Skating Force

Lamentations, Measurements and Influence on Reproduction

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Contents

1. Introduction

Skating force (skating) has been widely known for quite some time as a crucial parameter which directly influences the quality of vinyl reproduction. Alas, it is rarely talked about, especially in relation to other related parameters, such as alignment, tracking force and vertical tracking angle.

Not because of it being of less importance, but rather due to the difficulties in understanding the parameter itself - specifically, how it comes about, how measurable it is, and what is its influence on reproduction, both on its own and in conjunction with other parameters.

Manufacturers, and specifically tonearm designers, while acknowledging the existence of skating force and the need for compensation mechanisms, rarely share their insights. When they do, their positions range from *skating has no influence on reproduction* to *skating is crucial to proper tonearm operation*.

This research came about as a means to understanding skating, its formation and influence, as well as the need and scope for a compensation mechanism. Through data, it aims to draw general, usable conclusions.

Before it does, though, a few words on the parameter, applied methodology and reasoning.

2. Skating

2.1 Discovery

As the vinyl record rotates, the tip of the stylus riding on the surface of the microgroove results with a particular friction coefficient. The tonearm, carrying the cartridge (and the stylus) makes every effort to let the stylus track microgrooves with the least possible amount of distortion.

To excel at that, the stylus needs to, at every moment, be positioned tangentially to the microgroove itself. With tangential (linear) tonearms, that is easy to achieve throughout the record side. With pivoted tonearms, however, the stylus can achieve this, at best, on two single points throughout the entire path it traverses across the record side.

Majority of pivoted tonearms concede to a design approach which forces them to follow an arc with a radius slightly larger than the pivot to spindle distance - the difference in length between this radius and the pivot to spindle distance being the *overhang*. Not only this, the cartridge (and thus the stylus) is mounted at the end of the tonearm by a fixed angle called the *offset angle*.

Putting these aspects together results with the stylus being aligned to track an arc that minimizes distortions, and at two points on said arc, all but eliminate them. Various approaches *(alignments)* to calculate the parameters of this arc aim to move the area of larger distortions to different areas of the record side in an attempt to diminish their influence.

Be that as it may, with every pivoted tonearm (apart from ones of infinite length), the ugly side of reality is that some amount of distortion is inevitable, though not always audible.

Given all this, the majority of pivoted tonearms can be represented by a triangle with the following sides - (1) line connecting the tonearm pivot to stylus tip, (2) line parallel to the cartridge body, angled to the first side by the value of the offset angle and (3) line representing the linear tonearm offset - a length which is a function of the offset angle.

And going back to the first paragraph of this section, a defined friction coefficient, combined with rotational force results with a force (force #1) the vector direction of which follows the tangent of the microgroove. The tonearm opposes said force with an equivalent resistive force due to being anchored at the pivot point (force #2).

The vector of this other force is of the same magnitude as the excitation force, but its direction is along the length (1) of the described tonearm triangle, the line connecting the stylus tip to the tonearm pivot, and due to the offset angle, it almost never equates the groove tangent.

These vectors thus do not cancel each other, but sum to form a third vector (force #3) with a magnitude smaller than the two, and a direction towards the platter point for rotation, towards the inside portion of the microgroove.

This third vector is the skating force.

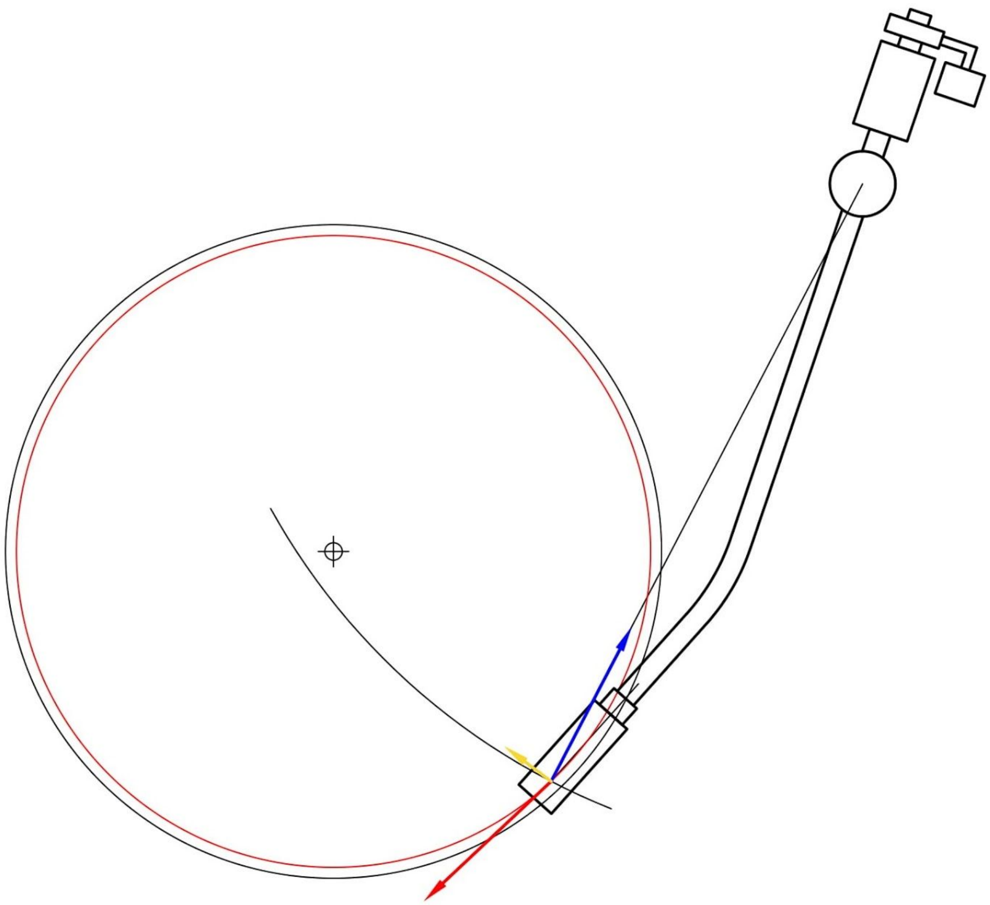

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Illustration 1. *Visualization of skating force with a model of an SME 3012 at the outer groove.*

Applying the drawing to the forces being discussed earlier, the red vector is the excitation force, the product of the rotational movement and friction coefficient (force #1), the blue vector is the tonearm resistance (force #2), and the yellow vector is the resulting skating (force #3).

The magnitude of the excitation force (red vector) on the graphic is arbitrary, due to the fact that of greater importance is its relation to the absolute magnitude than the absolute magnitude itself (which may, but does not need to, be calculated). Of course, in order to calculate it, based on this relation, we would need a few starting points.

So, taking into account a few premises…

- *Total friction coefficient is independent of linear speed (kinetic friction).* As long as the surfaces in question move at a velocity lower than the thermal variations of surface molecules (~300m/s), the friction coefficient is independent to velocity - not only because the highest linear velocity of a typical record is ~0.69m/S (outer groove of a 12” record rotating at 45rpm);
- *Total friction coefficient is dependent on tracking force (static friction).* A direct increase of the tracking force (tracking weight) leads to a linear increase of the friction coefficient, thus increasing skating force proportionally.

...skating force can be illustrated as a fraction of the excitation force, which occurs as a result of rotational movement and static friction.

Using CAD, one can illustrate said vectors at 5 key positions of the tonearm, traversing a standard 12” disc:

- Outer groove (radius of 145mm - close to the IEC/DIN standard);
- Outer null point according to Löfgren A (radius of 121mm);
- Arbitrary middle groove (radius of 94mm);
- Inner null point according to Löfgren A (radius of 66mm); and,
- Inner groove (radius of 60mm - close to the IEC standard).

Visually, the movement of the tonearm across the record, along with the changes in vector magnitude and direction, can be showcased via the following animation:

https://github.com/stojnev/dwr-skating/blob/master/Diagrams/skating_animated.gif

Calculated results allow for a graphical analysis and display of the scope of the skating force.

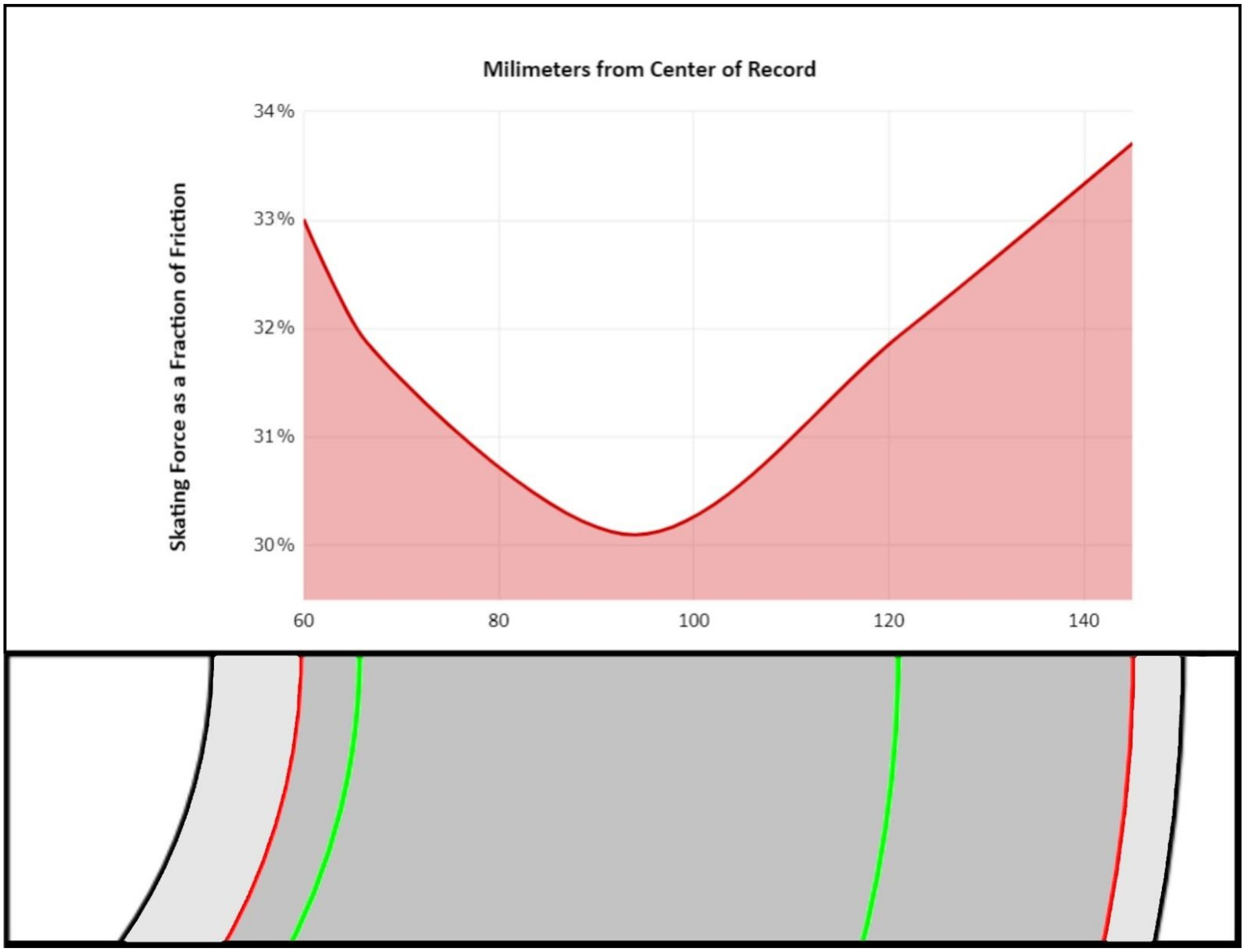

Illustration 2. *Visualization of skating force intensity across a typical 12” record.*

The above illustration aims to graphically overlay the intensity of skating force on top of a segment of a 12” record. Focusing on the lower portion of the illustration, black arcs represent the records outer edge (right) and label edge (left), red arcs represent the beginning and the end of actual groove modulation, and the green arcs represent Löfgren A derived null points.

Skating force intensity plots as a parabolic curve, a conclusion shared with virtually all existing and published research efforts involving skating force. A larger intensity is present at the beginning and the end of a modulated groove, with the lowest point being reached somewhere at the middle of said groove.

After the low point, skating force grows exponentially towards the inner groove.

Interestingly so, contrary to popular belief, skating force is not inexistant (nor lowest) when the tonearm reaches null points, although that is the low point of tracking distortion. Due to the offset angle, even at null points, an inclination (and thus skating force) exists.

2.2 Significance

Once it is established that skating force (1) is not insignificant, (2) is inevitable, and (3) varies throughout reproduction, a few words relating the importance of skating force and the possible influence on reproduction (playback) quality.

Around 1978, the Boston Audio Society[1], published a discussion on a study titled *“Results of Skating Force Study for Moving Magnet Cartridge Tracking at One Gram”*, establishing:

- Speed of the record has no effect on skating force;
- Stylus shape has very little effect, if any, on skating force;
- Skating force is proportional to tracking force;
- A modulated groove products 10% to 20% more skating force than a silent groove;
- Groove radius has no measurable effect on skating force; and,
- Record material has the most pronounced effect on skating force. The harder the material, the less friction, and the less skating force.

Additionally, around 2009, Klaus Rampelmann published an extraordinary elaborate paper covering skating force[2], reproduction influence and the possibilities for compensation. In said paper, he surmised that the friction force seen by the cartridge stylus is a product of the tracking force and the friction coefficient:

$Ff = Ft * \mu$

As the subject of this discussion are typical, Westrex 45/45 records[3], a nominal microgroove angle is 45 degrees per side, for a stereo groove. For each side, Ff = 0.7 * Ff *(sin(45) = 0.7)* yielding a final result of friction force being higher by 2 * 0.7 (1.4):

$Ff = 1.4 * Ft * \mu$

What does that actually look like?

[1] Boston Audio Society, 1978, “Results of Skating Force Study for Moving Magnet Cartridge Tracking at One Gram”

[2] Klaus Rampelmann, 2009, Skating Force and AntiSkating
https://www.vinylengine.com/ve_downloads/index.php?skating_force_and_antiskating.pdf

[3] How the Westrex 45/45 System Was Adopted by the Record Makers (Mar. 1975)
https://www.gammaelectronics.xyz/audio_03-1975_westrex.html

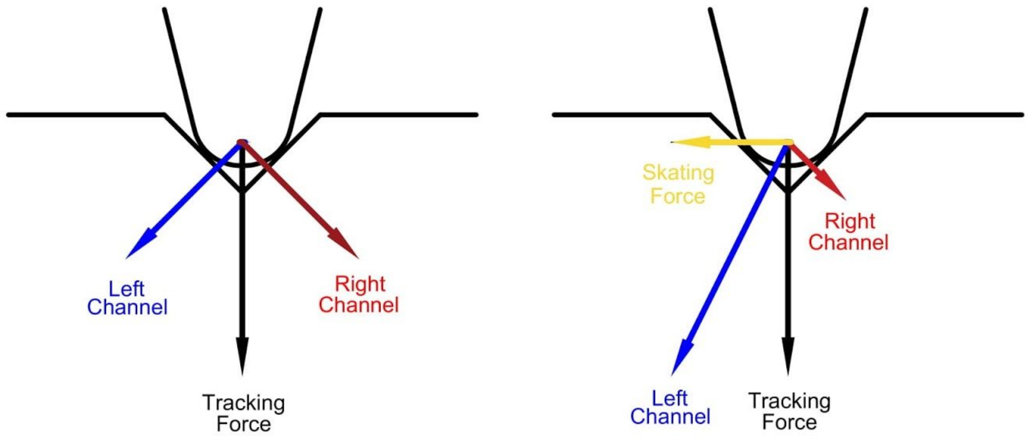

Illustration 3. *Visualization of skating force acting on the stylus level.*

On the left, a cross section of the stulys tip within a standard 45/45 microgroove is shown along with the force vectors when the cartridge is mounted in a linear (tangential) tonearm. Skating force is non-existent (there is no deflection nor inclination) and the tracking force applied to the cartridge/tonearm system is equally split on both sides (both stereo channels).

On the right, a cross section of the same stulys tip withn a standard 45/45 microgroove is shown, albeit mounted in a typical radial tonearm. Skating force is now visible with a yellow colored vector pointing towards the point of rotation of the record. The influence of the skating force vector introduces a disruption in the composure of the tracking force, thus increasing (very much disproportionally) the pressure on the left channel in relation to the right channel. What this does is introduces a difference in tracking between channels, resulting in increased distortions on the right channel in line with reduced tracking.

What can be expected?

1. Skating force, when not compensated, causes different *(measurable)* distortion levels between channels during reproduction; and,
2. Skating force, when not compensated, causes different *(measurable)* output levels between channels during reproduction.

Channel disbalance is audible even with difference in levels hovering around 1dB. As far as distortions, during the 1970s Bob Carver had helped determine[4] that with individual tones, distortion levels as low as 0.2% are noticeable.

Ultimately, we need to understand if uncompensated skating force is audible?

[4] Bob Carver, 1973, Amplifier Distortion Measurement
https://thecarversite.com/topic/3580-amplifier-distortion-bob-carver-1973/

2.3 Tooling

First, a few words on the tonearm to be used as a basis for measurements, and the capacity of its mechanism for repeatable setting of skating force compensation.

Illustration 4. *Rear end of SME 3012, with a view of the anti-skating mechanism.*

The photograph shows the bearing column and rear end of the SME 3012 tonearm, with a custom weight set made from C-932 bronze with precise matching to OEM, a bronze knife edge bearing and a bronze 10mm spacer.

SME 3012 has a very raw method of skating force compensation, a typical and common string + pulley + weight system. While somewhat crude and linear, it has the distinct advantage of having the compensation level being readily (1) changeable, (2) verifiable and (3) repeatable, making it appropriate for these types of analyses. The anti-skating weight has been designed to be the equivalent of the SME OEM P/N 1915DBW (1915 double bias weight) weighing in at ~5.6g. Combined with the bias yoke (segmented in 6 parts), it allows for repeatable setting of skating force compensation between 0.0 grams force (0mN) and 3.0 gf, in steps of 0.5gf (5mN).

The cartridge used is an Ortofon SPU #1 E[5], which had clocked 184 work hours at the beginning of this research, ensuring its suspension has settled. The set tracking force which is both (1) recommended and (2) accepted is 4.0 grams. With that in mind, the influence of the skating force is reviewed in line with this value, being a direct proportion of the same.

NB. In order to maintain at least a decent level of efficiency when writing, when discussing the compensation of skating force, the diagrams and value tables display the raw value of compensation, and not the percentage of said value in relation to the tracking force. That said, every time a value is mentioned (i.e. 1.0 grams force), it needs to be reviewed in the context of the established tracking force of 4.0 grams (for this set of measurements).

Tonearm alignment is in line with Löfgren A, with null points at 66mm and 121mm.

Second, a few words of the associated components which are crucial for these measurements:

- Devialet Expert 200 (0.25mV, 1976 RIAA, 140Ω);
- A turntable of own design, development and manufacture[6];
- AudioQuest Coffee USB;
- Windows PC with Audacity.

Devialet's built-in A/D allows for direct recording of analog signals through the USB interface.

Third, a few words of the associated software.

- Audacity 2.3.3, to record, edit, normalize tones and calculate FFT spectra;
- Google Sheets, to design THD+N calculation scripts and analyze results; and,
- HFN 002 (Hi-Fi News Test Record - second edition, Producer's Cut) - bands 1 + 4 + 8 on side B (300Hz, L+R, +15dB).

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[5] Ortofon SPU #1 E (elliptical) phono cartridge
https://www.ortofon.com/spu-1-p-698

[6] A closed loop controller for a turntable drive system
https://github.com/stojnev/dwr-controller

2.4 Methodology

To track the influence of the skating force (and the compensation mechanism) throughout the surface of the record, we would need to gather data at the outer groove, middle of the record and the outer modulated microgroove. This is where the HFN 002 test record comes in, and the spread of its 300Hz tone bands.

The process is split in three phases, (1) gathering, (2) processing and (3) analysis.

Gathering

Data is gathered by recording the reproduction of a 300Hz test tone, with varying levels of force for the skating compensation mechanism. The compensation values reach from 0.0 grams force (0mN) to 3.0 grams force (30mN), in 0.5 gf steps (5mN), for a total of 7 values of the skating compensation mechanism at every location on the record.

Recordings are made on three locations of the record surface (band 1 - outer groove, band 4 - middle of the groove and band 8 - inner groove), for a total of three locations. Combining these two parameters results with a total of 21 data points which can be further distilled.

The result of each measurement point is an individual WAV file, L+R, 44.100Hz, 32-bit float.

Processing

Recorded files undergo further minor editing procedures in the recording software (Audacity), including (1) shortening each file to an exact length of 5.0 seconds, (2) separating stereo files to two separate files (L + R) for further analysis, and (3) individual per channel FFT spectra are produced (Function = Welch, Size = 65536, Axis = Log Frequency).

The results of said processing are two individual text files, tab-delimited, with 32,768 individual values for frequency bins with an average width of ~0.7Hz per bin.

Analysis

The results of the FFT spectra are further added to a Google Sheets script which (1) determines the fundamental tone, (2) selects the first 20 harmonics (fundament + 20 harmonics), (3) calculates THD+N for each channel separately (including A-weighing), (4) plots a harmonics graph to approximately ~3kHz, and (5) calculates the difference in output levels between channels (for the fundament, minimum, maximum and average).

The results of each analysis are percentage distortion values (THD+N and channel balance), dB values, and corrected dB values (A-weighted, for a frequency of 300Hz).

2.5 Data

*The raw data which is the result of the measurements within this research is **open sourced.***

The data has been made available in an open GitHub repository, which contains all of the measurement tone files and generated data files, including graphics and illustrations, results and coded spreadsheets (including the actual methodology).

The repository is licensed under the MIT license, considered somewhat lenient.

https://github.com/stojnev/dwr-skating

Data points are further organized in individual folders, with each data point housed in an individual folder, containing (1) raw WAV files, (2) THD+N plot and (3) two individual text files with FFT spectrum data.

3. Results

3.1 Overview

Record		THD+N						Channel Balance													
Anti-Skating	Groove	LEFT	*db*	*dbA*	RIGHT	*db*	*dbA*	FUND	*db*	*H*	MIN	*dB*	*H*	MAX	*db*	*H*	AVG	*db*
0.0g	Outer	1.0934%	-39.22	-46.27	0.6699%	-43.48	-50.53	3.4249%	0.29	1	0.0484%	0.00	11	248.7025%	10.85	21	63.0007%	4.24
0.0g	Middle	0.4679%	-46.60	-53.65	0.2839%	-50.94	-57.99	4.3069%	0.37	1	4.3069%	0.37	1	226.9490%	10.29	21	70.8691%	4.65
0.0g	Inner	1.6750%	-35.52	-42.57	2.8155%	-31.01	-38.06	2.9157%	0.25	1	2.9157%	0.25	1	2080.9213%	26.77	21	654.4245%	17.55
0.5g	Outer	0.8364%	-41.55	-48.60	0.4827%	-46.33	-53.38	2.8476%	0.24	1	1.6319%	0.14	9	299.7422%	12.04	21	65.0674%	4.35
0.5g	Middle	0.3894%	-48.19	-55.24	0.2128%	-53.44	-60.49	3.9603%	0.34	1	3.9603%	0.34	1	276.7992%	11.52	21	68.1432%	4.51
0.5g	Inner	1.3214%	-37.58	-44.63	2.5822%	-31.76	-38.81	2.3872%	0.20	1	2.3872%	0.20	1	1450.5115%	23.81	21	617.6586%	17.12
1.0g	Outer	1.1690%	-38.64	-45.69	0.6732%	-43.44	-50.49	2.5020%	0.21	1	2.5020%	0.21	1	199.7713%	9.54	21	40.3816%	2.95
1.0g	Middle	0.5152%	-45.76	-52.81	0.2946%	-50.61	-57.66	3.6041%	0.31	1	3.6041%	0.31	1	263.7936%	11.22	21	72.9415%	4.76
1.0g	Inner	1.6400%	-35.70	-42.75	2.0208%	-33.89	-40.94	2.6287%	0.23	1	2.6287%	0.23	1	2754.3025%	29.11	21	881.7032%	19.84
1.5g	Outer	1.0390%	-39.67	-46.72	0.6484%	-43.76	-50.81	2.8125%	0.24	1	1.9718%	0.17	18	275.4871%	11.49	21	52.9869%	3.69
1.5g	Middle	0.2001%	-53.98	-61.03	0.1285%	-57.82	-64.87	3.8279%	0.33	1	3.8279%	0.33	1	175.1852%	8.79	21	51.0498%	3.58
1.5g	Inner	1.2072%	-38.36	-45.41	1.4229%	-36.94	-43.99	3.2685%	0.28	1	3.2685%	0.28	1	2094.0928%	26.83	21	768.6644%	18.78
2.0g	Outer	1.1574%	-38.73	-45.78	0.6749%	-43.42	-50.47	2.4980%	0.21	1	2.4980%	0.21	1	347.8937%	13.02	21	64.7062%	4.33
2.0g	Middle	0.3433%	-49.29	-56.34	0.1992%	-54.01	-61.06	3.4320%	0.29	1	2.9438%	0.25	17	105.6838%	6.26	21	34.9335%	2.60
2.0g	Inner	1.3838%	-37.18	-44.23	1.3825%	-37.19	-44.24	2.9432%	0.25	1	0.3344%	0.03	3	1232.8000%	22.50	21	457.1383%	14.92
2.5g	Outer	1.1535%	-38.76	-45.81	0.7001%	-43.10	-50.15	2.1524%	0.18	1	0.7906%	0.07	6	230.9139%	10.39	21	58.7082%	4.01
2.5g	Middle	0.3017%	-50.41	-57.46	0.1728%	-55.25	-62.30	2.9708%	0.25	1	2.9708%	0.25	1	188.5161%	9.20	21	47.0661%	3.35
2.5g	Inner	1.0401%	-39.66	-46.71	1.0370%	-39.68	-46.73	2.9339%	0.25	1	0.9718%	0.08	2	1000.0819%	20.83	21	382.3598%	13.67
3.0g	Outer	1.1335%	-38.91	-45.96	0.6288%	-44.03	-51.08	1.8213%	0.16	1	1.8213%	0.16	1	317.5755%	12.41	21	68.9469%	4.56
3.0g	Middle	0.3768%	-48.48	-55.53	0.2138%	-53.40	-60.45	2.5744%	0.22	1	1.8615%	0.16	11	139.4694%	7.58	21	34.1190%	2.55
3.0g	Inner	1.1197%	-39.02	-46.07	1.1978%	-38.43	-45.48	2.5818%	0.22	1	2.5818%	0.22	1	935.1302%	20.30	21	255.5401%	11.02

Illustration 5. *General result display table.*

The table has been split in three segments, i.e. three column groups.

Group #1 (Record) - containing measurement parameters:

1. Skating compensation force, shown in grams (specifically, gram-force) *(**)*; and,
2. Microgroove position - outer, middle and inner groove.

(**) Throughout the text, as well as within the illustrations, grams force are used alternatively with mN. A crude conversion from grams force to mN is multiplication by a factor of 10.

Group #2 (THD+N) - containing results from THD+N calculations:

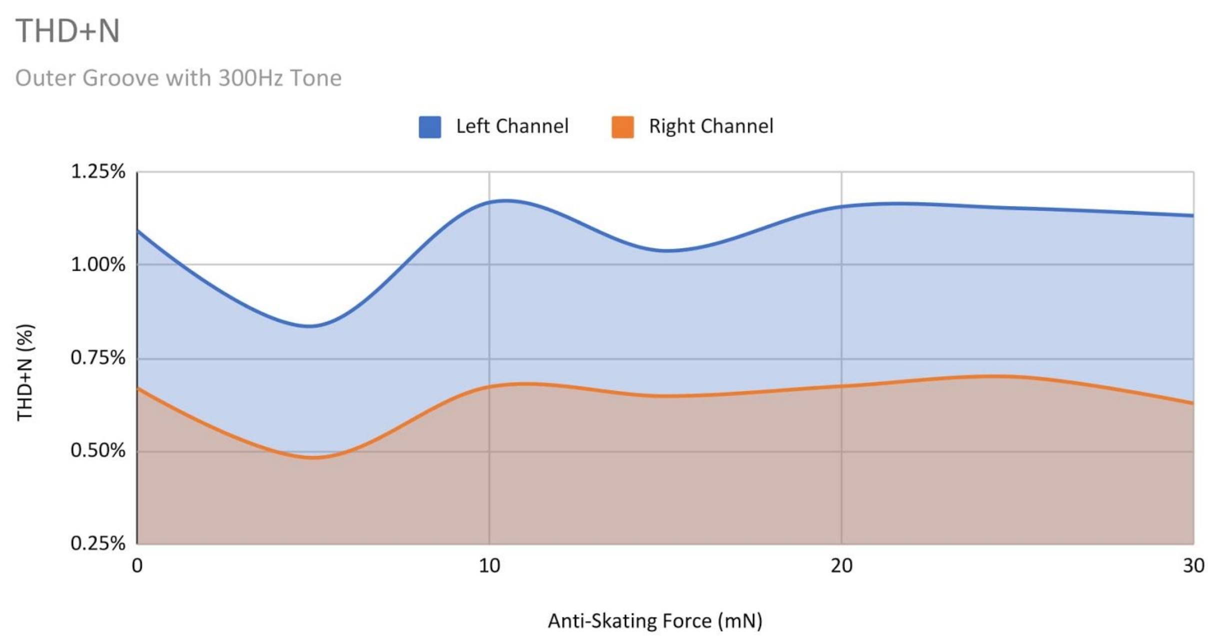
1. Total distortions (THD+N) in percent for the left channel;
2. Total distortions (THD+N) in decibels (dB) for the left channel;
3. Total distortions (THD+N) in decibels (dBA) (A-weighted) for the left channel;
4. Total distortions (THD+N) in percent for the right channel;
5. Total distortions (THD+N) in decibels (dB) for the right channel; and,
6. Total distortions (THD+N) in decibels (dBA) (A-weighted) for the right channel.

Group #3 (Channel Balance) - containing results from disbalance in output levels per channel:

1. Channel balance in percent for the fundamental tone (300Hz);
2. Channel balance in decibel for the fundamental tone (300Hz);
3. The harmonic of the fundamental tone (always 1);
4. Lowest channel balance value in percent for the fundament and the first 20 harmonics;
5. Lowest channel balance value in decibel for the fundament and the first 20 harmonics;
6. The harmonic with the lowest value of channel balance;
7. Highest channel balance value in percent for the fundament and the first 20 harmonics;
8. Highest channel balance value in decibel for the fundament and the first 20 harmonics;
9. The harmonic with the highest value of channel balance;
10. Average value for channel balance in percent for the fundament and the first 20 harmonics; and,
11. Average value for channel balance in decibel for the fundament and the first 20 harmonics.

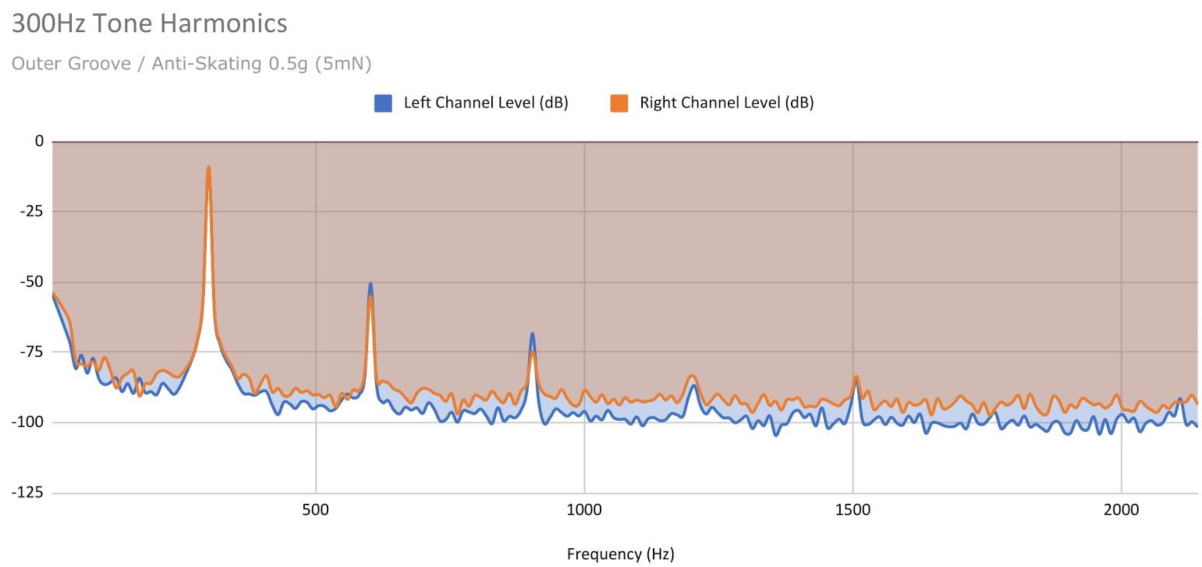
To understand what this means, a few trends.

Trend #1. Influence of skating force compensation on distortions at the outer groove.

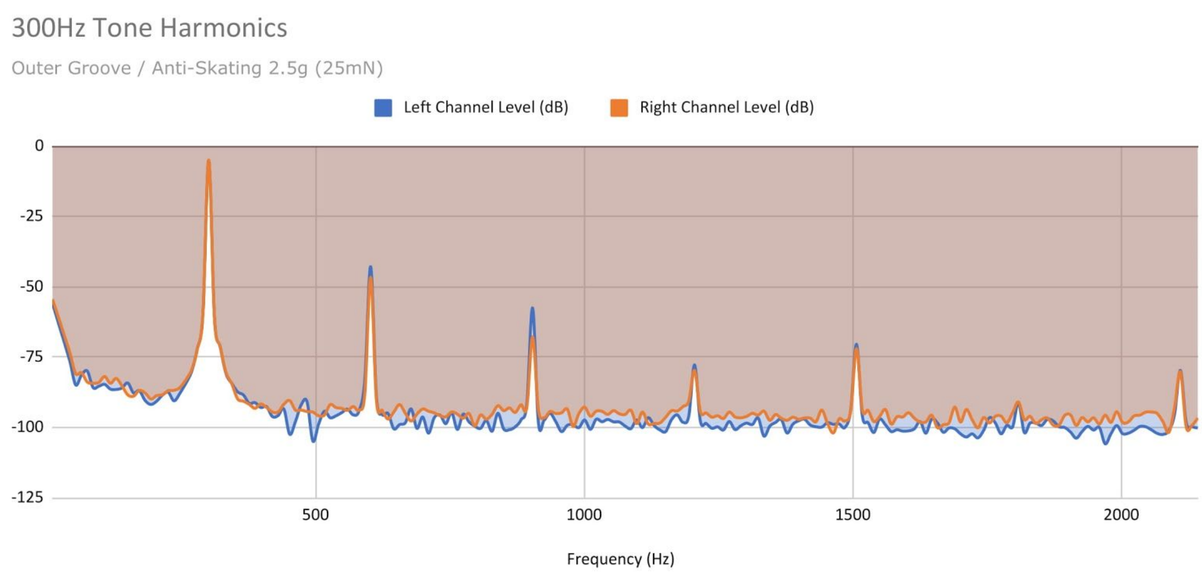


Distortions are relatively similar in proportion on both channels. However, they are lowest with a compensation value of 0.5 grams force (5mN), or 12.5% of the tracking force, and highest with a value of 2.5 grams force (25mN), or 62.5% of the tracking force..

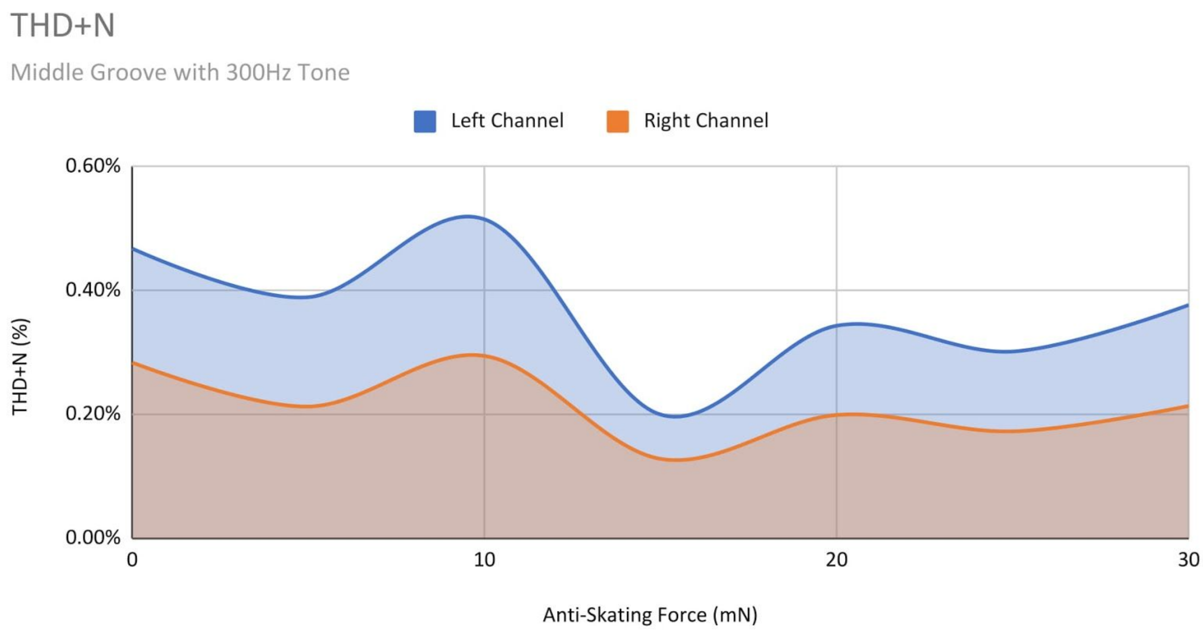
Lowest distortion at the outer groove - 0.5 grams force (5mN), L = 0.84%, R = 0.48%.



Highest distortion at the outer groove - 2.5 grams force (25mN), L = 1.15%, R = 0.70%.

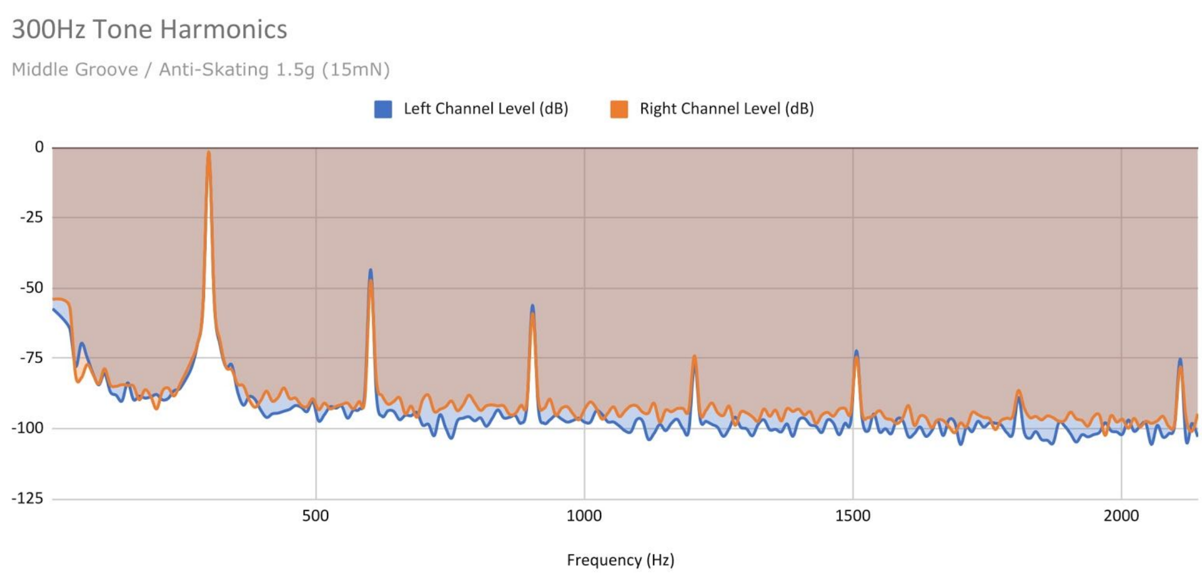


Trend #2. Influence of skating force compensation on distortions at the middle of the groove.

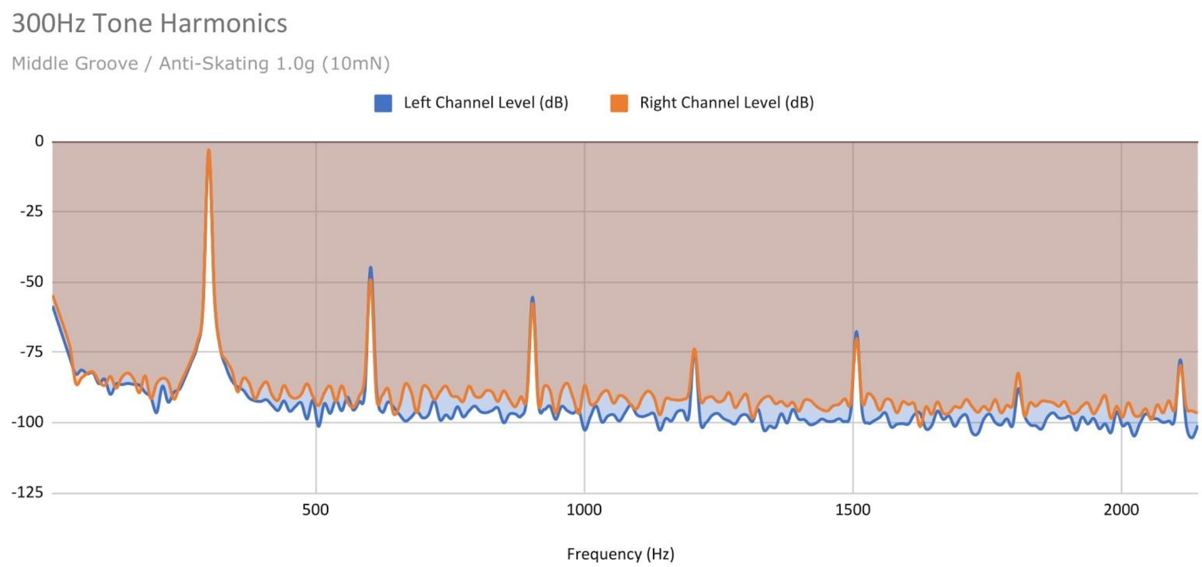


Middle groove distortions are generally the lowest of all values across the record (as can be expected - see Illustration #2), with the lowest value at 1.5 grams force (15mN), or 37.5% of the tracking force, and highest at 1.0 grams force (10mN), or 25% of the tracking force.

Lowest distortion for the middle groove - 1.5 grams force (15mN), L = 0.20%, R = 0.12%.

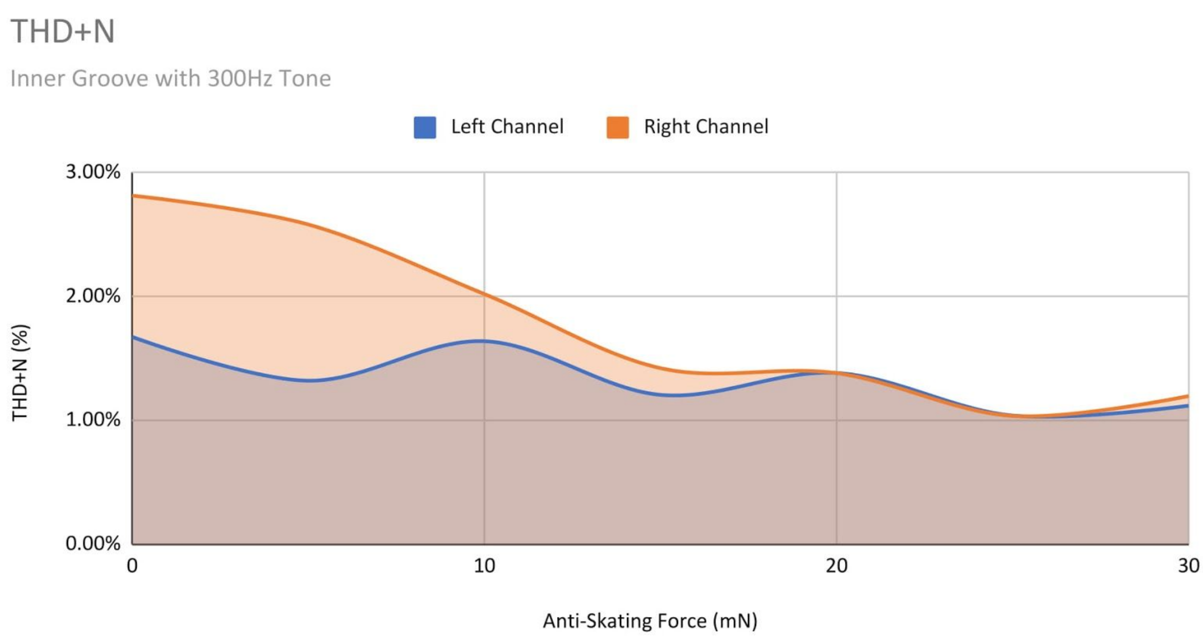


Highest distortions for the middle groove - 1.0 grams force (10mN), L = 0.39%, R = 0.21%.



