 }
```

Nodal variables

{x, y, z, rx, ry, rz} at node

Parameters

F force in Newtons (required if M is not used)

M moment in Newton-meters (required if F is not used)

oy initial rotation about y-axis (required if not 0)

oz initial rotation about the vectors's z -axis (required if not 0)

5.2.8 gap2de

Describes a 2D electrostatic gap, which consists of two electronic, mechanical beams.

Example

```
gap2de { a, b, c, d; material=p1, l=100u, w1=5u, w2=5u,
          oz=0, gap=2u, R1=100, R2=100 }
```

Nodal variables

{x, y, z, rx, ry, rz, e} at all four nodes

Parameters

l beam length meters (required)

w1 beam1 width in meters (required)

w1 beam2 width in meters (required)

gap initial gap spacing

h thickness of both beams in meters (optional; supplied in process info)

R1 beam1 resistance in ohms (required)

R2 beam2 resistance in ohms (required)

oz initial rotation about beam1's z -axis (required if not 0)

5.2.9 gap3de

Describes a 2D electrostatic gap, which consists of two electronic, mechanical beams.

Example

```
gap3de { a, b, c, d; material=p1, l=100u, w1=5u, w2=5u,
        oz=0, gap=2u, R1=100, R2=100 }
```

Nodal variables

{x, y, z, rx, ry, rz, e} at all four nodes

Parameters

l beam length meters (required)

w1 beam1 width in meters (required)

w1 beam2 width in meters (required)

gap initial gap spacing

h thickness of both beams in meters (optional; supplied in process info)

R1 beam1 resistance in ohms (required)

R2 beam2 resistance in ohms (required)

oy initial rotation about y-axis (required if not 0)

oz initial rotation about beam1's z -axis (required if not 0)

ox initial twist about the beam1's x-axis (required if not 0)

5.2.10 Vsrc

Describes a voltage source.

Example

```
Vsrc { e, d; V=5 }
```

See Fig 5 for nodes. Note: only mechanical element display.

Nodal variables

{e} at both nodes

Parameters

V voltage in volts (required)

5.2.11 eground

Describes a electronic ground.

Example

```
eground { e }
```

Note: only mechanical elements display.

Nodal variables

{e} at nodes

Parameters

none

Chapter 6

Function Reference

6.1 Load netlist

Calling sequence

```
net = cho_load(name, params)
```

Loads and processes a netlist.

Inputs

name String naming the netlist file to be loaded

params (Optional) - a structure whose entries are the values of the parameters to be overridden.

Example

```
nfingers = 10; % Set the nfingers parameter  
net = cho_load('comb.net', params); % Load netlist
```

6.2 Device display

Calling sequence

```
cho_display(net, q)
```

Display the mechanical structure described by a netlist.

Inputs

net Netlist structure returned from calling cho_load

q (Optional) - the displacement of the original structure, as returned by the static analysis routine or the transient analysis routine. If **q** is unspecified, the undisplaced structure will be displayed.

Example

```
net = cho_load('beamgap.net'); % Load netlist for beam-gap system  
cho_display(net); % Display undisplaced structure
```

Caveats

There is no display of electrical components.

6.3 Viewing displacements

Calling sequence

```
dqcoord = cho_dq_coord(dq, net, node, coord);
```

Extract the displacement corresponding to a particular coordinate from a displacement vector `q` (as output by `cho_dc`), or an array of displacement vectors (as output by `cho_ta`).

Note that a node “node” completely internal to an instance “foo” of some subnet would be named “node.foo”.

Inputs

`dq` : Displacement vector or array of displacement vectors.

`net` : Netlist structure returned from calling `cho_load`

`node` : Name of node.

`coord` : Name of coordinate at indicated node.

Outputs

`dqcoord` : Value (or vector of values) from `dq` associated with the indicated coordinate.

Example

```
net = cho_load('beamgap.net');           % Load netlist
dq = cho_dc(net);                        % Perform static analysis
dy = cho_dq_view(dq, net, 'c', 'y');    % Get the y component at c
```

6.4 Static analysis

Calling sequence

```
q = cho_dc(net, q0, is_sp);
```

Finds a solution of the equilibrium equations

$$Kx = F(x)$$

using a Newton-Raphson method.

Inputs

`net` : Netlist structure returned from calling `cho_load`

`q0` : (Optional) Starting guess at the displacements from starting position for an equilibrium position. If no `q0` is provided, or if `q0 =` the search will start at `q0` of 0.

`is_sp` : (Optional) If true, the code will use sparse solvers. The current default is true (use sparse solvers).

Outputs

`q` : The computed equilibrium state, expressed as displacements from the initial position.

Example

```
net = cho_load('beamgap.net'); % Load netlist for beam-gap system
dq = cho_dc(net);             % Perform static analysis
cho_display(net, dq);         % Display the deflected structure
```

Caveats

The zero-finder currently used by SUGAR is very simple, and may fail to converge for some problems. If the function fails to converge after 40 iterations, it will exit and print a warning diagnostic:

```
Warning: DC solution finder did not converge after 40 iterations
```

In this case, the result `q` returned by the routine is likely to be useless. Failure to find equilibrium occurs in such cases as an electrostatically actuated gap operating near pull-in voltage.

When SUGAR finds an equilibrium point, it may not always be the equilibrium point desired. In the case of an electrostatically actuated gap, for example, there are two equilibria below pull-in voltage: one stable and one unstable. When the equilibria are close together, especially with respect to the distance from the starting point `q0`, the solver may move to an unstable equilibrium.

Good initial guesses for an equilibrium point can often be attained by finding the equilibrium point for a “nearby” problem. For example, in trying to find the equilibrium point for a electrostatically actuated gap operating near pull-in, a good initial guess `q0` would be the output of a static analysis for the same device at a lower voltage.

6.5 Modal analysis

Analysis routine

Calling sequence

```
[freq, egv, q0] = cho_mode(net, nmodes, q0, find_dc)
```

Find the resonating frequencies and corresponding mode shapes (eigenvalues and eigenvectors) for the linearized system about an equilibrium point.

Inputs

net : Netlist structure returned from calling `cho_load`.

nmodes : (Optional) If `nmodes > 0`, use sparse solvers to get `nmodes` modes. If `nmodes == 0`, use the usual dense solver to get all the modes. If `nmodes < 0`, solve with `eig(K \ M)` rather than `eig(M,K)`. This last option can potentially cause trouble (for instance, if `K` is singular), but it is faster.

q0 : (Optional) Equilibrium operating point, or initial guess for a search for an equilibrium operating point. If not supplied, or if `q0 = []`, the routine will search for an equilibrium point near 0.

find_dc : (Optional) If true, search for an equilibrium point near the supplied `q0`.

Outputs

freq : Vector of resonating frequencies (eigenvalues)

egv : Array of corresponding mode shapes (eigenvectors)

q0 : Equilibrium point about which the system was linearized

Display routine

Calling sequence

```
cho_modeshape(net, freq, egv, q0, s, num)
```

Display the shape of a resonating mode of the mechanical structure.

Inputs

net : Netlist structure returned from calling `cho_load`.

freq : Vector of resonant frequencies from `cho_mode`.

egv : Array of mode shape vectors from `cho_mode`.

q0 : Equilibrium point from `cho_mode`.

s : Scale factor. Eigenvectors from `cho_mode` are normalized to be unit length; for eigenvectors with significant components (within a few orders of magnitude of 1) in directions corresponding to components which normally move a few microns, a scale factor of 10^{-4} often makes the display of the mode more comprehensible. The scale factor can be omitted, in which case SUGAR uses a heuristic to determine scaling.

num : Number of the mode to display. Modes are numbered in order of decreasing frequency.

Example

```
% Show the first (lowest-frequency) mode shape for the system,
% scaled by a factor of 0.1
net = cho_load('beamgap.net');
[f,e,q] = cho_mode(net);
cho_modeshape(net, f,e,q, 0.1, 1);
```

Caveats

While SUGAR will attempt to find an appropriate linearization point, it is not guaranteed to converge to one. See the caveats for static analysis.

The modal analysis routine neglects damping forces.

As noted above, using `cho_modeshape` with a too-large scaling factor often results in the displayed device being stretched to incomprehensible proportions. Currently, trial-and-error guesses at an appropriate scale factor seem to work best.

6.6 Steady state analysis

Calling sequence

```
find_ss(net, q0, in_node, in_var, out_node, out_var)
```

Make Bode plots of the frequency response of the linearized system about an equilibrium point `q0`.

Inputs

net : Netlist structure returned from calling `cho_load`

q0 : Equilibrium position for the system, as determined via the static analysis routine `cho_dc`

in_node : Name of the node at which an input signal is to be applied.

in_var : Name of the nodal variable to be excited.

`out_node` : Name of the node where the response is to be observed.

`out_var` : Name of the nodal variable to be observed.

Example

```
net = cho_load('multimode.net');
dq = cho_dc(net);
find_ss(net, dq, 'node10', 'y', 'node14', 'y');
```

Caveats

Steady-state frequency response analysis currently fails for devices involving purely algebraic constraint. Such devices include electrical resistor networks with no inductances or capacitances considered, for example.

The steady-state analysis routines currently use functions from Matlab's Control Toolbox, which may be unavailable to some Matlab users.

6.7 Transient analysis

Note: Transient analysis has not yet been implemented in SUGAR 3.0

Calling sequence

```
res = cho_ta(net,tspan,q0)
```

Simulate the behavior of the device over some time period.

Inputs

`net` : Netlist structure returned from calling `cho_load`

`tspan` : Two-element vector [`tstart` `tend`] indicating the start and end times for the simulation.

`q0` : (Optional) Initial state at `tstart`. If `q0` is not provided, the default is zero.

Outputs

`T` : Time points where the solution was sampled

`Q` : Array of state vectors sampled at the times in `T` (i.e. `Q(i,:)` is the state vector at time `T(i)`)

Example

```
net = cho_load('beamgap.net')           % Load the netlist
[T,Q] = cho_ta(net,{0, 1e-3});          % Simulate 1 ms behavior
dy = cho_dq_view(Q, net, 'c', 'y');     % Get the y component at c, and
plot(T, dy);                            % plot how it moves over time
```

Caveats

The transient analysis routines currently take an impractically long time to simulate even some simple examples over modest time spans (like a millisecond). Mixed electrical-mechanical simulations are particularly problematic.

Like frequency-response analysis, the transient analysis routine fails completely for devices involving purely algebraic constraints.

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