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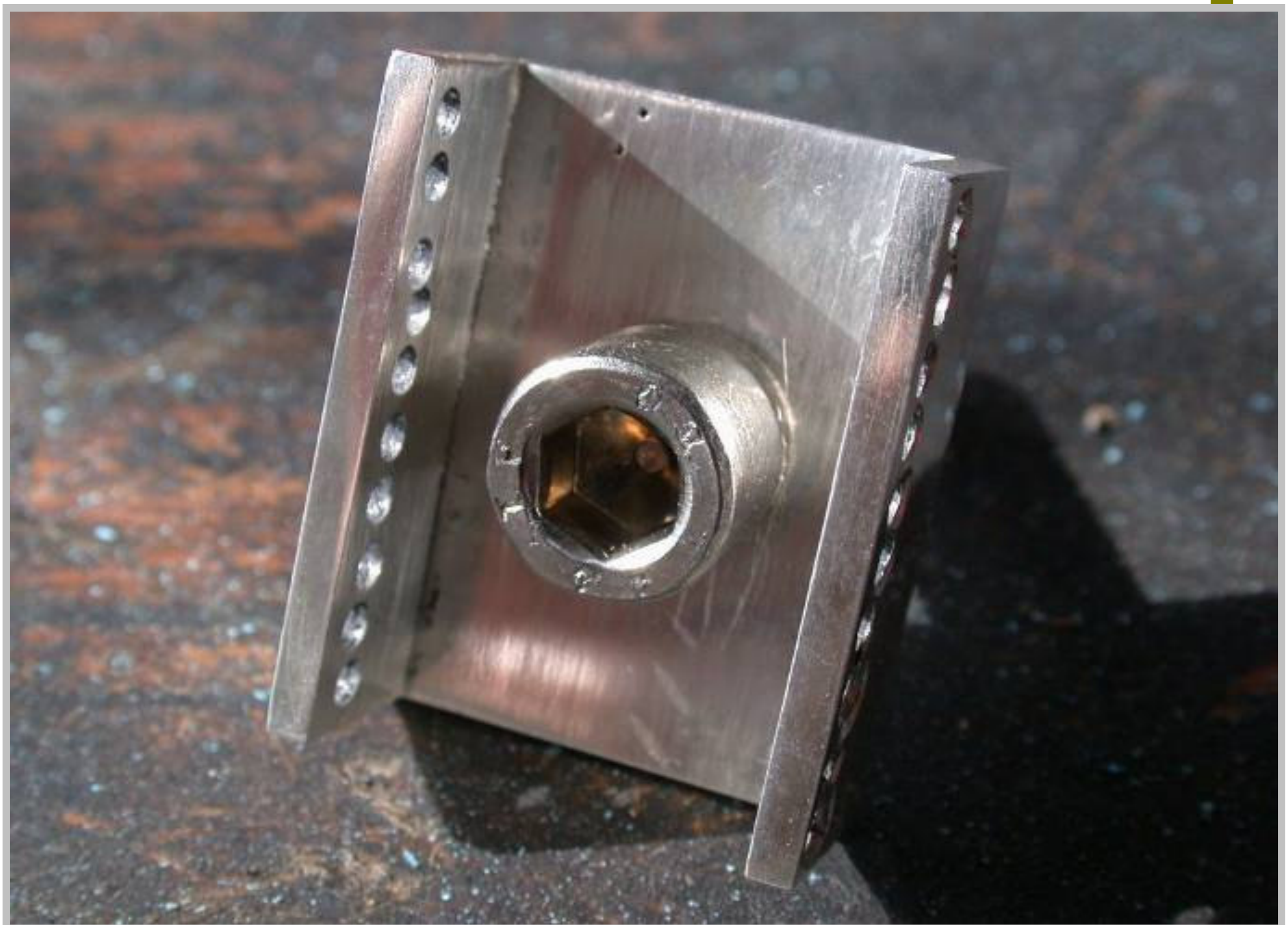


Magazine for Men or Women who think they can do it better...

Turntable Motors

By Mark Kelly

Motors for turntables generally fall into the following categories:

AC induction motors (single phase)

AC synchronous motors (single phase)

