Digital Drive of 3HMS

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ABSTRACT

The Hyperbolic Helical Horn Mass Spectrometer (3HMS) [1] operates using RF sine wave voltages on the deflection grids. The frequency must be variable in order to scan a spectrum, requiring relatively complex and costly circuitry. This paper describes the use of square wave drive, which is much easier to implement with digital electronics. It also consumes lower power.

BACKGROUND

The original proposal for 3HMS [1] specified sine wave voltage drive for the horn's deflection grids. This created a perfect force field for generating a circular trajectory (in the XY plane). The double integration from force (acceleration) to velocity to position is inherently simple with sine waves, as the solution is just another sine wave (with phase change).

Symbolic integration of nonlinear waveforms is a bit more difficult, if not impossible. Instead, numerical integration using a computer is preferred. Accurate results are easy using known methods.

INTEGRATION

The first experiment is to simulate the field and trajectory of an ion in an octopole 3HMS. The field is generated using a positive voltage on three adjacent grids, an equal but negative voltage on the opposite three, and zero volts on the remaining two. The electric field isopotential lines thus generated appear as in Figure 1. There are eight possible angular rotations. That is, the field can be stepped in 45-degree increments.

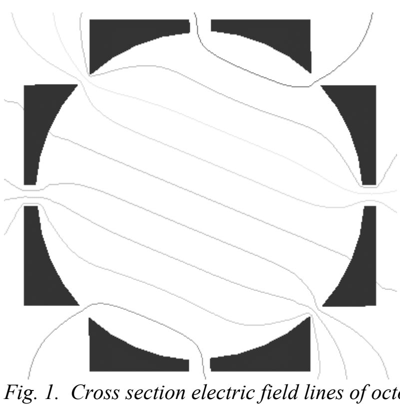

Fig. 1. Cross section electric field lines of octopole 3HMS.

The normalized electric field force on an ion along an axis is then either sin(0) = 0, sin(45) = 0.707, and sin(90) = 1. When the field is incremented rotationally, the force (and thus acceleration) appears as shown in Figure 2. This waveform is then integrated with respect to time to calculate the resulting ion velocity. A second numerical integration solves for position.

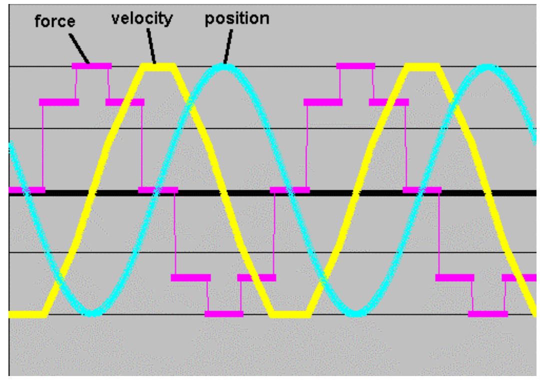

Fig. 2. Octopole integration waveforms.

It is clearly seen that the resulting ion position waveform is very close to an ideal sine wave, exactly the result we were hoping to achieve! Obviously, with more poles the force field approximation improves.

Interestingly, even the minimal quadrapole proposed by the REFIMS [4] attains reasonable results with square wave drive. The caveat is that three voltages (force) are required, not just positive and negative, but zero as well. Perhaps "square wave drive" is a misnomer, and "digital drive" is more correct. A simulation for the quadrapole is shown in Figure 3. The pseudo-sinewave trajectory has only a few percent distortions.

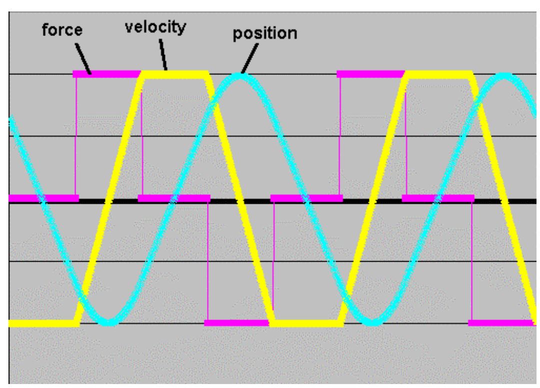

Fig. 3. Numerical integrations for a quadrapole.

