# PID Tuning Principles

Why do we tune?

Your quad is controlled by what is known as a "PID loop". As we are doing flips and rolls we are changing the "Command" (what we know as the Setpoint in the quad world [a.k.a. the sticks]), causing the PID loop to react. The goal of tuning is to tweak the PID loop gains so that it achieves the fastest response to command changes as possible, without overshooting/oscillating. These Principles apply for **ALL PID CONTROLLERS!** ANY flight firmware and ANY quad copter class. The guide and videos focus on Betaflight because it is the most widely used firmware in the industry for freestyle and racing. But the same principles apply to: FalcoX, KISS, iNAV, Cleanflight, EmuFlight, Baseflight, etc. They all use a PID controller!

In this example, "Command" goes from 0 to 110% at time zero. The PID loop then reacts to move the machine - in our case the quad - to the new value. The Command line is our sticks. The red, green, and yellow lines are different gyro (quad movement) responses based on different PID tunes.

You want a tune that produces a "Critically damped" response (measured by the gyro feedback to the PID loop).
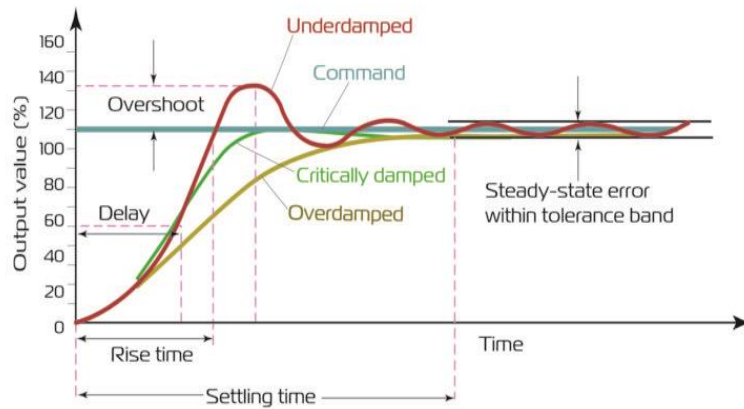
Tuning your quad copter is an easy process involving the below 4 key steps. It only takes 1 or 2 packs. It can be done Line-of-Sight (LOS), with FPV goggles, or using Blackbox. I use Blackbox a lot because it helps to understand what is happening (to explain it) and also it gives the most precision in tuning, but it is NOT necessary to use blackbox to tune your quad.

The steps are outlined in more detail below. Steps #1 thru #3 are critical for good general flight performance, including:

- good prop wash handling;
- no wobbles or oscillations;
- no "throbbles" (bobble of the nose on throttle punches);
- good reaction to wind
- tight stick tracking (direct feel).

How do we tune?

Step #1 – Tune your Filters – The PID controller can't work well if it's fighting vibrations in the gyro signal

Step #2 – Tune 'P/D Balance' – Every quad has a specific P/D Balance that we need to find

Step #3 – Tune 'PD Gain' gain – increases the speed of the influence (force) the PID gains exert on the motors

Step #4 – Tune FeedForward ("FF") – Adding a fourth control term to reduce the inherent latency in a standard PID controller

Step #1 – Tune your Filters:

a) Setup your quad using the new RPM filters. See Betaflight 4.1 Filter Setup - RPM Notches are the Future! for details on that process. The advantage of RPM filters – FOR ANY QUAD CLASS – is twofold: **1) the RPM filters more accurately track and crush motor peak noise. 2) it frees up the Dynamic Notch to look for and track frame resonance or other peaks of noise** (antennas vibrating, frame cracked, etc…) **and crush it out.** Once RPM filters are setup per the video (with the Dynamic Notch adjustments) move on to Step b).

b) Work up the lowpass filter sliders <u>TOGETHER</u> at the top of the Filters tab to try to get to a 1.5 or 2.0. With the other settings (as outlined in the video above) this will result in a reasonable balance of filter delay savings vs. not going too low and under filtering your quad. **MILEAGE HERE WILL VARY!** So do it slowly moving up one or two steps at a time with full throttle / hard move flights in-between.
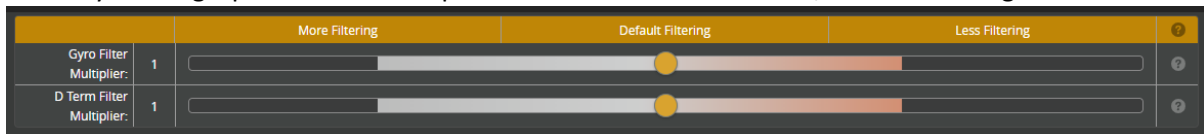

Figure 1: Gyro and D-term (lowpass) Filters sliders in Filters tab

<u>CHECK YOUR MOTOR TEMPS</u> as you move up the sliders. Listen for excessive noise (grinding) sounds on the motors at idle or during flight. <u>Do prop wash turns and sharp moves</u>. See if things are getting better or worse as you move up the sliders. **If better**, move them up some more. **If worse**, stop and move back one position. It is possible that motor will not be hot, but flight performance can get worse with higher filters (noise to signal ratio gets too high on D-term). Use your senses and perception on if prop wash is getting better or worse as you move up the sliders.

OPTIONAL: Do a blackbox log with the following settings in the BlackBox tab: Do a <u>full throttle</u> and <u>hard moves</u> flight. <u>Do NOT hit stuff</u> and avoid any ground bouncing at the beginning or ending of the flight (not critical, but can throw analytical tools off if not trimmed out). Look at a spectrum of the Gyro signal and D-term signal. Make sure all peaks of noise are completely crushed out in the gyro signal spectrum and that the D-term signal doesn't have excessive noise between 100hz and 200hz.
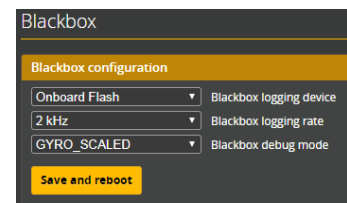

Figure 2: Blackbox Setting in Blackbox Tab

For a video guide on the flight and looking at logs to tune up your filters, see:

1. PID Tuning Principles: Step #1 - Filters Tuning (guide on getting the raw noise log)
2. PID Tuning Principles: Step #1 Follow-up - Finalize YOUR Filters (how to customize your filters)

For the basics on filters OR an in-depth understanding of how filters work and what "phase delay" is, see my Filter Fundamentals series.

In general, you want to use Gyro filters to crush out any motor peaks of high frequency vibrations ("noise"). Then use the D-term filtering to tame the D-term property of doubling gain response to noise as the noise doubles in frequency. Meaning, higher frequency noise (100hz+) drives the D-term to go crazy, resulting in vibrations in smooth flight or HOT motors.

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Step #2 – Tune the 'P/D Balance':

Paste the below into the CLI tab in BF. This will turn off all the BetaFlight advance PID control features; features that push the PID controller beyond basic fundamentals. Once pasted, do a flight with lots of flips and rolls (Line-of-Sight or FPV), sharp stick inputs back and forth, and keep

Figure 3: PD Balance in PIDs tab

increasing P-gains until you see sharp bounce-back. For LOS or FPV you really need to listen for it vs. seeing it (it is so fast). It is easy to visualize however in blackbox (BBL). You can set your D-gains to the same number for Pitch and Roll based on the noise floor after your filtering setup in Step #1. This is subjective based on how noisy you want your D-term signal to be to the PID Sum. Best advice is 30's or 40's for a 4S 5-in quad. For 6S 5-in quad could be down in 20's and 30's. For a brushless whoop, more like 60's or 70's. **You want to keep raising P-gains until you start to get overshooting based on sharp stick inputs and then back it down a little to get the "Critically damped" stepped response (see Figure 7).** Again, it is easiest to listen for it LOS or FPV. To see it check out a BBL.

For a video guide on this step, and what to look for in blackbox, see:
PID Tuning Principles: Step #2 - Tune the PID Controller (P/D Ratio)

CLI commands to paste and save before completing Step #2:

#PID Gains Settings	#PID Controller Settings
set d_min_pitch = 0	Set pidsum_limit = 1000
set d_min_roll = 0	set pidsum_limit_yaw = 1000
set f_pitch = 0	set feedforward_transition = 0
set f_roll = 0	set abs_control_gain = 0
set f_yaw = 0	set use_integrated_yaw = OFF
	set iterm_relax_cutoff = 10
	save

Once you have found the proper P vs. D ratio (Balance) you can re-enable the PID tuning Sliders and move them around (between "Master Multiplier" and "PD Balance") to get close to the numbers you had set manually. NOT all quad classes will be covered by the

Figure 4: Enable Sliders button on PIDs tab

sliders extent. So if you are tuning a whoop, toothpick, or 10-inch they may not be flexible enough to suit your needs. