New SPICE features aid motor simulation

Nano-technology is increasingly featured in the science pages of serious newspapers as well as the technical journals. The developments in this field are often demonstrated by the construction of a capacitance motor built to dimensions to which few of us can relate. What is a capacitance motor and what are its characteristics? This article explores capacitance motors using SPICE as a simulation tool and taking advantage of some new features added to IntuSoft's latest version of this popular simulator.

The primary feature of a motor is that it produces torque. If this torque changes sign as a function of shaft angle the device is usually referred to as an actuator. Many types of motor consist of a number of actuators set with an angular spacing so that by switching the drive from actuator to actuator a continuous torque can be produced. Capacitance motors are in this class.

Take the simple geometry of Fig 1. Here a pair of rotor electrodes can vary in angular alignment with a pair of stator electrodes. The capacitance seen across the stator pair varies with angle reaching a maximum twice per revolution. If a voltage V is applied across the stator plates a torque T will be developed in a sense that will seek to maximise the capacitance. The torque can be calculated from the equivalence in the work done in moving through a small angle $\delta\theta$ and the change in electrical stored energy due to the change in capacitance across the small angle.
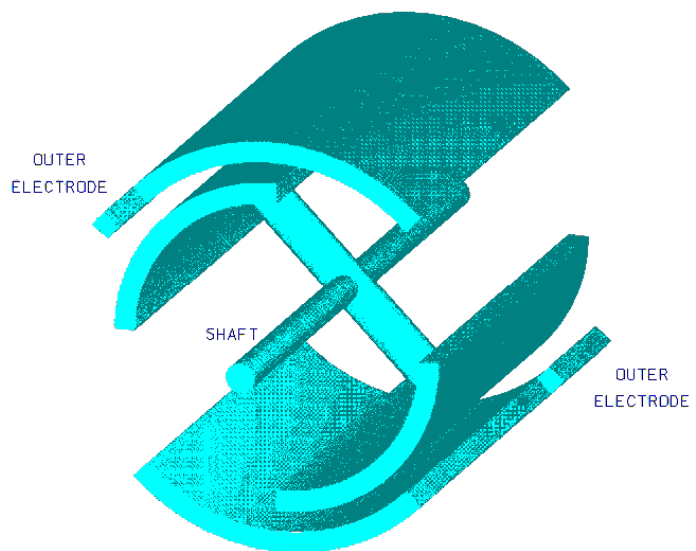

OUTER ELECTRODE

SHAFT

OUTER ELECTRODE

$$T\delta\theta = \tfrac{1}{2} C_1 V^2 - \tfrac{1}{2} C_2 V^2 = \tfrac{1}{2} \delta C V^2$$

giving:

$$T = V^2 \, dC/d\theta$$

Note: The V^2 dependence shows the torque direction is independent of the polarity of applied voltage.

Figure 1

Our simple geometry suggests a triangular wave variation of capacitance with position, maximum at 0 & 180 degrees, zero at 90 & 270 degrees. Field fringing and construction details will modify this ideal into a more complex function.

In a real motor we could calculate the capacitance at a number of angles using field modelling software with a parameter extractor. Using this data we could then curve fit to a function.

It is at this point that we come across our first simulation problem. In looking at the motor dynamics we will want to simulate across several revolutions of the motor. This presents no problem if our curve fit is to a periodic function such as a sine wave and we could make other functions periodic by expanding them as a Fourier series. There is now an easier way. IntuSoft have introduced a number of extensions to the arbitrary source syntax one of which is a fractional function. For our purposes, if the rotor position in radians divided by 2π is the argument of the FRAC function the output will be the fractional part of the total number of revolutions. We can use this fractional part as the argument in a non-periodic function to give a repeating capacitance variation with angular position.
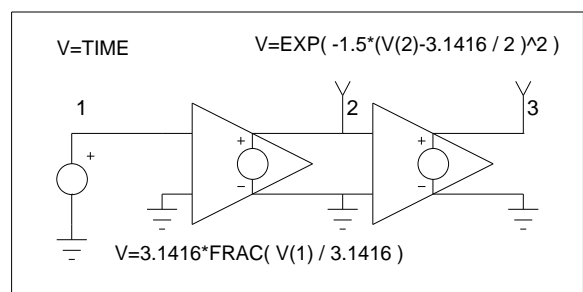

V=TIME V=EXP(-1.5*(V(2)-3.1416 / 2)^2)

1 2 3

V=3.1416*FRAC(V(1) / 3.1416)

Figure 2

In the SPICE circuit of Fig 2 I have chosen to use a gaussian function to represent the change of capacitance with angle. Since there are two maxima per revolution the angular position is divided by π not 2π.

The resulting capacitance against angle plot is shown in Fig 3.