DC brushed motors

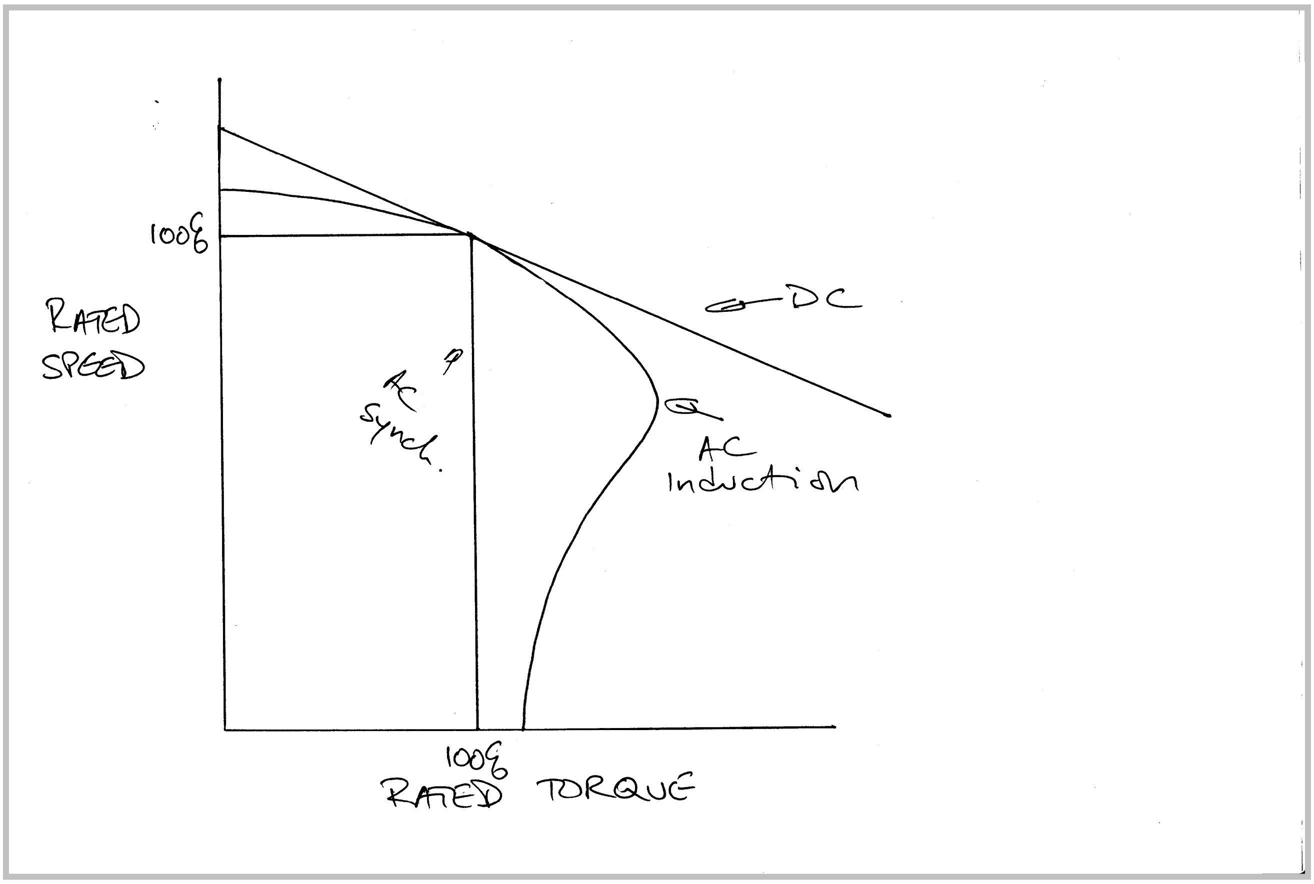


Fig.1. Speed / torque curves for typical motors, taken at similar rated torque levels. Note that an AC shaded pole motor will be much larger than an AC synch motor for a given rated torque and will require more input power. A DC motor will be smaller again, and require less input power.

AC Induction (usually Shaded Pole, eg Garrard 301.

These are all induction motors, meaning that the rotor magnetisation is induced by relative motion between the rotor and the stator field. This relative motion shows up as non-synchronous speed, slower than the supply frequency by an amount known as "slip". Because the current in the rotor (and thus the total torque) is dependent on the degree of difference, the higher the torque the higher the slip. This allows speed control by load variation which is the principle behind eddy current brakes. The degree of slip for a given load is affected by supply voltage and the interaction between these three variables gives a torque/speed curve which is not linear, as can be seen in the graph above. Shaded pole motors also give some cogging torque although this can be minimised by skewing the rotor.

The motor is designed to run at a torque which corresponds to about 10% slip, which is in a reasonably linear part of its speed / torque curve. Other types of induction motors generally run at lower slip levels. Note that the motor will produce 200% of rated torque at lower speed, so it will start a heavy platter quite quickly. The motor can be very noisy, both electrically and mechanically. The AC supply also acts as a source of noise.

AC synchronous (eg Linn Sondek)

Because the rotor magnetisation is permanent, there is no slip induced between the rotor and the stator field so the rotor moves in synchrony with the stator field, hence the name. Generally the motors found in TTs are two phase multi-pole synchronous motors with iron stators. The run speed equals 120 x fsupply / pole number so a 24 pole motor gives 250RPM on a 50Hz supply and 300 RPM on a 60Hz supply. A synchronous motor must run at this speed until its pull out torque is reached where it abruptly stops, giving the "squared off" speed / torque characteristic shown in the graph. Loading techniques like eddy current brakes therefore have no effect. Changing the voltage supply only changes the pull out torque so cannot be used for speed control. This also means that the motor must be run with excess voltage which contributes to noise.

To vary speed an AC synchronous motor needs a variable frequency drive. These can be either digital or analogue, with digital being far more common as they are cheaper and easier to design to a given specification. Electronic supplies can be designed to give two output waves "in quadrature" - 90 degrees apart. On a single phase supply (like the mains) the motor uses a phasing capacitor to generate the cosine equivalent of the sine wave supply.

DC (brushed).

Many modern machines use these and they are offered as upgrades for existing AC TTs. The current required by a DC motor is directly proportional to torque produced so the voltage required to drive this across the windings is also proportional to the torque and the winding resistance. The motor also produces a back emf (voltage) which is directly proportional to its speed. Taken together these mean a DC motor will always accelerate to the point where the sum of the voltage required for the given torque and the back emf exactly equals the drive voltage. Increasing the torque required slows the motor down. The motor can produce many times its rated torque at slower speeds so they are excellent for accelerating heavy loads.

The absence of overvoltage and the absence of AC ripple mean these motors are inherently quiet. The brushes create mechanical noise as they run on the commutation rotor and the commutation gaps create arcs at changeover giving rise to commutation noise on the supply. The use of precious metal brushes and capacitive loading can reduce this to miniscule levels.

EC (Electronically Commutated, aka Brushless DC)

The only current turntables using these are the SMEs and the Caliburn. The application of EC motors is complex and is therefore often poorly understood. The most common EC motors are actually 3 phase AC motors with permanent magnet rotors, so the motor will run at synchronous speed (governed by the supply frequency according to the number of poles).The comments above also apply to these motors except they need a three phase AC supply with three precisely sinusoidal waveforms of equal amplitude and equal phase delay (120 degrees). In this condition the speed torque curve looks like that for an AC synchronous motor except that the EC motor will be much more powerful for a given size and much quieter. Multi-pole EC motors are not commonly seen – most EC motors are single pole to reduce the supply frequency required for a given speed at the very high design speeds (up to 30,000 rpm). These high speeds also mean they are usually built with precision ball bearings which are mechanically noisier than sleeve bearings but more robust.

Although they are commonly called brushless DC motors they cannot be driven directly on DC as the supply needs to be fed to each of the three windings in sequence. For this reason these motors are usually fed from a specialised supply which can synthesise the required waveforms. The motor speed is controlled by the voltage supplied and the speed for commutation is fed back from the motor itself, usually from hall effect sensors mounted on the "back" of the motor

In the simplest case, known as "block commutation" the three waveforms are simply approximated by turning the positive and negative polarity DC supplies on and off at intervals determined by the output from the sensors. The output to the motor thus consists of a series of pulses on three channels resulting in a great deal of electrical noise. These pulses can have their leading and trailing edges ramped to reduce this, known as trapezoidal commutation. A slightly more complex form uses multiple voltage steps to better approximate a sinusoidal supply. All these schemes suffer from torque cogging due to the deviation from the sinusoidal wave.