GENERATION

The question now is how to generate the appropriate RF voltages to provide a symmetric digital drive. The electric field must have three levels: push, pull, and null, thus requiring three voltage levels. Normalized, these are 0, +1, and –1. See Figure 4. A conversion to normal binary logic circuits is needed.

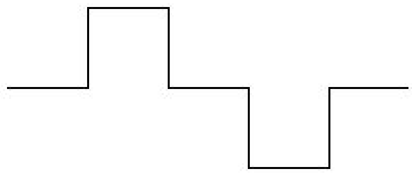

Fig. 4. Tri-level voltage drive.

One solution is offered in Figure 5. It uses a center-tapped secondary on a transformer for the two opposing outputs, A+ and A-. Using a transformer insures symmetric drive between opposing grids. It also has a low impedance dc path to ground for discharging colliding ions. Two high-powered logic gates drive the primary. If both gates are logic high, there is no voltage across the primary and the output voltage is zero. Same if both gates are logic low. Only when A1 and A2 are different is there an output voltage.

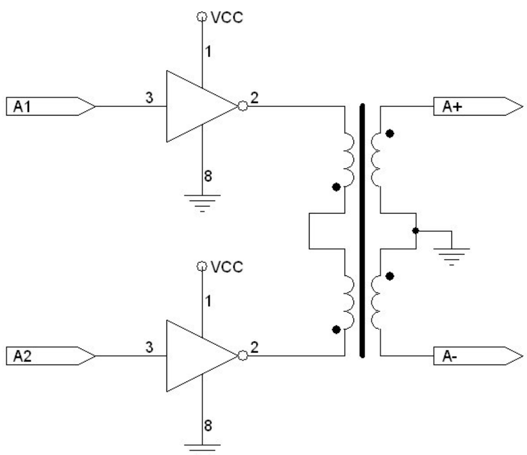

Fig. 5. Tri-level output circuit.

The following table defines the possible states for the output A+, corresponding to Figure 4. Note this comprises a Gray code, such that only one gate switches at a time. It is also symmetric so that no dc flux exists on the transformer core. The transformer can also provide voltage gain via turn ratios.

	0	+1	0	-1	0
A1	L	H	H	L	L
A2	L	L	H	H	L

The circuit in Figure 5 drives just one pair of grids (a pair being 180 degrees apart). Therefore, an octopole would need four of these drive circuits, properly sequenced to generate an incrementally rotated electric field. Figure 6 shows the grid arrangement for this discussion.

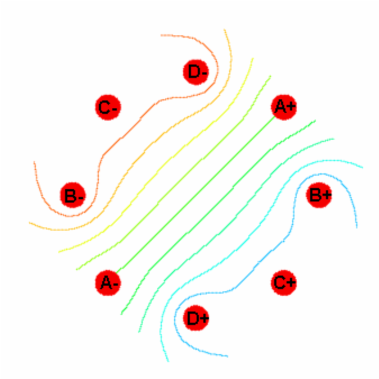

Fig. 6. Octopole grids.

The resulting electric field amplitude along any given axis for an octopole is repeated in Figure 7, with the sequenced states labeled zero through seven.

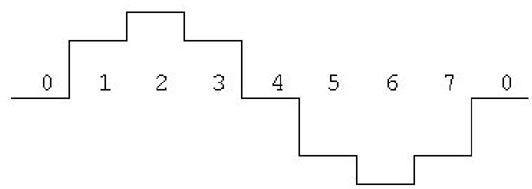

Fig. 7. Field amplitude cycle.

The best field linearity is obtained (for an octopole), with three adjacent grids actively driven to +1 or –1, with the remaining two at zero. With a higher number of grids, this parameter can be adjusted as desired to achieve various field curvatures [3]. The sequence for proper rotation of the octopole is given in the following table.

	0	1	2	3	4	5	6	7
A	0	-1	-1	-1	0	1	1	1
B	1	0	-1	-1	-1	0	1	1
C	1	1	0	-1	-1	-1	0	1
D	1	1	1	0	-1	-1	-1	0

This logic sequence is easily created by microprocessor, FPGA, or even simple logic circuits. It is important to note that the output rotational frequency is $1/8^{th}$ the system clock rate. Or conversely, the system clock must be *n* times the desired rotation frequency, where *n* is the number of grids. This concept can be extended to any number of grid pairs.