The expression for torque includes the derivative of capacitance with respect to angle. For the Gaussian function chosen this has the analytic form :

$$-2\theta e^{-\theta^2}$$

The circuit of Fig 2 is extended in Fig 4 to generate the torque output from the drive voltage input. The capacitor across the input drive voltage represents the actuator input capacitance and uses another new feature of IntuSoft's SPICE that allows capacitor (and L & R) values to be written as functions of circuit voltages and currents. An additional input allows us to rotate the torque characteristic through an offset angle.
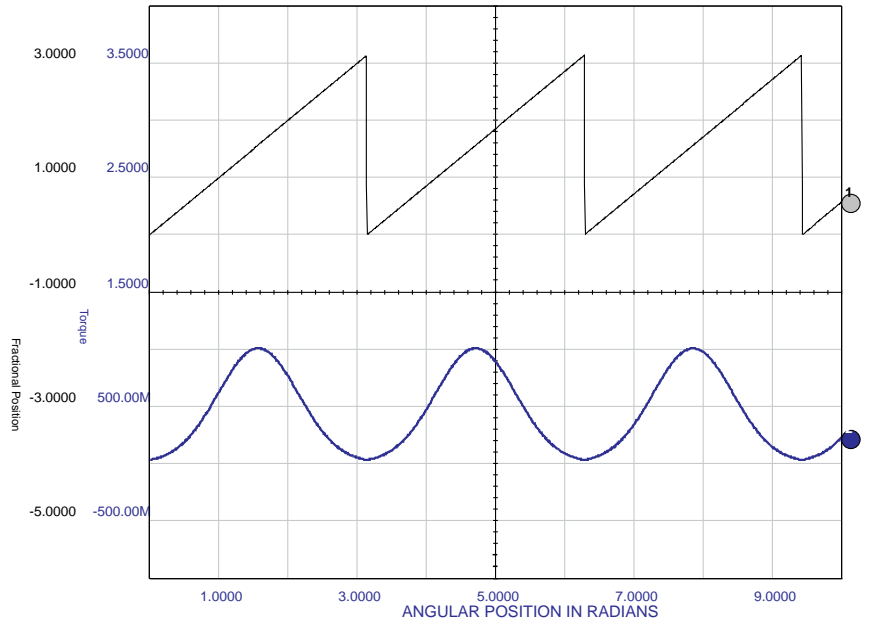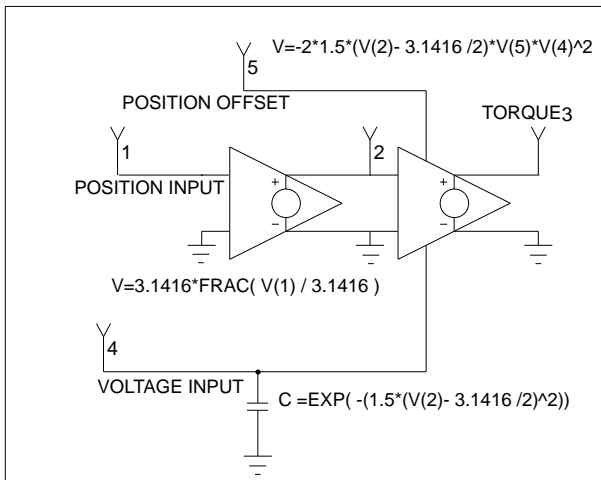

Figure 3

Figure 4

Figure 6

A typical motor might consist of three of these actuators disposed at 120 degree angles. The torque / rotation curves are then as shown in Fig 5 and we can see that we can always energise at least one of the actuators to produce a positive or negative torque.

The next step is to use the torque/rotation characteristic to simulate the dynamics of the motor.
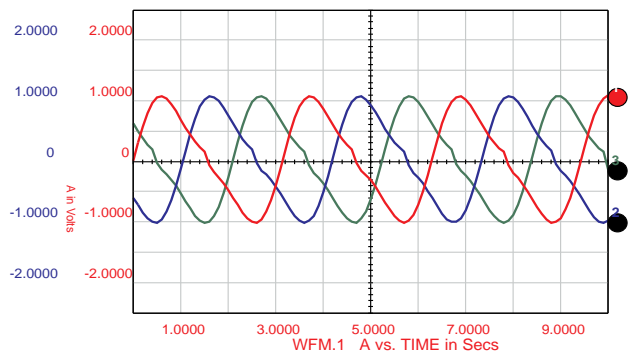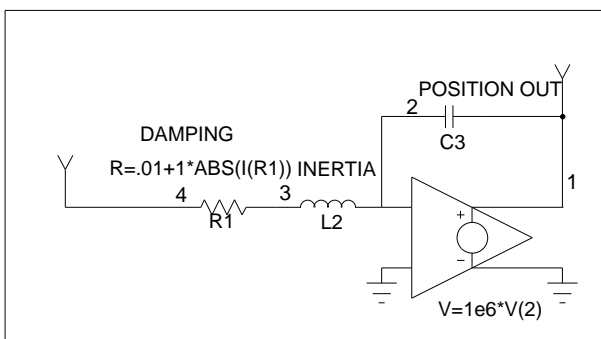

Figure 5

Motor position is the double integral of the torque/ inertia ratio. A compact way of producing the double integral is using an L and C combination around a gain stage as in Fig 6. The LC node is a virtual earth point, the current in the inductor then represents angular velocity with the output voltage representing angular position, since

$$Vout = \int\int Vin/LC$$

L is equivalent to inertia while C scales the output.