Stepper Motors

Stepper motors are a specialised type of synchronous motor which are constructed to allow accurate positioning of the rotor WRT the stator. The interesting features to note are that to achieve micropositioning accuracy (the design goal of the manufacturers) these motors use teeth on the rotor and stator. This will inevitably result in some torque cogging in use, estimated as 5% in an app. note by Oriental Motor . They have significant benefits in terms of the ease with which they can be driven to achieve very accurate rotational speeds, and could form the basis of a direct drive system.

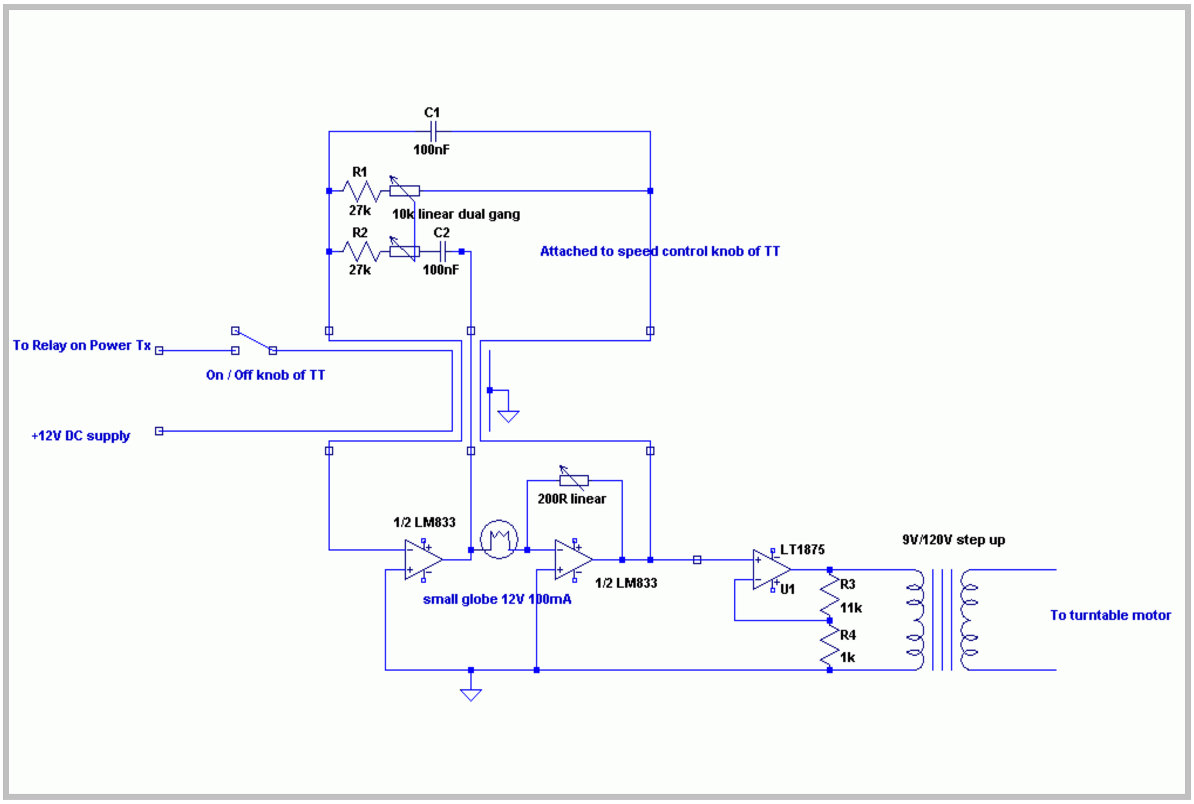
OK, now we are clear on the different motors, here's how to drive them.

AC synchronous drives

The single phase oscillator I present here is based on the one I built for my Garrard 301 Drive and although it works quite well it does not achieve the performance levels of the later and more complex drives.

The circuit consists of a basic Wien bridge oscillator with a very simple PTC gain control which creates the variable frequency sinewave, running into an LM1875T power amplifier and then into a step - up transformer. It could easily be improved by inserting one or more low pass filters between the oscillator output and the power amp IC, also by running the power amp IC in inverting mode. I have not made either of these modifications so there may be pitfalls I haven't foreseen.

Fig 2 (circuit)

