THRUSTMASTER®

NEW ERA – PAPER 2

DIRECT AXIAL DRIVE: UNVEILING THE NEXT GENERATION OF DIRECT DRIVE WHEEL BASES.

2024, September 13

A few weeks ago, Thrustmaster shared how the First-Generation Direct Drive technology had many limitations preventing the creation of a good, affordable Direct Drive wheel base. We identified several pain points, such as the expensive amount of copper needed, the heat generated by the copper and the associated difficulties with managing that heat, and the physical problems related to this motor typology such as cogging and iron losses.

We concluded years ago that First-Generation Direct Drive wheel bases could not meet our quality standards or pricing aspirations for the entry and mid-level markets. And so we focused on finding alternative Direct Drive solutions, which led to the Next-Generation of Direct Drive technology.

Today, we are proud to present the industry's first, and only **Direct Axial Drive (DaD)** wheel base technology, its advantages for sim racers of all levels, and how we expect it to evolve in the future.

Contents of this paper:

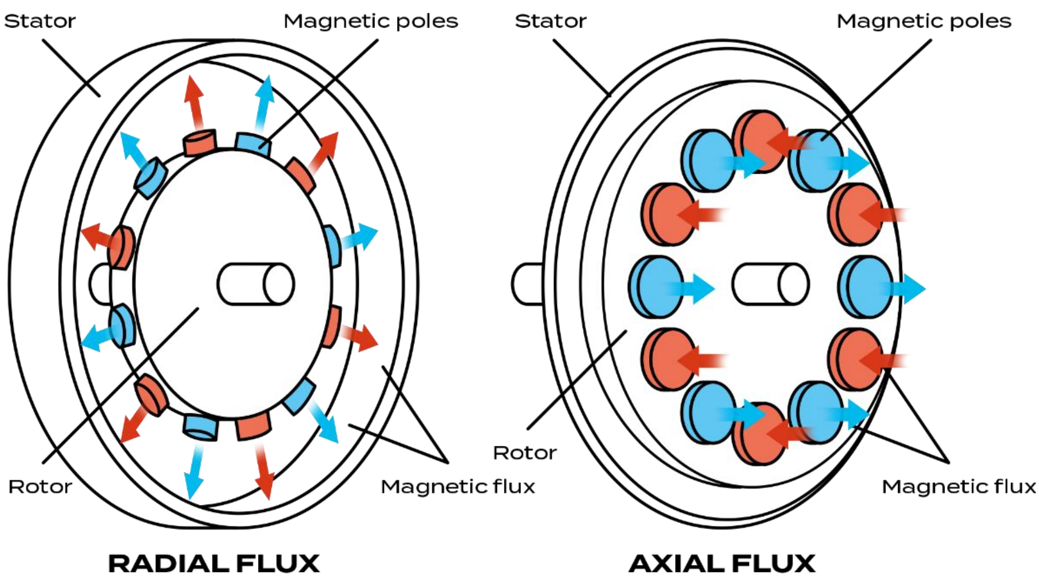
1. What is a Direct Axial Drive wheel base?

DaD wheel bases are made from a completely different type of motor called an "*Axial Flux Motor*". They are used more and more in aeronautics, high-tech factories, and multiple high-end electric vehicles. By combining our years of expertise in Sim Racing wheel bases with the technical knowledge of partners already developing Axial Flux Motors, we were able to craft new sim racing wheel bases which even outperformed our initial, high expectations.

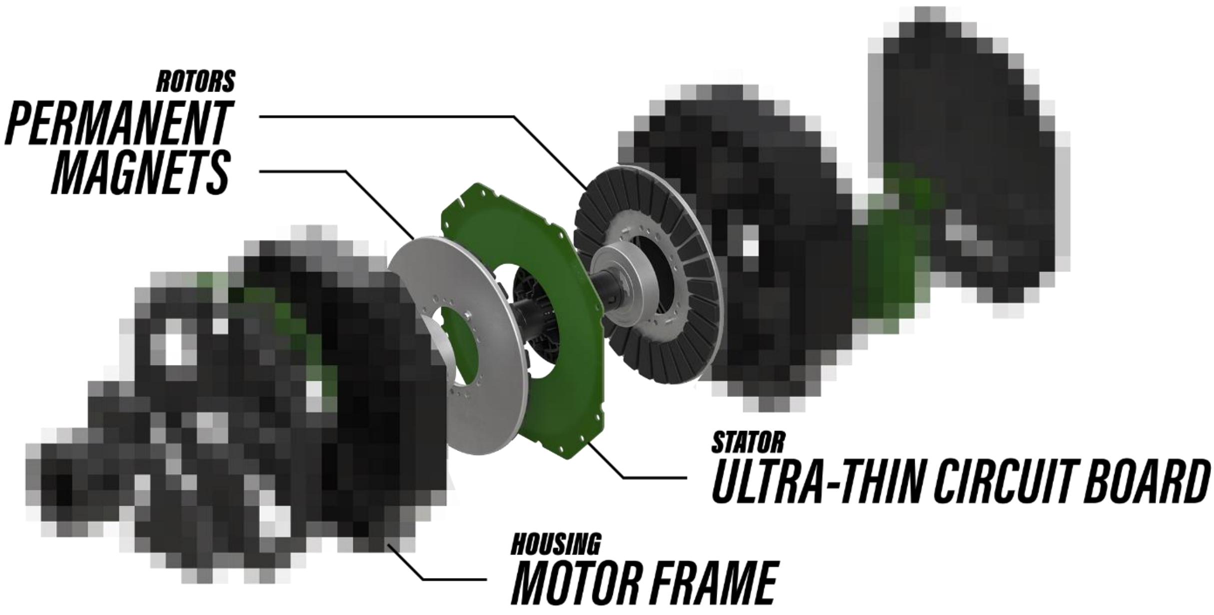
a. Design Differences between Axial Flux Motors and Radial Flux Motors

In our first New Era paper, we went into detail about the "*Radial Flux Motors*" used in First-Generation DD, and how they were built: a stator tube made with a lot of copper coils surrounding a shaft (the rotor) with many permanent magnets onto it. The shaft rotated depending on which coils you turn on. We called these motors "Radial" because the magnetism is "radial" to shaft, meaning **perpendicular** to the rotation axis.

An Axial Flux Motor, on the other hand, is built differently and its design allows the magnetic flux to be **parallel** to the shaft, in the rotation axis. This difference is the key to obtaining a smooth rotation, sharper reaction times, an increased flexibility in motor scaling, and better electrical-to-mechanical performance (everything that is required in a wheel base, basically).



Axial Flux Motors were theorized a long time ago by Michael Faraday (1791-1867) but are barely sold to the public: it was always difficult to manufacture this type of motor at volume, and we're only recently seeing reductions in production costs.



In Axial Flux Motor design, the stator does not surround the rotor as it does on Radial Flux Motors. Instead, the motor is made up of many parallel layers along the shaft. It uses an ultra-thin Stator that is suspended parallelly between two rotors supporting the permanent magnets. The copper coils are embedded directly into a circuit board, and we've partnered with experts to tailor its pattern specifically for sim racing, allowing never-before-seen levels of precision, reaction time and rotation speed. In fact, Axial Flux Motors can output **identical** torque with only a **fraction** of the copper used by a Radial Flux Motors, with the added bonus of being cogless. Why? Thanks to the two parallel layers of magnets on either side of the Stator, the magnetic field is used much more efficiently, as less magnetic field is wasted (which is the case for Radial Flux Motors, as more than half of the magnetic fields go 'outwards', away from the motor).

b. *Scaling advantages*

Thanks to its design, an Axial Flux Motor scales much better than a Radial Flux Motor, so increasing or reducing its output torque is more cost-efficient.

In First-Generation Direct Drive (Radial Flux), there were three variables to scale the power of the motor, which can be simplified this way:

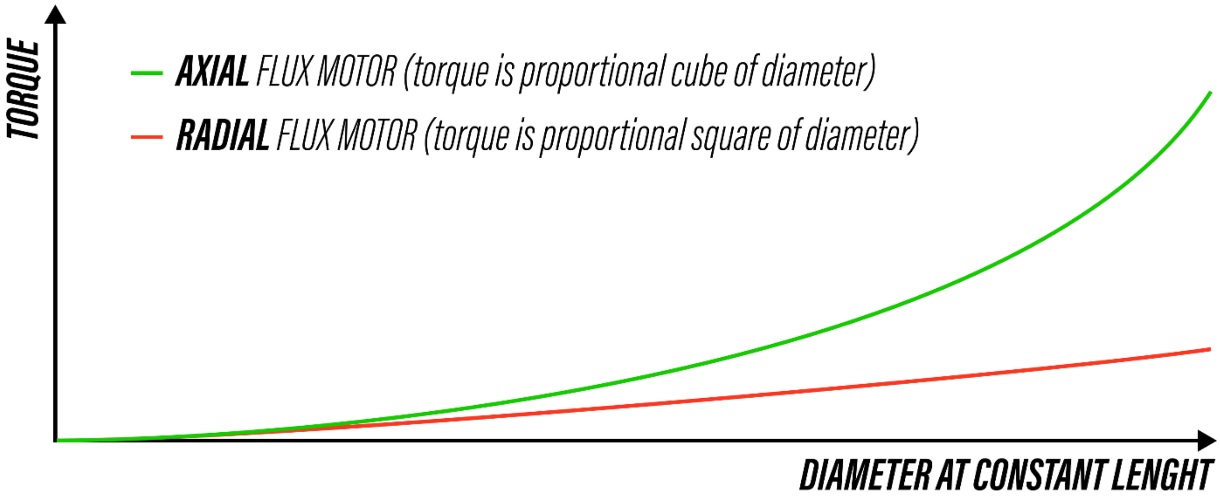
Radial Torque output = *Magnetic Force* x *Length of the motor* x *Radius of the motor (squared)*

Because the magnets were only on one side of the copper coils, and were placed along the rotor, in order to increase torque output, Radial Flux Motors had to increase both the length **and** the radius of the motor, both of which resulted in more copper usage.

An Axial Flux Motor has no magnetic field waste as magnets cover **both** sides of the Stator, so the length of the motor does not matter. And because its magnetic field usage is more efficient, the radius is much more important and scales much better. This is the calculation of how it scales:

Axial Torque output = *Magnetic Force* x *Radius of the motor (cubic)*

Here is quick illustration of the difference in scalability between the two motor typologies:



By scaling more efficiently with no sacrifice to quality, Axial Flux motors offer a cost-effective solution to make Direct Drive wheel bases more accessible to more sim racers.

c. A cooler and more efficient wheel base

Because Axial Flux Motors use much less copper, our Direct Axial Drive wheel bases generate much less heat and transform electrical power into mechanical power more efficiently.

In fact, First-Generation wheel bases used copper wires (~1 mm radius) with a high linear resistance. Those resulted in great electrical losses via heat output, which massively impacted performance.

In our Direct Axial Drive (DaD) wheel bases, which use Axial Flux Motors fitted with ultrathin stators, there are no thick copper wires. Instead, we use thin lines of printed copper (~ 70µm radius, or ~0.07 mm). But because of the more effective magnetic power distribution, this reduced quantity of printed copper is actually **more** powerful than thicker copper wires.

One of the primary reasons why Axial Flux Motors went unused for so many years is that dissipating heat generated can be very complicated. Even if Axial Flux Motors generate a lot less heat, this small amount still needs to be evacuated for it not to continue heating up until the temperature starts negatively affecting performance.

The motor design does not naturally lend itself to dissipating heat and cooling down. Because all components of the stator and rotors are so close to each other and there is no air flow in the base, you can’t simply put a fan or casing radiator to cool it down.

To tackle this problem, our Direct Axial Drive wheel bases use patented solutions from our partner, who founded the solution, to evacuate the heat by adding heat pipes in the PCB itself, giving the wheel base a passive, quiet, affordable and innovative way to cool down while maintaining peak performance.

2. Better Sim Racing Immersion and Performance

While Radial Flux Motors had inherent flaws that required a lot of workarounds to make the motor feel good, Axial Flux Motors are far more efficient, making those workarounds a memory of a previous generation of direct drive technology.

a. Cogless motor: no more notching

In our first paper, we mentioned that cogging was a big issue in Radial Flux Motors: when magnets and coils are not aligned perfectly, the magnetic forces make the wheel rotate on its own, both making the game information notchy and making you feel “steps” when turning the wheel slowly. With First-Generation Direct Drive wheel bases, cogging was always artificially manipulated by complex algorithms that did their best to stick to the game information, but inevitably a lot of effects were missed because the algorithm couldn’t compensate for impossible movements. The algorithm basically managed two types of force feedback and sacrificed a lot of information to offer an authentic feedback experience:

- Static friction forces are the “heavy forces” which fight against you when driving. They require strong precision, and avoid oscillation at all costs. The more cogging a wheel base has, the less the base can accurately turn the wheel, making movements to overcompensate the cogging, that can lead the car onto the wrong trajectory. A cogless motor will always accurately angle the wheel, meaning more precise control, around corners as you manage your car’s weight and adherence, and along straightaways where parasitic movements of the wheel can affect your trajectory.
- Dynamic friction forces are the “boost forces”, the ones that provide all the little details you need. In a Radial Flux Motor, even a perfect anti-cogging algorithm couldn’t output a specific torque that provided a detailed effect, because the cogging would approximate all values. Cogless Axial Flux Motors will always output an accurate torque, providing more depth to the details, providing nuance and color to each individual piece of information.

Our Direct Axial Drive (DaD) wheel base reduces cogging by 99.9999% compared to all other Direct Drive (DD) wheel bases on the market. At this value, the cogging is not perceptible to human touch, therefore considered non-existent (it has zero impact on your sim racing). DaD is able to provide all the details the game wants the player to feel. Being cogless means that the motor can angle the steering wheel accurately at any time, with no more need for elaborate firmware or algorithms to artificially translate the game’s outputs.

b. Slew Rate: the game changer

We’ll spare you the technical calculations, but basically, when we’re trying to perfect a motor’s slew rate, it’s important to decrease Inductance and increase Resistance, assuming we can control the resulting heat output.

Inductance defines how fast a coil can switch its polarity, primarily due to the number of turns the coils make, which is a key part of having a good slew rate. The less turns the coils have to make, the higher the slew rate, as the motor reaches maximum performance in less time.

Resistance is essentially the force that counteracts electrical current. The higher the Resistance of a coil, the higher the slew rate of the motor, BUT resistance will lead to increased heat output and its associated problems (loss of performance, deterioration of the materials, need of safety measures, etc.).

Why finding the right balance between Inductance and Resistance matters

We said we need a high slew rate in a great sim racing motor. Higher slew rates mean more accurate details and faster reaction time, and that's achievable when the motor's coils have less turns, a smaller cross-section area, and a longer length of wire, all while managing to dissipate heat while maintaining slew rate. It's pretty complex!

We spent countless hours finding the perfect balance in our new Direct Axial Drive (DaD) wheel base, to provide an unprecedented level of motor reactivity for sim racers to react to all the details the game has to offer, as quickly as possible. As a result, our DaD wheel bases react, on average, **2000x faster than a First-Generation DD** ever could, changing the scale from milliseconds down to microseconds. With a Direct Axial Drive wheel base, the motor itself is no longer an issue in the latency of a setup.

c. Controlled Overshoot : precise, fast reaction times

Having an accurate position of the wheel would not be enough if the reaction time was not perfect. This is where the Direct Axial Drive also shines: our Axial flux Motor delivers unprecedented reaction time thanks to its controlled overshoot capacity.

In an electric motor, overshoot refers to a temporary excess of the desired target torque, quite literally the motor's power over-shooting its typical constant range. This usually happens due to inertia as the system quickly calibrates itself to quick actions: once the wheel is correctly angled after a quick movement, the motor stops the rotation, but the inertia of a complex system of multiple moving parts makes the wheel turn slightly more, "overshooting" its target value.

While overshoot is typically something motor manufacturers try to avoid, we saw it as an opportunity to capitalize on a traditionally negative effect, and turn it into a positive; when it's controlled, overshoot can actually enhance the wheel base performance and immersion:

- A controlled overshoot minimizes the motor's response time. Embracing a slight, controlled overshoot allows the wheel to reach its target torque quicker, providing drivers with unbeatable control of their car's engine power.

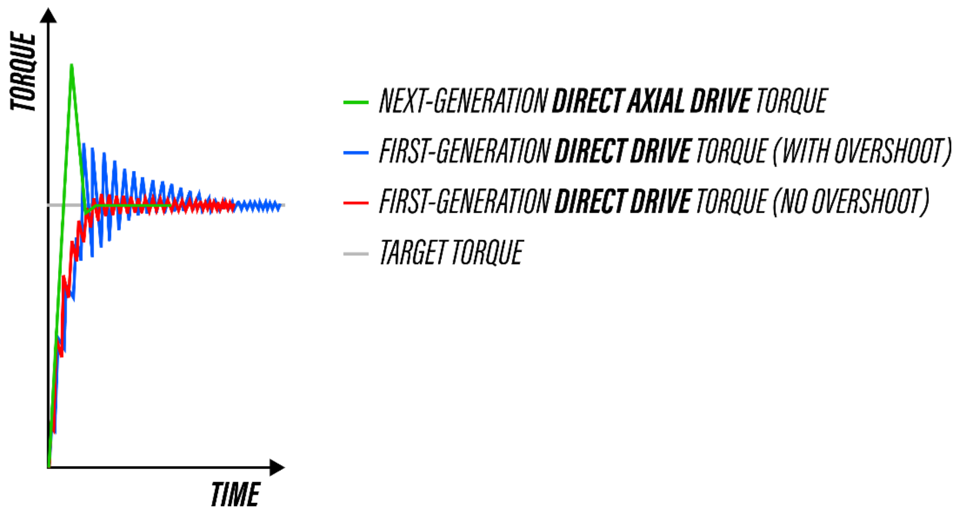
- Controlled overshoots also allow players to feel more feedback details in their wheel, including road imperfections, tire grip, etc. This means a clearer vision of how the car will react to both the track environment and the driver's actions.

Keep in mind that we're talking about **controlled** overshoot here: all wheel bases have overshoot at some point, but First-Generation Direct Drive wheel bases were not responsive enough to control it, and when adding the effects of cogging on top of this, players would start experiencing undesired torque ripple (you accelerate to 10Nm, it overshoots to 12, then overshoots the correction down to 9, then overshoots back up to 11, then 9.5, then 10.5), all in a matter of milliseconds, leading to microscopic speed and steering stabilization issues that gamers need to fight back against.

Some manufacturers try to counteract overshoot by slowing the rotation/torque delivery **before** reaching the desired target position/torque. This helps to more quickly stabilize the output torque but provides a damper feeling which many players, especially those competing at high levels, do not want as it takes away the fidelity of the car's performance and information transmitted by the game, both of which can lead to a lack of anticipation.

To make it easier to understand, try it yourself! When throwing a ball as far as possible with your arm, you see that right when you release the ball, your arm still keeps moving due to inertia. If you try to stop your hand at the exact moment you let the ball go, you will either need to dedicate some of your muscles as a counterforce to the natural inertia of your arm, or you'll need to slow down your arm before releasing the ball, and reduce the inertia (no overshoot, but the ball won't go as far).

