# Study of Cogging Torque in Technics SL-1200 Turntables

Abstract: Cogging torque is produced in the pre-2016 Technics turntable direct drive motors simply because of the magnetic attraction between the rotor mounted permanent ring magnet and the steel stator. However, the cogging torque is small at under 3 grams, competing with the frictional drag of the bearings themselves. Cogging torque mostly reveals itself as a rumble component at 26.64Hz at 33.33RPM. This is outside the normally weighted roll-off of the rumble measurement (100hz), and is 56dB below a standard test signal and therefore is not audible.
This paper serves to describe how the motors work and how the measurements compare between direct drive and belt drive turntables of the day.

**Technics Direct Drive Motor (1973-2010)**

All the motors used in the technics 1200 series are 3 phase variable power factor Brushless DC motors. That is, the speed is analogous to the applied power. And the power is controlled by applying a DC Control Voltage to the motor drive circuits.
At the low operating speeds of these motors, the power factor is actually very low. And while these motors are capable of fast start up times, at operating speed the running torque is quite low.
I think the fast start up feature is what led many to call these high torque motors. But as we will learn later in this article, in order to optimize such a motor for turntable use, torque is a necessary sacrifice for smooth rotation at low speed.
To control the speed of these early designs (1973-1978), an integrated(bifilar) motor coil winding was used to develop a feedback voltage that could be used to control the speed of the motor.
This signal voltage is filtered by a simple resistor/capacitor network which converts it into a DC voltage with a time constant of approximately 1 second.
This speed signal voltage would then be compared to a reference voltage and the resultant DC Control Voltage would be used to hold the motor speed at the desired operating RPM. These early motors had very good wow and flutter measurements (0.03%) but because the DC Control Voltage was developed across simple resistors, the speed was known to drift over time and need constant re-adjustment. Furthermore, the response time was also slow (>1 sec) needing 1/2 revolution or so to make a speed correction. ( A good description of this motor operation and circuitry can be found in the SL-1100 service manual available at www.vinylengine.com)

**Quartz Phase Locked Direct Drive Motor**

Technics direct drive motors made after 1979 use a different kind of frequency generator to provide feedback for platter speed control.
This generator is comprised of a flexible printed circuit coil that is placed directly around the motor magnet making the signal it produces a true representation of platter position.
In this way, as the motor rotates, the magnetic field cuts through the coil and generates a 50.55hz signal when the platter is moving at 33.33 rpm. This is compared against a quartz crystal reference. The crystal frequency(4.19328Mhz) is passed through 4 dividers 1/16, 1/8, 1/54 and 1/12 to arrive at a matching 50.55hz reference. When the platter is rotating, these two signal waveforms are maintained in perfect alignment or phase by using a circuit called a phase lock loop (PLL). If the two signals are in phase we know that the platter speed and position is precisely locked to the quartz crystal timing. You can think of the frequency generator and the crystal oscillator as gears that are in perfect mesh with each other when the PLL is in a locked condition.

The PLL produces two square wave signals, a speed signal (Vo) with a fixed frequency, and a phase signal (Po) which reflects changes in platter relative position. The two signals are combined in a circuit called an Integrator. This converts the square waves into a saw tooth wave which is then filtered again by a simple resistor/capacitor network with a time constant of approximately 300ms. This DC voltage is compared to a reference voltage and the resultant DC Control Voltage is use to control the power of the motor.

To summarize, both older and newer motor designs use a DC control voltage to control the platter speed. They just use different means to achieve the same end.
Both control systems achieve equilibrium at the set speed. And while the older method has issues with long term drift and dynamic load response, the later method does not.

The response time to a change in platter load friction is approximately 1000 milliseconds(1/2 revolution) in the older models and 300 milliseconds(1/6 revolution) in the later version.
The response time governs just how well the platter speed can maintain equilibrium for a change in load as happens when the stylus encounters a loud modulation.
Ideally, you want the platter speed to remain steady during this time. A belt drive for example, achieves load stability by using a very heavy platter. The direct drive with a PLL emulates that electronically.