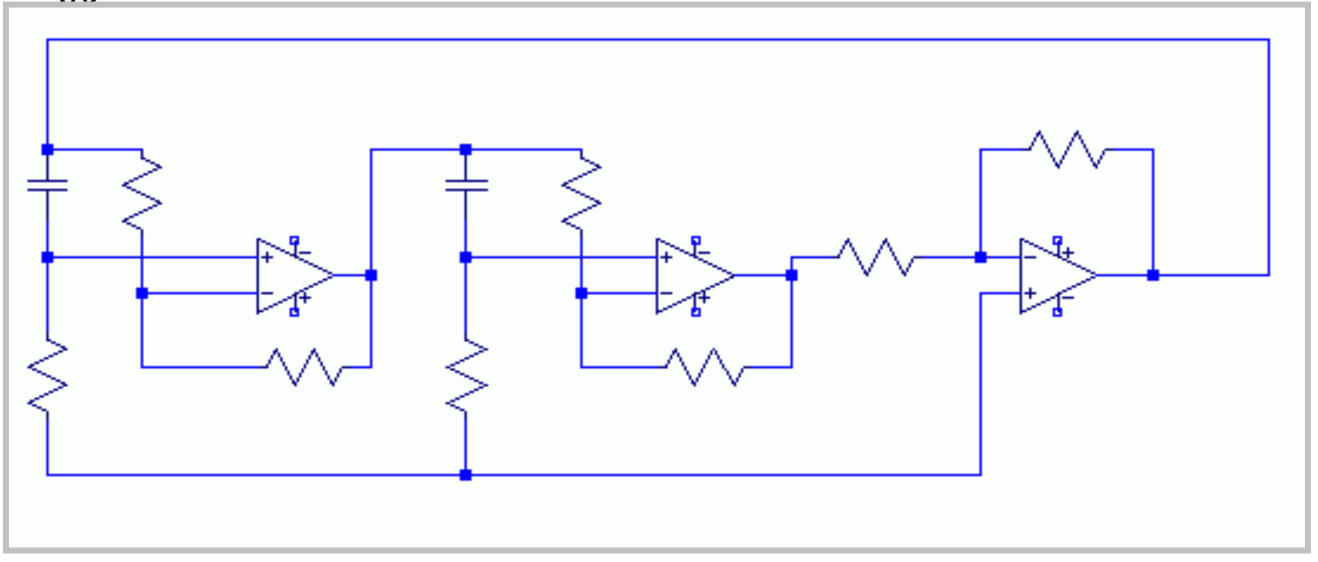


The values shown will give an output frequency variable either side of 50Hz. For 60Hz use 120nF capacitors. Also note that this requires a +/- 18V supply to achieve 15 watts at 110 V and that means using step-down regulators for the oscillator ICs supply rails, +/- 12V is fine. For lower powers you may run the whole thing from these voltage supplies but the transformer step up ratio must be changed. +/- 12V and a 6 volt transformer will achieve approximately 5 watts.

Quadrature.

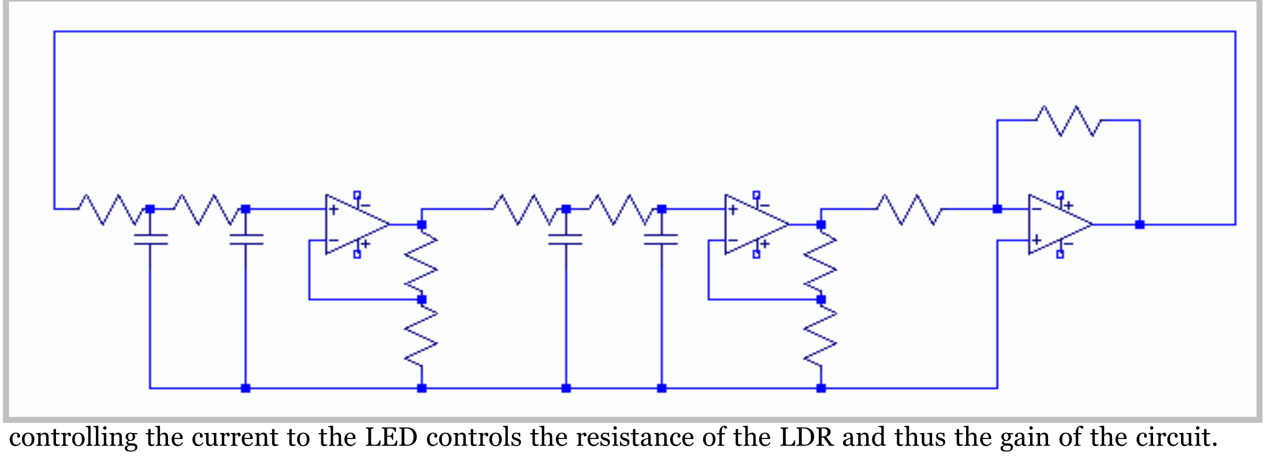
A more sophisticated approach is to generate both phases electronically rather than "faking" one. There are many avenues to doing this, using both analog and digital techniques. The neat analogue solution is simply to build an ultra low distortion oscillator which produces both of the required waveforms and then just amplify them as needed with no filter components.

Fig 3 Fraser Oscillator



This circuit is based on the old Fraser oscillator, which uses a pair of all-pass phase shift networks to achieve a pair of 90 degree delays at the specified frequency then an inverting amplifier to bring this to 360, ensuring oscillation. Because the all-pass networks pass all frequencies without attenuation, it can suffer from parasitic oscillation at a frequency where the sum of the parasitic phase delays in the three amplifiers also sums to 180. With my prototype this occurred at about 600kHz, not difficult to remove but still inconvenient. I decided to rebuild the circuit with passive two pole low pass filters as the 90 degree phase delays, making a hybrid between the Fraser design and the Dippy phase shift oscillator (see later) Using low pass filters as phase shift elements also reduces higher order distortion as the distortion products are above the cutoff frequency of the LP filter.

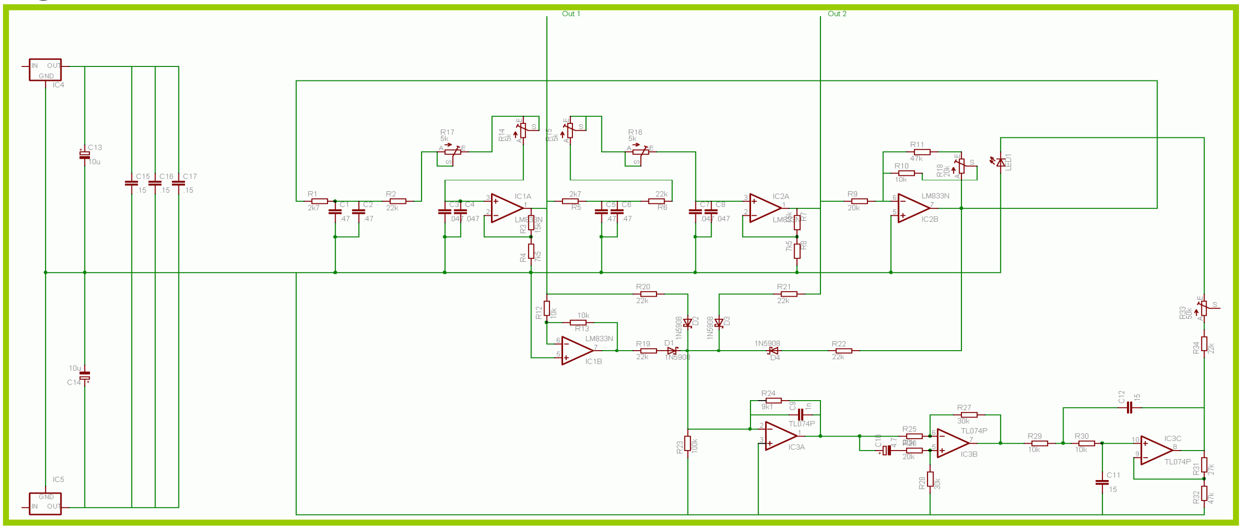
Fig 4 Modified Fraser / Dippy Oscillator



controlling the current to the LED controls the resistance of the LDR and thus the gain of the circuit. To feed the DC equivalent of the AC circuit output to the LED driver I used a modified version of the

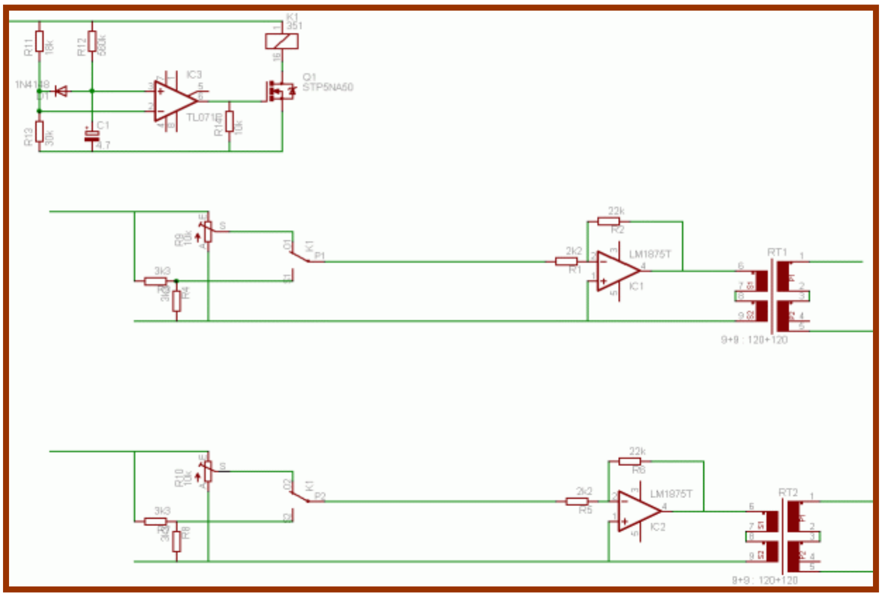
the multiphase rectification / differential amplifier scheme I had developed for my three phase oscillator project. Since the Fraser oscillator gives three phases at 0, 90 and 180 I used a fourth amp as an inverter on the 90 degree output so I had four equally spaced phases to reduce the ripple level. These four phases were each rectified and fed to a summing amplifier, the output of which is fed to a differential amplifier. The diff amp has a series capacitor in one input leg so the difference amplified is the DC level shift between the summed rectified waveform and its level shifted equivalent, thereby removing most of the ripple by the differential action. This is then low pass filtered and drives the LED through a variable resistor for gain control. After building all these myself I discovered the Vactrol analogue optoisolator which is basically a single part version of the same thing with guaranteed specs. I have some on order, I'll report back when I've tried them.

Fig 5 Oscillator Schematic



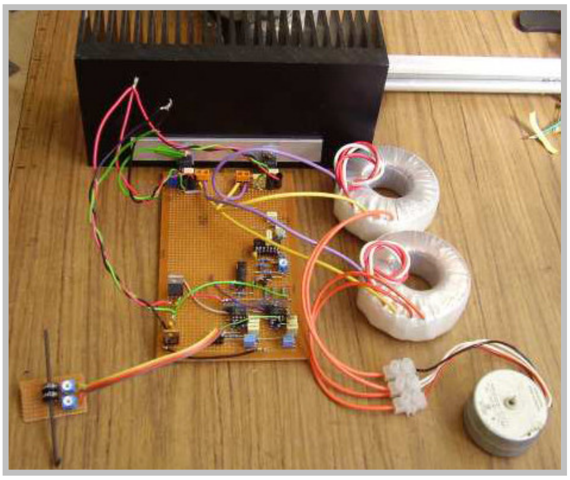
As expected this circuit gives very good distortion results if audio grade op-amps like the LM833 are used for the primary amplifiers and the output is kept to a sensible fraction of the supply voltage. To preserve these good results the output amplifiers are LM1875s connected as inverting amplifiers, reducing the common mode voltage at the inputs reduces distortion significantly.

Figure 6:



The outputs of the LM1875s are connected to two toroidal output transformers chosen for their very low magnetisation current. This is an important point – I tried this with a pair of IE core low voltage lighting transformers and they overloaded the LM1875 outputs which overheated very rapidly, one even let the smoke out. The transformers are run "backwards" since they were designed for use as step downs not step ups. Don't forget that the voltage outputs of transformers generally have a percentage of regulation built in, so the actual turns ratio is slightly lower than the advertised voltage ratio. Accordingly, I use 10 volts RMS into a "9 volt" transformer.

Fig 6 Output section



The independent voltage controls on the outputs allow the voltage to the two phases of the motor to be altered with respect to one another and the phase control allows small variations either side of strict quadrature. On the motor I tried for my prototype these controls allowed the drive to be tuned to give a distinct sweet spot at a voltage ratio of 10:9 and a lesser spot on the phase control which appeared to be at around 89 degrees phase difference. With the values given the frequency is variable from about 57.5 Hz to 63 Hz, about +/- 5%.

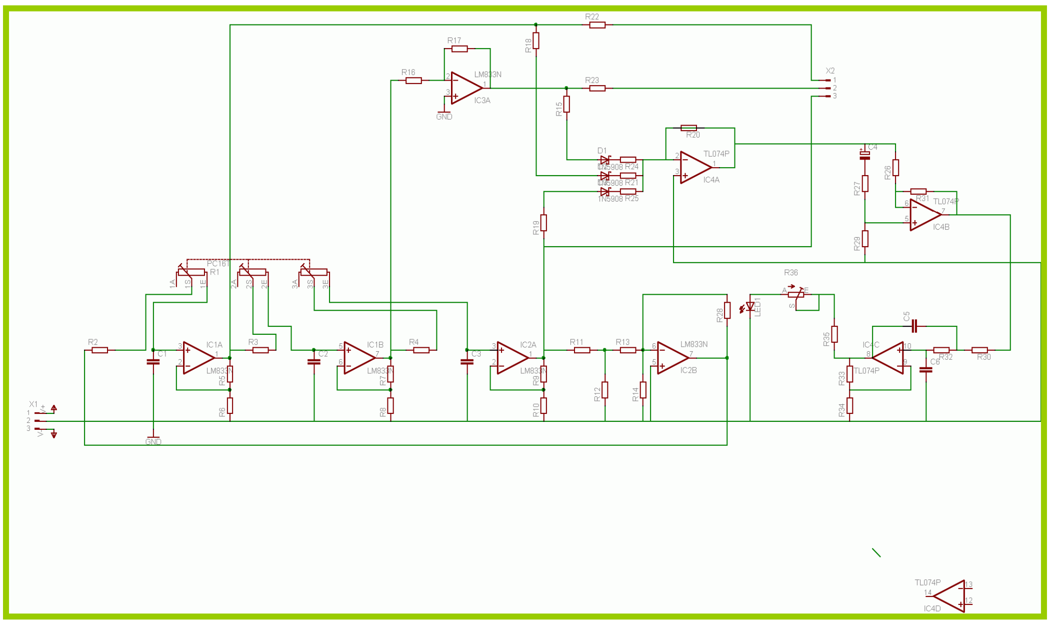
This things works a treat and didn't cost a lot - about $AUD 100 / $USD 75 / EUR 60 including all parts and transformers but not including enclosure and power supply. Enclosure and power supply very much depend on the size of the motor to be powered so it's hard to quote.

EC Motor Drive (3 phase)

Here I resurrected the old Dippy phase shift oscillator which oscillates at the frequency at which the total phase shift of the three networks is 180 degrees, which is logically where each of them has 60 degrees of phase shift, producing three signals at 0, 60 degrees and 120 degrees. Inverting the 60 degree signal produces (60 + 180) = 240 degrees so we now have a three phase variable frequency linear oscillator. For convenience we run each buffer so it compensates for the voltage division in the phase shift network (-6dB at 60degrees) so that each phase also has equal voltage. The rest of the detail is similar to the quadrature oscillator above except we don't need the output transformers as at these speeds the voltage requirement for the motor is of the order of 1 - 3 volts. Power supply is two 12V 65Ah SLA batteries and a charging circuit. Yes 65 Ah, this sucker really needs current.

This circuit costs about 50% more than the quadrature circuit for logical reasons, but since you don't need the transformers it comes out about the same. If you don't happens to have several hundred dollars worth of SLA batteries hanging about the power supply is not going to be cheap, but the real slug is the motor I used a Maxon EC32 # 118890 which set me back the better part of $AUD 500 / $USD 375 / EUR 300 by the time I replaced the bearings. Maxon make some flat EC motors which are cheaper and are multi-pole, making the design easier, but these have iron stators so they have a fair bit of stator cogging. They are still an improvement on any single phase AC motor I know of.

Fig 7 circuit



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DC Brushed Motor Drives

Drives for standard (brushed) DC motors use an entirely different principle from any AC drive because the commutation frequency is set by the action of the brushes on the commutator, so the motor will spin up to a speed determined solely by the voltage and current of the supply. At first cut this looks like it means that we can use simple voltage regulation as a speed control. Alas, not so, despite several sources having promoted such ideas. The devil, as always, is in the details. The motor generates a back emf according to its speed and requires a forward current according to its output torque, so the primary performance specifications of a DC motor are its speed constant, usually given in RPM per volt, its torque constant, usually given in mNm per amp (oz.in per amp in USA) and its winding resistance in ohms. The run speed for a given supply is determined by all three of these parameters, not just the voltage. The run speed will be determined by the voltage remaining after some of the supply voltage is used to drive the required current across the winding resistance. More torque = more current = less remaining voltage = less speed.

The equilibrium speed at a given voltage is given by :

$S = Ks. (V\ supply - (T\ load / Kt) . (Rw + Rd))$

This means that with constant voltage supply the motor has a constant negative speed / torque relationship with the slope given by

$Delta\ S / Delta\ T\ load = Ks (Rw + Rd) / Kt$.

Even given a perfect DC regulator with zero output impedance we would still have a negative slope, now equal simply to Ks x Rw / Rd . A constant speed DC drive thus requires that the sum of Rw and Rd be made as close as possible to zero. Since Rw is always positive, we need a negative Rd. More on this later.

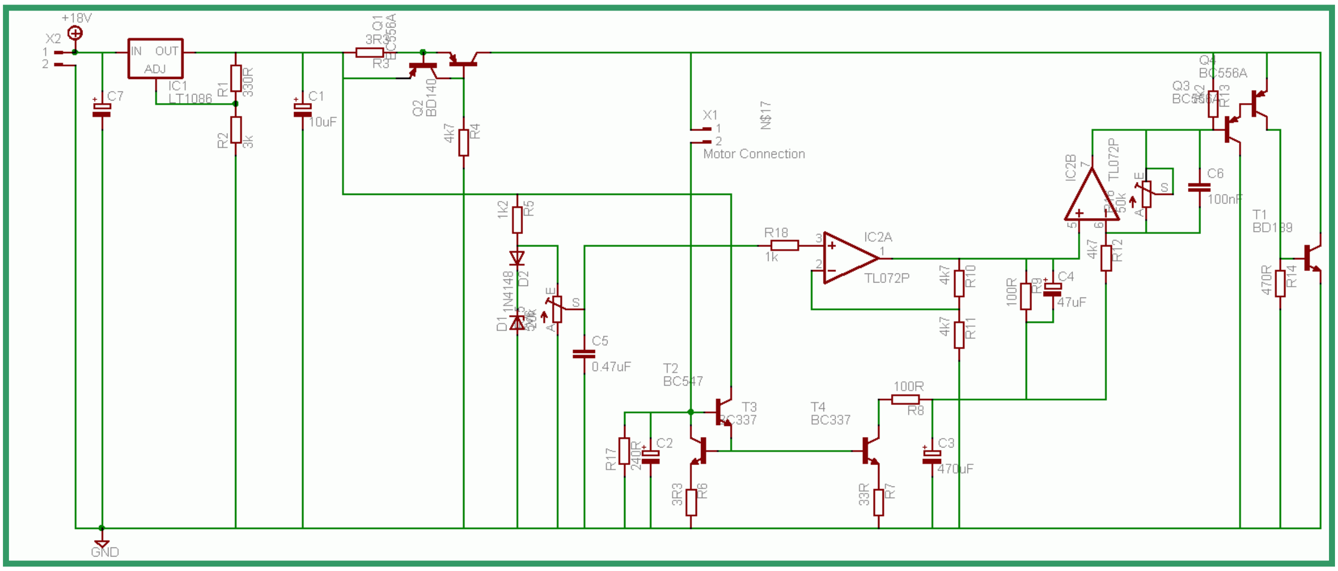
To give you an idea of the importance of all this, here's a table with several motors with their performance specs. I have included max continuous torque and the current required to achieve this as these are important later.
The last rows are the percentage speed change for a 10mN drag load applied at the outer groove (roughly the drag produced by a stylus down force of 18mN or 1.8 grams) for Rd = 0 and also for (Rw + Rd) = 1 ohm (an easily achievable figure). It should be noted that this speed variation is independent of platter mass or moment of inertia as these cannot supply the energy which the drag converts to waste heat, they merely slow the effect down so it happens over a period of the order of one second.

As an illustration of the importance of this effect, a standard DC motor on a turntable will usually show speed variation in the percent range simply due to the effective torque of the stylus drag changing across the record. With careful design and a good motor this can be reduced to less than 0.05%. I chose to use the Maxon #110191 motor for the first project as it seemed suitable for the belt drive turntable in which it was to be used.(at 600 rpm) It costs about $AUD 170 / $USD 130 / EUR 100 including shipping. The other promising motor is the # 226764 which is slightly more expensive, around $AUD 200 / $USD 150 / EUR 200 but is probably preferable for lower speeds such as 300 RPM. The higher torque of this second motor is probably more useful as a replacement for motors such as that in the Garrard 301 except to run it at the speed needed for the Garrard (900 rpm +) requires a higher voltage.

Fig 8. Simple DC drive

This includes a stabilised voltage reference based on the fact that the tempcos of a 5.6V zener and a pn junction are more or less equal but opposite, so the series combination has very low temperature drift. A precision bandgap or even an Xfet will give better performance, more later. The output of the voltage reference goes though a potentiometer to allow us to control the output voltage, the cap to ground shunts the zener noise. The use of the compensated zener locks us into a reference of 6.2V which is too low for the full range of outputs we might need. The output impedance of the resistive divider is high and variable, so it might affect the following stage. We solve these problems together by feeding the output of the voltage divider into a gain buffer. This buffer then feeds the output arm of a 10 :1 Widlar current mirror whose input is in the return arm of the motor circuit, allowing us to implement current compensation. The idea of current compensation is simple - we measure the current through the motor and use that to generate a voltage equal to the voltage required to drive that current across the motor winding (and any residual drive resistance). This is a form of positive feedback, in that the output voltage increases with output current. Another way of saying the same thing is that the drive's

Figure 8.



resistance becomes negative by the same amount that the motor's resistance is positive, so their sum becomes zero (or as close to it as we can manage without instability).

The current mirror reflects the current in the motor circuit and this current is fed from the commutator of the motor so it consists of a series of short pulses separated by even shorter blanks. The capacitive noise reduction in the motor smoothes this to a series of rounded pulses but they can be a significant percentage of the output current of the drive, especially when it's coasting. The input impedance of the current mirror is very low but this still results in some tens of millivolts of commutation noise on the return. This noise is fed through the current mirror so the current compensation circuit would amplify it back into the output if we didn't take steps to reduce it. The first of these is to reduce the current variation seen by the mirror by shunting it through a capacitor, which has to be fairly large to be effective. The second is to include some filtering in the output arm of the current mirror, these can be smaller but not too small.

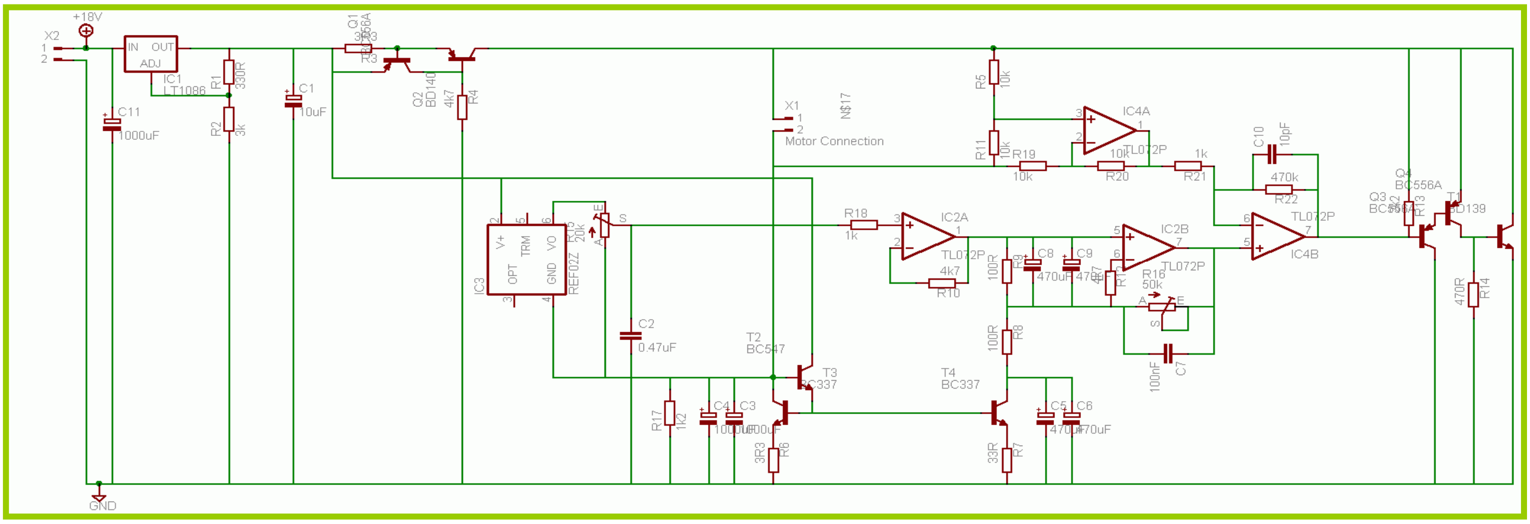
The current drawn by the current mirror circuit creates a voltage drop across its output resistor, this is amplified by the inverting op amp and summed with the reference voltage on its positive input, giving us an output voltage equal to V ref plus current times transimpedance gain. The gain of the inverting amp is variable, allowing the net transimpedance gain of the current mirror to be varied. If this is made equal to the resistance of the motor winding, the result is a reference output voltage which equals the reference voltage plus the voltage required to produce the current corresponding to the torque load on the motor, so the motor does not change speed with load. There is a small capacitor across the feedback element of the inverting amp to keep it stable and to further reduce noise. Note that the motor windings are copper so they will have a positive temperature coefficent of resistance. This actually works to give us a safety margin on our negative output impedance – if the net impedance drops below zero the current increases, the motor heats up and the winding resistance increases, pulling the net impedance back to zero.