Controlling the Overshoot is all about capitalizing on its benefit (reaching the target output torque quicker and providing an extra inertia-driven boost of torque) while controlling its consequences: allowing for a higher initial overshoot, to better use the motor's forces to stabilize faster back to the engine's target torque.



This is a comparison between an overshoot of our Direct Axial Drive wheel base, and First-Generation wheel bases from our competitors. You can see that controlled overshoot stabilizes the motor's performance far more quickly back to the motor's target torque, as it uses less unnatural counterforces to correct itself.

In our tests, we achieved controlled overshoots that were up to +107% the amount of the constant torque. As mentioned in the first paper, do not forget that peak and constant torque are two different things: the peak torque is how much you feel the details, while the constant torque is how much force you must physically provide to turn the wheel. A Direct Axial Drive wheel base that outputs a constant 5 Nm Torque will always require the same physical force, no matter if its peak Torque is 8Nm, 15Nm or higher.

d. Saturation, what's that?

In the previous paper we explained that First-Generation Direct Drive would saturate quickly. Either because the game detected that the wheel couldn't output what it was asking for (which is called "clipping") or because the Radial Flux Motor suffered Iron loss (a mechanical limitation generating eddy currents).

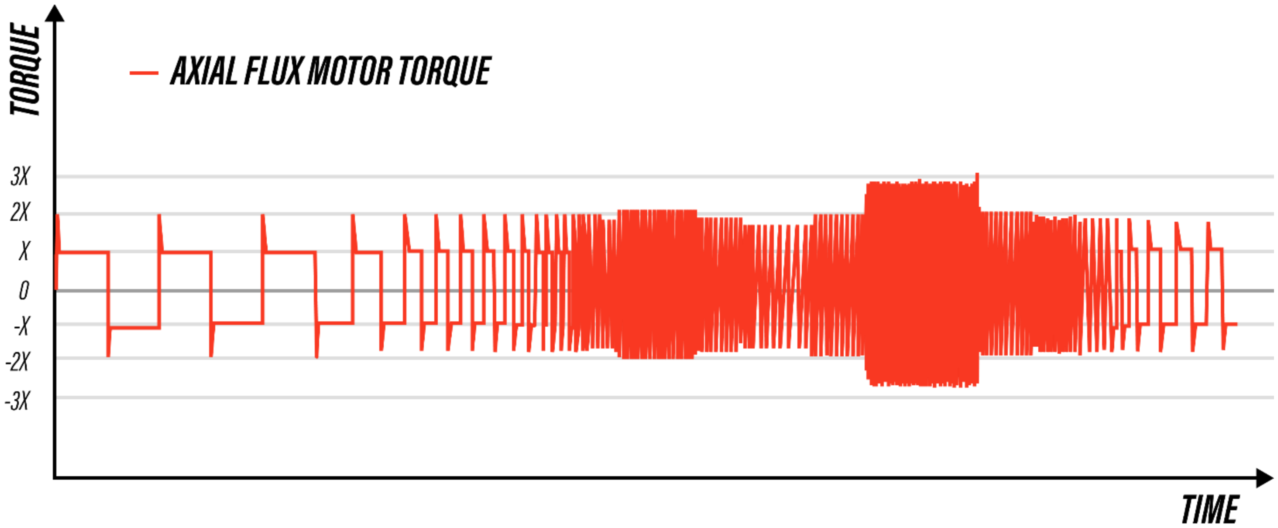
While game clipping can be managed in the game settings, Iron Loss was a physical limitation of the First-Generation wheel bases. However, because our Axial Flux Motor uses direct magnetic field, we considerably reduce eddy currents. Eliminating eddy currents eliminates parasitic movement and reduces the heat generated, both of which help the wheel base better translate the game's details thanks to sharper peaks in torque.