Another difference between the early motor vs the later ones, is bi-directional drive. The early motors could only push forward. The later motors could push or pull the platter allowing for an even greater degree of control over the platter's relative equilibrium. If you compare a 1200 original vs a 1200MK2 when switching from 45 to 33, you can immediately appreciate the bi directional drive. The speed change is instant with the MK2, while the original 1200 has to coast slowly down to 33 due to the inertia of the platter. As an interesting aside, the Sansui SR-838 used a unique braking scheme to speed up the change from 45 to 33.
And while not as instant a speed change as a 1200 MK2 bi directional drive, the changeover was quite a bit faster than the original SL1200.

The Technics 1200 MK2 spec sheet indicates that speed change due to load torque is 0% for loads up to 0.8 LB-in.(180gm stylus force)
Wow and Flutter is specified as 0.025% weighted, and 0.035% peak. The weighted W&F measurement taken directly from the internal frequency generator is 0.01%
Speed Drift within 0.002%

Speed drift is the average speed measured over time. Audio magazine measured drift as speed change over 42 seconds (Ed Long).
Using the 1200 MK2 drift number of 0.002%, the turntable speed can vary between 33.3339 and 33.3326 rpm (33.3333 X 1.00002 and 33.3333/1.00002)
That would allow for example, a 20kHz frequency to wander between 19.999.6kHz and 20.0004kHz, a 1kHz tone would wander between 1000.02 and 999.98 Hz. This is not audible.
From wiki page on wow and flutter:

### Absolute speed

"Absolute speed error causes a change in pitch, and it is useful to know that a semitone in music represents a 6% frequency change. This is because Western music uses the 'equal temperament scale' based on a constant geometric ratio between twelve notes; and the twelfth root of 2 is 1.05946. ***Anyone with a good musical ear can detect a pitch change of around 1%, though an error of up to 3% is likely to go unnoticed, except by those few with 'absolute pitch***."

- End of wiki

This helps to put the 0.002% into real world perspective.
As a comparison, the highly regarded Well Tempered Lab belt drive turntable reviewed in Audio magazine in July 1988, had a long term drift of 0.15% and Ed Long rated that as very good.

**Cogging**
Now, regarding the use of the term cogging. Let's start here with the definition from Wikipedia:
**"Cogging torque** of electrical motors is the torque due to the interaction between the permanent magnets of the rotor and the stator slots of a permanent magnet machine. It is also known as *detent* or *no-current torque*. This torque is position dependent and its periodicity per revolution depends on the number of magnetic poles and the number of teeth on the stator. Cogging torque is an undesirable component for the operation of such a motor. It is especially prominent at lower speeds, with the symptom of jerkiness. Cogging torque results in torque as well as speed ripple; however, at high speed the motor moment of inertia filters out the effect of cogging torque.

- End of wiki

And yet, no one would look at a Technics turntable platter in rotation and suggest that the motion is "jerky". Just looking at the strobe display confirms that. Furthermore, simply rotating the platter slowly by hand also shows that there is no discernable pole to pole attraction. And while these motors are capable of fast start up times, at normal running speed, they are, by design, low torque motors; easily stopped by hand when running at normal operating speed.

So why has the word cogging been used so often in our hobby to describe a deficiency in the sound of direct drive turntables?
Maybe it has to do with the kind of information you encounter when you research brushless DC motors online.
There you will find things like this:
Cogging, by definition, is a force that interferes with the continuous torque delivery of an electric motor. In the worse situation, cogging torque can be so great that the motor will not even start up.
https://www.youtube.com/watch?v=pYa5VOaQHyo&t=911s

All DC Brushless motors that feature a steel core will exhibit some degree of cogging.
However, motors can be designed to minimize the effects of cogging torque to a degree where it competes with the general friction of the bearings themselves.

## Reducing the cogging torque

"Cogging torque is produced, in a brushless PM machine, by the magnetic attraction between the rotor mounted permanent magnets and the stator teeth. It is the circumferential component of attractive force that attempts to maintain the alignment between the stator teeth and the permanent magnets"
http://www2.ece.ohio-state.edu/ems/files/TechReportProtected/Study%20of%20Cogging%20Torque%20in%20Permanent%20Magnet%20Machines.pdf

## Cogging Torque Minimization Techniques

Cogging torque minimization techniques have been analyzed for various electromechanical machines. In this paper, results for the following cases are provided:
(1) variation in magnet strength,

(2) variations in magnet arc length [5, 11],
(3) shifting magnetic poles [9-12],
(4) radial versus parallel magnetization [5, 13],
(5) rotor eccentricity,
(6) variations in the slot width [9],
(7) variations in the radial shoe depth,
(8) variations in yoke notch radii,
(9) permanent magnet skewing [7, 9, 11, 14-17], and
(10) permanent magnet overhang [9].

According to this paper, of the 9 items listed, the ones most obviously employed in the Technics motor to reduce cogging magnitude are items 1 & 2, variation in magnet strength, and variations in magnet arc length.

Further, "Another way to mitigate the effect of cogging is to select a fractional slot combination in which the number of stator slots divided by the number of rotor poles is a non-integer number. As a result, only one side of the rotor magnet lines up with the stator slots. The edges of the slots do not line up with the poles, which, reduces cogging torque."
Taken from https://www.automate.org/tech-papers/understanding-the-distinctions-among-torque-ripple-cogging-torque-and-detent

The Technics SL-1200MK2 motor uses a 16-pole magnet and a 12-slot stator and so exhibits a fractional slot combination, 12/16 = 0.75. It also uses a continuous low energy ring magnet with 16 integrated poles (8 pole pairs) thus optimizing the magnet pole arc. It does not use 16 separate magnets as you might find in truly hi torque motors.
Just rotating the platter slowly by hand and releasing shows that there is just barely perceptible cogging torque acting on the platter: The platter comes to a near stop and then only slightly rocks backwards as it stops; that is the extent of the pole-slot attraction. By making the number of slots divided by poles fractional, you minimize attraction and encourage motion thus reducing cogging torque. A great explanation of how to minimize cogging in ac motors is shown here:
https://www.youtube.com/watch?v=pYa5VOaQHyo&t=911s beginning at 6 min in and especially focus at 8:38 – 10:36.

**Measuring cogging torque**
More importantly, it is possible to measure the cogging torque with a simple gram pressure gauge. I think this reveals the true insignificance of cogging torque on Technics motor performance.
Cogging torque measured on a Technics SL-1200 MK2 with a gram pressure gauge:

Using a stock platter with the magnet removed, to measure just the bearing friction torque:
Measuring 1.5" from the spindle (the stator radius) I get 3.5 grams
Measuring 6" from the spindle at the edge of the platter I get 1.5 grams.

Using a platter with a magnet to capture bearing friction plus cogging attraction:
Measuring 1.5" from the spindle (the stator radius) I get 10 grams
Measuring at the edge of the platter I get 3.5 grams.

If you subtract the top from the bottom set of numbers:
The cogging torque alone as seen from the motor stator is 10-3.5 or 6.5 grams.

The cogging torque alone as seen from the platter edge is 3.5 – 1.5 or 2 grams
2 grams referred to the outer edge of the platter (12.0”).
6.5 grams referenced to the diameter of the actual motor/magnet (3.25”).
Calculated centrifugal force of the platter (5lb 14” at 33.33 is 501 grams
( http://www.calculatoredge.com/mech/flywheel.htm )
2 grams is 0.4% of 501 grams

It is important to note that most of the academic articles on cogging torque use examples of very high torque motors in their discussions.
One such example
https://www.academia.edu/19661425/A_Novel_Cogging_Torque_Simulation_Method_for_Permanent_Magnet_Synchronous_Machines?email_work_card=view-paper
shows a motor having a peak cogging torque of 203 grams. They then go on to discuss a technique that reduces cogging torque to 6 grams(page2174). Quoting “There is a noticeable reduction of 97.5% with respect to the 2 Nm value obtained from the proposed HMPP analysis. A significant improvement benefit using skewing rotor has been proved quantitatively. It thus is an effective way to minimize the undesirable cogging torque.”

https://www.unitconverters.net/torque/newton-meter-to-gram-force-meter.htm (you can use this to convert between Newton-meters and grams)

They say, and justifiably so, that going from 203 grams to 6 grams effectively minimizes undesirable cogging torque.
Bear this in mind when you look at the measured cogging torque of the 1200 motor at just 2 grams.

Also, since the Technics 1200 mk2 motor is stated to provide 0% speed variation with up to 180 grams of drag, 2 grams would seem rather inconsequential.

**Cogging Torque Ripple**
Once the platter is in motion, the startup cogging affect is diminished and what remains is something called cogging torque ripple.
This is calculated by first determining the cogging steps.
The angular slots = 360/12 = 30
The angular poles = 360/16 = 22.5
30 – 22.5 = 7.5
360/7.5 = 48 cogging steps per revolution.
The Cogging Frequency at 33.33rpm = (33.3333/60) * 48 = 26.64hz.
So as the platter is rotating at 33.33rpm, the motor EMF is experiencing a modulation or vibration of 26.64Hz.
From the paper listed above: “*Cogging torque adds a ripple component to the desired constant output torque from the machine. This can produce vibration and noise.”*
So, this 26.64Hz signal would be seen as part of the rumble specification, but as specified rumble is already quite low at -56dB (unweighted, 5-700hz) so it is not significant.
https://en.wikipedia.org/wiki/Rumble_(noise)

**Conclusion**

From this study, my conclusion is that the technics motor speed stability does not suffer from the effects of cogging torque.

The rumble measurements may be influenced by the motor torque ripple of 26.64hz, but this too would seem insignificant when looking at the rumble measurements.

The belt drive Well-Tempered Turntable reviewed by Ed long for Audio Magazine in July, 1988 shows an unweighted rumble of -66dB.

When the weighted(150-700Hz) measurements are taken, the two turntables are even closer -78dB for the Technics, -82 for the Well-Tempered Turntable.

**Historical Questions**

Yet there does remain this comment which M Fremer found for me in this article: https://www.stereophile.com/content/linn-sondek-lp12-turntable-lingo-power-supply-measurements From Stereophile back in 2002.

In describing drive system non linearities in a Linn turntable, John Atkinson wrote: "If you are thinking that a servo-controlled direct-drive design would be the way to eliminate these spuriae, think on this: in a direct-drive turntable, the motor acts directly on the platter spindle. There is therefore no mechanical filter to reduce the effect of any variations from perfect rotational behavior on the part of the motor. In addition, all servo systems will have a natural frequency around which they will 'hunt,' albeit in a damped manner in a well-designed system. In the direct-drive turntables that were popular in the 1970s, this natural servo frequency was around 3kHz—right in the middle of the region where the ear is most sensitive."

I inquired recently about what model he was referring to and was told "If I recall correctly, I was talking about the original pre 1979 Technics SL-1200". But he did not offer the authority or reference source for this 3kHz comment.

I am still trying to get some clarification on this because if you study the original 1200 motor(a great description is written in the SL-1100 service manual); it uses a frequency generator yes, but that signal is rectified and filtered to create a DC control voltage with a very slow time constant of 1.12 Hz.( 6800ohm x 33e-6 farad x 5) I use 5 time constants because it takes 5 time constants for an RC network to reach the applied voltage level.

There is no indication in the service manual that anything in the circuitry is running as fast as 3000hz. Servo motors with a large flywheel, such as a turntable are going to achieve equilibrium. If there is any "hunting" of the control voltage, it is not going to be a repetitive waveform, but rather it will be random in response to frictional changes such as encountered with dynamic stylus drag. And the time constants of the control voltage circuitry, as discussed earlier, are not fast enough to respond at 3000hz(0.33mS). If anyone knows the origins of this 3kHz. claim, it would be most helpful.

Also, the comment that "the motor is directly coupled to the platter spindle and there is therefore no mechanical filter…" is not accurate as the motor power is applied through a magnetic field which, with the mass of the platter creates a spring.

So, to one degree or another, the inertia of the platter does act as a low pass filter. Again, under normal operation, these are low torque motors, as they would have to be to minimize the effects of cogging torque. https://www.osti.gov/servlets/purl/100261 , Pg 3. Paragraph C & D.

In other words, the magnetic field in a direct drive is analogous to the belt in a belt drive. Both offer compliance to the rotating mass of the platter(flywheel).
The advantage of the direct drive is that it is rotating at 33.33RPM, which keeps the frequency of most rumble noise well below the audible range. That cannot be said for the belt drive where the motor is likely spinning at 3600 RPM and this produces rumble frequencies which are much higher and therefore more likely to be audible.

It is important to note that when a linear positional frequency generator is used with phase locked control, very small changes in speed (i.e. platter position) can be detected the instant they occur anywhere within the 360 degree cycle of rotation.
Technics calls this full cycle detection.
Because these corrections are so small, they do not produce audible artifacts because they are infrequent and also because they are smoothed out even further by the flywheel effect of the 4-pound platter.

It has always seemed odd to me that the very feature that is claimed to benefit a belt drive is neglected as a feature benefit for direct drive turntables as well.

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