Any practical motor contains and drives some form of friction, friction absorbs torque that would otherwise accelerate the motor and is related to angular velocity. A resistor in series with the inductor effectively absorbs an amount of torque proportional to velocity i.e. viscous friction. Some losses (e.g. windage) increase with the square of velocity. Here we can use the ability to write expressions for resistance values to make the resistance proportional to velocity.

Fig 7 shows a complete three phase capacitance stepper motor, each actuator is represented by a sub-circuit symbol, the total torque is summed into the integrator of Fig 6 and the output angle is fed back to the actuators. The actuator drive voltages are provided from a state machine (see next page) programmable for full step or half step drive

Fig 8 shows the results obtained when driving the motor in full step and half step mode respectively. The ringing following each step is a consequence of the spring like characteristic of the torque curve. The lower frequency ringing on half steps is a result of the reduced slope of the torque/ position characteristic with two phases energised.

The completed simulation model can now be used to investigate such features as the maximum stepping rates achievable, the

Figure 7

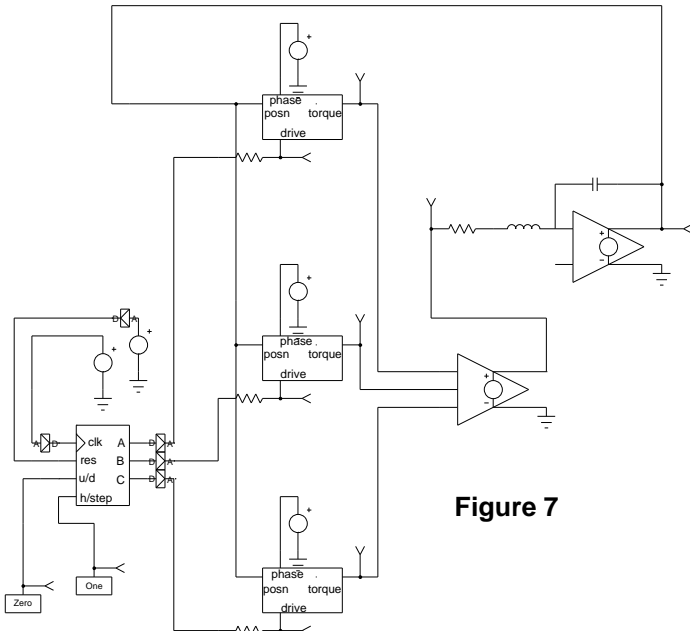importance of friction in damping the ringing and the effects of more complicated drive strategies such as micro-stepping.

Variable reluctance motors can be treated in a similar way though inductance in such motors is a function of both rotor position and excitation due to the non-linearities of the magnetic core.

Figure 8

The motor model can be made a single sub-circuit and represented by a symbol. Some simulation packages provide such "ready wrapped" models but it is important for designers to understand the workings of these models in order to account for their limitations. The model developed here, for example, does not include voltage breakdown, more torque can always be obtained by increasing the drive voltage.

Full details of the SPICE circuits used in this model can be obtained from Mike Penberth at:

STATE MACHINE

The state machine used in Fig 7 is an example of the "code" models provided by IntuSoft. They are "C" based extensions to the SPICE simulator and cover a number of analog and digital parts. The state machine is specified by a simple text file. This is the file for the stepper:
*state machine for stepper motor
*

*State A	B	C	U/D	h/step		Next state	
0	0s	0s	0s	0	0	->	1
				1	0	->	1
				0	1	->	1
				1	1	->	1
1	1s	0s	0s	0	0	->	5
				1	0	->	3
				0	1	->	6
				1	1	->	2
2	1s	1s	0s	0	0	->	1
				1	0	->	1
				0	1	->	1
				1	1	->	3
3	0s	1s	0s	0	0	->	1
				1	0	->	5
				0	1	->	2
				1	1	->	4
4	0s	1s	1s	0	0	->	1
				1	0	->	1
				0	1	->	3
				1	1	->	5
5	0s	0s	1s	0	0	->	3
				1	0	->	1
				0	1	->	4
				1	1	->	6
6	1s	0s	1s	0	0	->	1
				1	0	->	1
				0	1	->	5
				1	1	->	1
7	1s	1s	1s	0	0	->	1
				1	0	->	1
				0	1	->	1
				1	1	->	1