The peak Torque of a Direct Axial Drive base goes much higher than First-Generation DD bases of the same constant torque ever did, and the overall curve is much more detailed. You may wonder if reducing the overall force feedback strength of a strong First-Generation wheel base (example: a constant 25Nm Direct Radial Drive base reduced to 5Nm) would give the same results? If we take aside the technical challenges required to manage cogging, it could, but it would require rare (and expensive) materials to achieve the same kind of performance.

3. How Direct Axial Drive technology resonates with Harmony

Did you know that many industry innovations were discovered accidentally? Penicillin, X-Rays, Dynamite, Microwaves, Corn Flakes, … Well, now Harmony is one of them.

To test the accuracy of our Direct Axial Drive wheel base in achieving target torque, we wanted to see how fast a 5Nm constant-torque Direct Axial Drive wheel base could vibrate and still control the resulting overshoots, switching from +5Nm to -5Nm over and over, faster and faster. Up to the point where we were measuring erratic values, with overshoots so high we thought we broke our test bench! So we reinforced the bench and tried again. With the same results. Here is what we observed that day:



We realized that, for the first time, a sim racing wheel base resonated. We mean it, it literally resonated.

a. What is the Resonance Phenomenon?

When an object vibrates at its natural frequency over a longer period of time, it starts experiencing higher amplitude of vibrations, without the need to increase the input force.

Need help visualizing this resonance? Imagine bouncing on a trampoline. Because you fall from a higher position on your second jump, your third jump will go even higher. This is exactly what happens in our Direct Axial Drive wheel base. Basically, the stator acts as a trampoline, and at the right frequency it vibrates perfectly in sync with the rotor that helps it change direction (similar to a slingshot effect) and overshoots its target value.

This phenomenon was discovered by physicists and mathematicians a long time ago, but since First-Generation DD could not vibrate that fast (due to eddy currents, again), we never thought Direct Axial Drive bases would be able to resonate. When resonating, the controlled overshoots reach up to

+150% of the constant torque. For example, when maxed out, a 5Nm wheel base generates more vibrations than the TGT-II transducer, in the same frequency range.

b. What it brings to Sim Racing

We quickly realized this phenomenon could be a cool feature in a wheel base when **controlled**. Resonance can amplify specific effects and give enhanced haptic feedback to the player when an important event happens (car collision, gear switch, curbs, etc.). Because our Direct Axial Drive motors do not saturate, we are able to give an extra layer of information to the player, even as the wheel base outputs a constant torque.

Once testing the feature as a gear jolt for example, we heard from multiple people the same comments: "*Did you put a butt kicker in the seat?*" or "*Do the pedals have haptic feedback?*". Of course not, but the vibrations from the base propagate through the cockpit, giving drivers sensations they never felt before in sim racing. Once this feature gets integrated in the games by the developers, it will bring an even more immersive experience out-of-the-box, without the need to add extra vibrations modules to your setup!

4. So… Direct Axial Drive when?

Direct Axial Drive will be the new sim racing standard. It simply outperforms First-Generation Direct Drive wheel bases in every category, at a price-to-materials ratio that scales more efficiently and affordably. Our papers' purpose is not to convince you, but to explain the change and why it matters.

Sometimes reality gets lost behind appealing marketing terminology, and we believe it's important to explain that even if *Direct Drive (DD)* and *Direct Axial Drive (DaD)* share a similar name, they are based around completely different motor technology.

Thrustmaster will present the industry's first ever Direct Axial Drive (DaD) wheel base on October 11th. We don't expect it to be the last. Because a New Era of sim racing has begun.

Don't miss the opportunity to be the first to discover it: subscribe to our newsletter, follow us on our social media channels and join the discussion on Discord to get all details. If you want to be the first to try the upcoming Direct Axial Drive wheel base, you can visit our booth at ADAC Sim Racing Expo on October 18, 19 & 20.

See you on the track!

The Thrustmaster Team