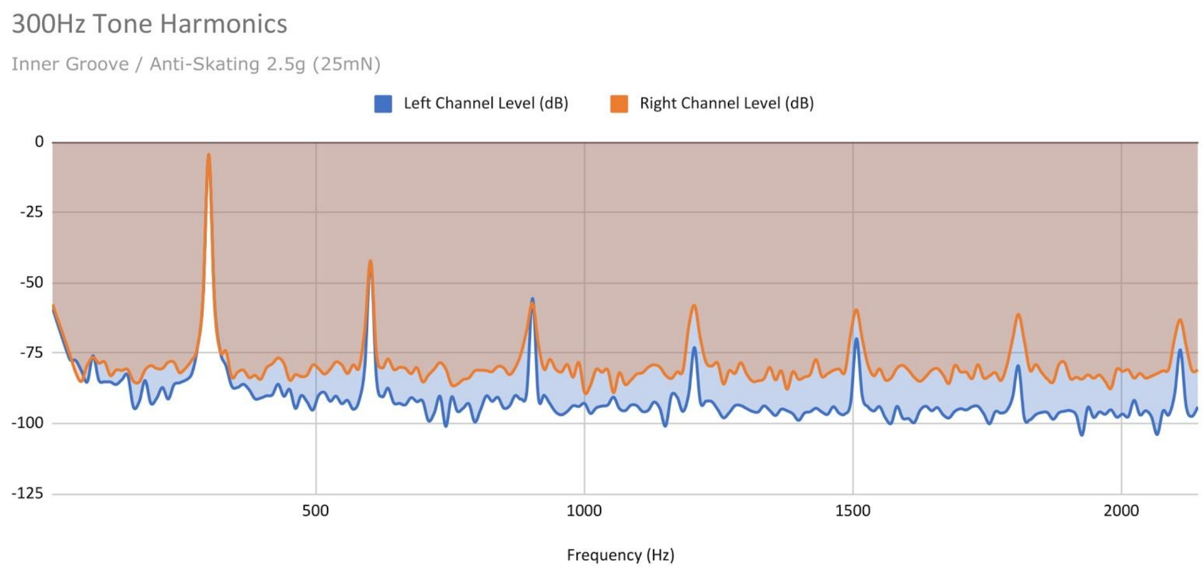
The proportions here are quite interesting. A change in compensation force of only 0.5 grams force (5mN) results with a decrease in THD+N of close to 50%. Total distortions are still quite small, but differences with minute changes are most visible here.

Trend #3. Influence of skating force compensation on distortions at the inner groove.

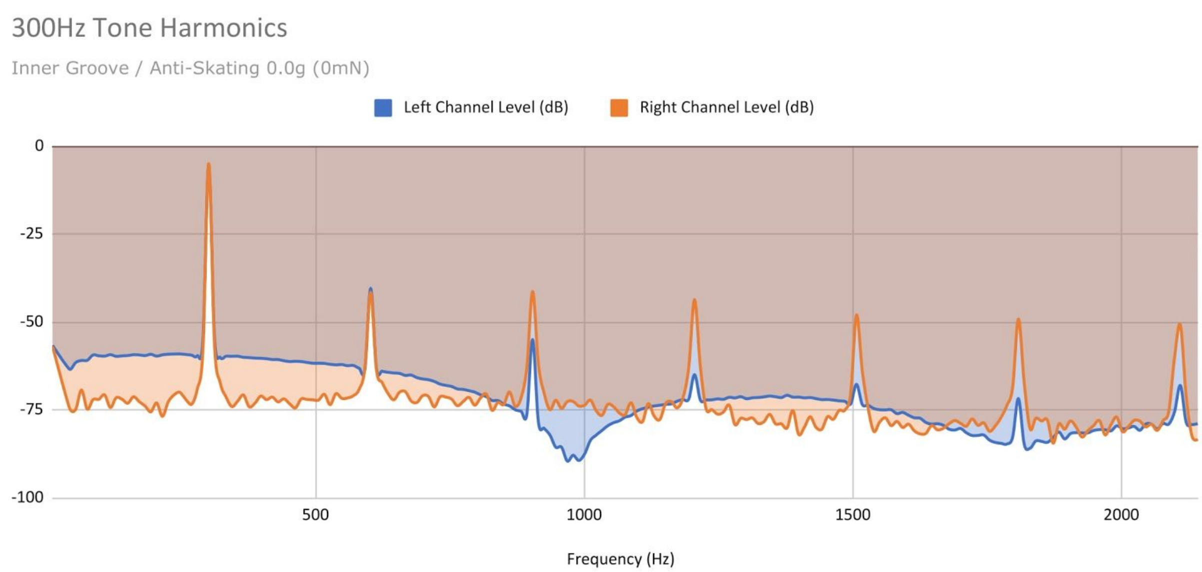


Inner groove tests make for an interesting revelation. Increasing skating force compensation results with an almost linear decrease in distortions. Differences here are largest - the addition of skating force compensation leads to a decrease of absolute THD+N of up to 2%, well above the audible range (by a factor of 10x!). Lowest distortions with a compensation value of 2.5 grams force (25mN) and highest distortions with a compensation value of 0 grams force (0mN).

Lowest distortions for the inner groove - 2.5 grams force (25mN), L = 1.04%, R = 1.04%.



Highest distortions for the inner groove - 0 grams force (0mN), L = 1.68%, R = 2.82%.

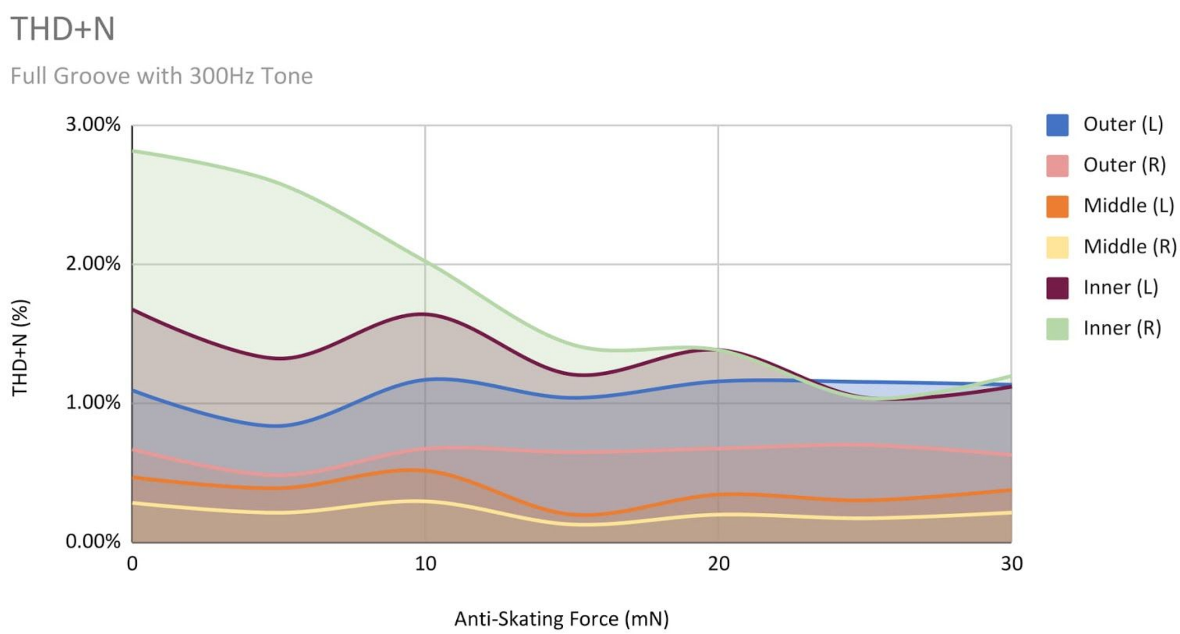


Trend #4. Influence of skating force compensation on distortions throughout the microgroove.

Looking back to the individual plots, one might notice that the vertical axes are different in scope. This is done on purpose, for illustrative purposes, so that differences can be more readily perceived, in relation to the skating force compensation mechanism.