REALIZATION

One method to realize the logic sequence is to use a 3-bit counter that continually rolls over. It is clocked by a frequency 8 times the resulting output (for octopole example) and has output bits XYZ. The logic table can thus be written as follows.

	X	Y	Z	A 1	A 2	B 1	B 2	C 1	C 2	D 1	D 2
0	0	0	0	0	0	1	0	1	0	1	0
1	0	0	1	0	1	0	0	1	0	1	0
2	0	1	0	0	1	0	1	0	0	1	0
3	0	1	1	0	1	0	1	0	1	0	0
4	1	0	0	1	1	0	1	0	1	0	1
5	1	0	1	1	0	1	1	0	1	0	1
6	1	1	0	1	0	1	0	1	1	0	1
7	1	1	1	1	0	1	0	1	0	1	1

This can be rewritten with Karnaugh-style reduction minterms:

A1 = X
A2 = !XZ + !XY + X!Y!Z
B1 = !X!Y!Z + XZ + XY
B2 = !XY + X!Y
C1 = !X!Y + XY
C2 = !XYZ + X!Y + X!Z
D1 = !X!Y + !X!Z + XYZ
D2 = X

These equations can be programmed into an FPGA or other combinational logic device. Interestingly, by looking at the logic table, it can be seen that there is a repeating pattern and that A1 precedes B1 by 45 degrees, C1 by 90 degrees, and D1 by 135 degrees. This can be seen in Figure 8.

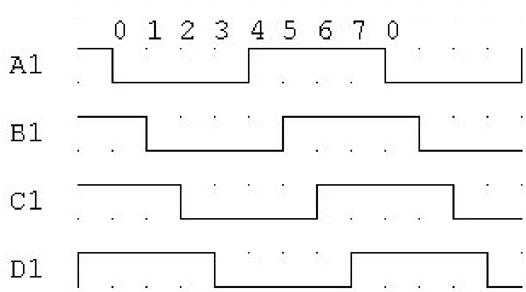

Fig. 8. Relationship between octopole phases.

Therefore, another approach to logic reduction is by using three levels of divide-by-two flip-flop stages. This is because 360 degrees divided by 8 is 45 degrees, and that $2^3 = 8$ (hence three levels). Such a circuit is shown in Figure 9. This is a very simple circuit to construct, and it performs both logic reduction and frequency division. This technique applies to any 2^n system. Note both A1 and D2 are equal, just as shown in the above minterms.

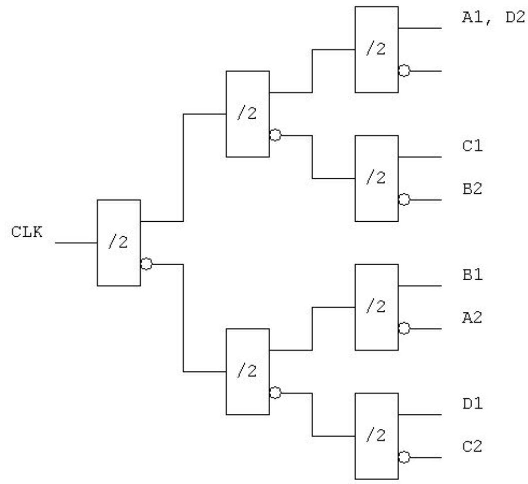

Fig. 9. Three stage logic reduction.

SUMMARY

This paper described a digital drive method of electrical field generation for a 3HMS, as opposed to the prior art of analog sine waveforms. The simplicity of digital drive provides similar performance at lower cost.

REFERENCES

1. "Hyperbolic Horn Helical Mass Spectrometer (3HMS)", Hagerman, 2005.
2. "Image Plane of 3HMS", Hagerman, 2005.
3. "Fan Blade Construction of 3HMS", Hagerman, 2006.
4. "Rotating Field Mass and Velocity Analyzer", Patent 5,726,448, Smith, 1997.