The reference voltage plus compensation voltage is then fed to the output stage of the shunt regulator. Note that there is an emitter follower driving the drive transistor, this is not because we need any huge amount of current gain but simply to ensure that there are two pn junctions between the reference output voltage and the actual output.
This all fits on a 80 x 100 mm (half eurocard) PCB and works a treat. This is one of my recommended circuits. The other is an elaboration of this which includes an error amplifier and lots of global feedback but allows us to dispense with the capacitor on the ground return leg of the motor circuit. It's

your choice which to build, they both fit on the same circuit board, the error amp version has about one tenth the commutation ripple of the straight version but they're both so low this is probably immaterial. If you really hate feedback, use the first. If you really hate electrolytic capacitors, use the second.

To use the error amplifier circuit we must be able to compare the output voltage to the reference voltage. It is easiest to derive a scaled version of the output voltage to compare to the reference rather than boosting the reference to the output level. Since we are interested in the voltage across the terminals of the motor rather than from the drive output to ground, we construct the voltage divider between the output terminals and feed this to a differential amplifier. We also connect the voltage reference so that it connects to the negative motor terminal. Note that this puts the reference current which is not part of the output through the current mirror, to avoid this source of error we put a shunt across the current mirror to equalise it.

Fig 9. Drive with error correction



The error amplifier then compares the divided output voltage to the sum of the reference voltage and the current feedback voltage and feeds the amplified, inverted result back to the output driver cascade. The amplifier itself is set at about x 500 and the output driver contributes a further x 20 or so, so we have overall feedback around x 10,000 or 80 dB. The high level of feedback means this circuit must be laid out carefully and debugged on a reasonably fast scope – on my prototype I got a lovely oscillation at 2.2 MHz at about 5 V peak to peak on the output, easily solved with a 100pF stabilisation capacitor on the error amp. This circuit fits on the same PCB as the other circuit and the difference in cost is very small you can afford to build both versions to try (I've included a jumper on the PCB that makes the circuit changes very easy indeed.

OK so far, but lots of DIY types are going to be thinking "how can we improve this?" These circuits were designed to be insensitive to parts quality, the prototypes were built with ordinary metal film resistors, commercial zener diodes and TL072 op -amps but that doesn't mean we can't do better. A quality specialised voltage reference would be the first change to make, we will use one of the REF02 series eg the TI REF02AP with a typical 5ppm tempco - that's a 0.005 percent change for a ten C temperature rise. It has a 5 V output so it restricts the output voltage slightly but we can compensate by changing the divider ratio or the buffer gain. The reference current is only 1 mA so the current mirror bypass resistor is 1k2. This is so cheap and effective that I've adopted it for all versions.

The next change is to upgrade the op-amps to ultra-precision instrumentation grade units like the OPA2277 or the AD 708. These are pin compatible with the TL072 so all we need is to mount the op-amps in sockets and we can substitute with no changes. We might as well use quality low noise metal film resistors like Dales. We use good quality low impedance electros like the Rubycon ZL or Elna RSH series because we don't use cheap electros, there's space on the board to parallel extra caps of the same value thus halving the ESR and doubling the capacitance. There's no provision for bypasses as I think they're a waste of time. The compensation cap on the error amp can be changed from a ceramic to silver mica, the ones on the voltage reference and the transimpedance amp are polyester film, you could sub polypropylene.

In the power supply we can move from a 7815 pre-regulator to the excellent LT1086 but the biggest improvement is probably powering the whole thing from an SLA battery. Depending on the motor RPM required and thus the voltage required, a 4 -5 Ah 12V SLA should be ample and will give around 20 hours per charge. You should jumper the pre-regulator out of circuit if you use battery supply (or don't include it in the first place).

The prototype worked very well and my beta tester seems very happy with the result, which measures at better than 0.1% speed accuracy. The costs for this project are quite reasonable given the outcome. The raw cost of the controller, including PCB, all parts, plugs, sockets etc but not including an enclosure or power supply is about $AUD 90 / $USD 70 / EUR 55. The upgrades mentioned above add about $AUD 40 / $USD 30 / EUR 25.

How much you spend on an enclosure depends on how much you want to spend. In Australia Jaycar HB5462 is $AUD 25.75, in the USA the Hammond 1402 DV is $USD 42.15 (Allied part 802-1366), or you could use something like a 1U rackmount.

A suitable power supply giving 18V at 300 mA using a standard 2.1mm DC plug (centre positive) is fairly cheap, you could use Jaycar part no MP3029 which is $AUD18.95, you'll need reasonable heatsinking for the pre-regulator as this is a 24 volt supply. In the US Allied part no 967 8102 is suitable, this costs $USD 7.11

If there is enough interest I can put together a couple of kits – the "Cheap as Chips" unit would be the boards, ordinary grade components, connectors and the cheap box, this would cost $AUD 115 / $USD 90 / EUR 70.

The "Ultra performance" version would include the upgrade components and a nicer box, this will set you back $AUD 175 / $USD 135 / EUR 105.

Shipping will be at cost, figure around $AUD 9 / $USD20 / EUR20.

You'll need to get your own power supply plus a pulley to suit your table. You'll also need the motor. If there is enough interest I could source both the motor and a "universal" pulley.

Email Bas if you are interested, include the diameter of the driven part of your table (eg the outer diameter if it's edge driven, the subplatter diameter if not) and whether you want me to source the motor.

This article has been condensed from a series of articles I have on my website. For further information on many of the points made here go to
http://www.members.iinet.net.au/~quiddity/audio/Turntable_motors.html
and navigate to the section of interest.

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