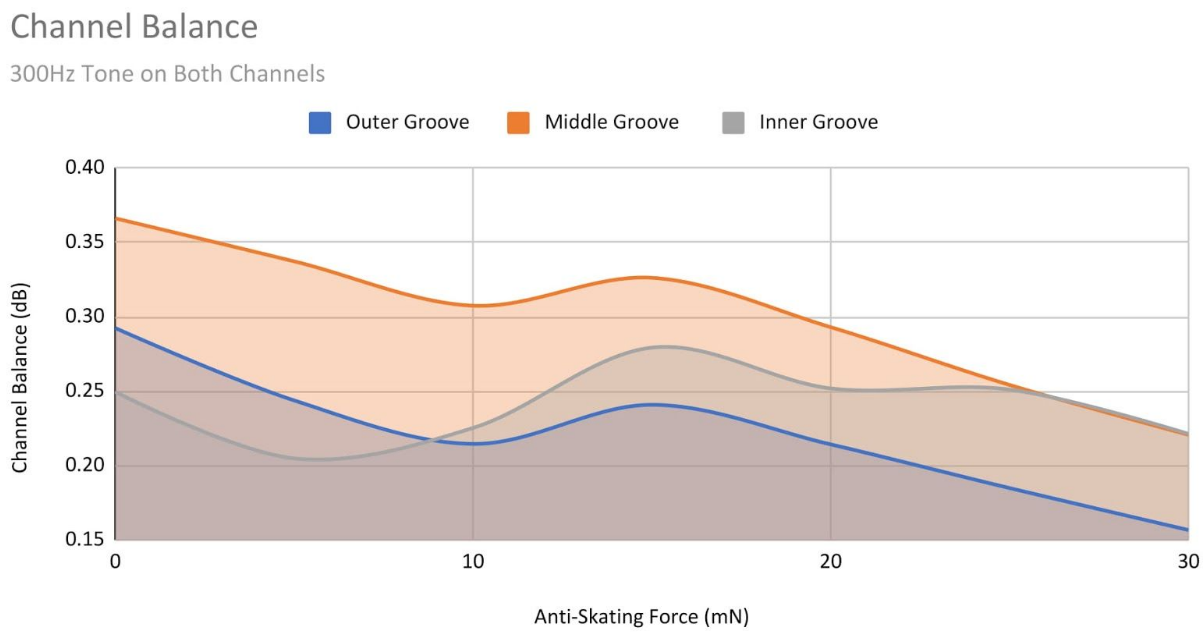
Having said that, compounding the earlier three trends on the same graph, with the same vertical axis scope, results with a key trend of distortion values between channels, across the surface of the record, in relation to the value of skating force compensation.

Individual groove sections may be more difficult to be perceived, but a general trend is more easily discernible.



Looking at this plot, it is relatively easy to determine the relative value of skating force compensation. However, in order to draw more complete conclusions, one more trend, reviewing the dependency of channel balance and skating force.

Trend #5. Influence of skating force compensation on channel balance throughout the microgroove.



Channel balance improves close to a linear fashion as the compensation of skating force increases towards the higher end. The absolute difference between channel outputs is ~0.21dB, which may be perceived as an inconsequential value, but it is large enough to confirm the trend.

Mathematically, all this data is more than enough to draw preliminary conclusions towards the questions (1) is skating force audible and (2) what is the optimal skating force compensation value - but this would not be complete without a subjective take on the matter, so onwards to some actual listening.

3.2 Listening

In line with the set methodology, listening has been limited to three separate tracks on three very familiar records, with key tracks at (1) the beginning, (2) the middle and (3) the end of the record, thus mimicking measurements at the outer, middle and inner groove:

1. Rios Negroes - Lester Bowie, The Great Pretender (ECM-1-1209);
2. News - Dire Straits, Communique (Vertigo – 3752904); и,
3. Take Five - Dave Brubeck, Time Out (APJ 8192).

Listening took place at three separate occasions, to perceive differences in line with the calculated positions for (1) least distortion, (2) most distortion and (3) no skating force compensation. The notion here was to focus on the positions with the highest measured differences to perceive the most impact to the reproduction quality, if present.

After listening for several days, a subjective conclusion is that reproduction is **significantly better** with both (1) engaged and (2) precisely set skating force compensation mechanism.

The effects are of a similar vein with the effects of proper azimuth adjustment:

- Soundstaging is more precise (even with hard panned stereo recordings as this older ECM), with the greatest gain towards the stage depth;
- Instruments are clear and easily discernible within the group, even with complex passages where details are increased, but not by hurting the musical whole; and,
- Total balance is more proper, with cleaner tones and brisker rhythmic sections.

3.3 Settings

Prior (and finally!) to establishing a conclusion, a simple question arises - how does one determine the optimal value of skating force compensation? Mathematically, taking in consideration the absolute values from the result table (Section 3.1) after a column/row pivot rearrangement, one can present a unified table headed by the compensation value.

Values taken in consideration include (1) channel balance (dB), (2) outer groove THD+N (dB), (3) middle groove THD+N (dB) and (4) inner groove THD+N (dB).

Anti-Skating Force (mN)	*Channel Balance (dB)*	*Outer Groove (dB)*	*Middle Groove (dB)*	*Inner Groove (dB)*
0	0.9084	-35.07	-42.48	-26.95
5	0.7861	-37.59	-44.40	-28.17
10	0.7476	-34.69	-41.83	-28.73
15	0.8466	-35.46	-49.67	-31.60
20	0.7594	-34.74	-45.31	-31.16
25	0.6904	-34.64	-46.47	-33.65
30	0.5990	-35.08	-44.57	-32.70

Looking back to the plotted trends, specifically the plots in relation to trend #4 (distortions throughout the microgroove), it is clear that the final value needs to be a compromise. Having in mind the scope of differences, the compromise needs to invoke the largest benefit, sorting values from the highest gain (lowest THD+N and best channel balance) to the lowest gain (highest THD+N and worst channel balance).

With that said, sorting is to happen in the following order - (1) inner groove THD+N, (2) outer groove THD+N, (3) middle groove THD+N and (4) channel balance.

Once sorted, it becomes clearer:

Anti-Skating Force (mN)	*Channel Balance (dB)*	*Outer Groove (dB)*	*Middle Groove (dB)*	*Inner Groove (dB)*
25	0.6904	-34.64	-46.47	-33.65
30	0.5990	-35.08	-44.57	-32.70
15	0.8466	-35.46	-49.67	-31.60
20	0.7594	-34.74	-45.31	-31.16
10	0.7476	-34.69	-41.83	-28.73
5	0.7861	-37.59	-44.40	-28.17
0	0.9084	-35.07	-42.48	-26.95

For the presented tonearm/cartridge system, the best compromise towards setting the skating force compensation value is 2.5 grams force (25mN). And with the value of tracking force at 4.0 grams in mind, *the ideal value for skating force compensation is ~65% of the tracking force.*

4. Conclusion

Objectively, planned tests show measurable differences:

1. Skating force changes intensity in line with a imperfect parabolic curve, exponentially larger at the beginning and the end of the modulated microgroove;
2. Lack of compensation of skating force leads to an increase in absolute distortion (THD+N) of up to 3%, specifically at the inner groove;
3. Setting an optimal value for skating force compensation is a matter of compromise;
4. Skating force compensation (setting anti-skating) leads to audible improvements throughout reproduction.

Subjectively, listening shows relatively immeasurable differences:

1. Properly set skating force compensation improves soundstaging;
2. Instrument definition is clearer, listening fatigue is decreased;
3. Tonal balance increases.

Recommendations:

1. Set skating force compensation at least at the minimum level recommended by the tonearm designer;
2. Regularly check cantilever deflection;
3. Align azimuth adjustments with skating force compensation adjustments.

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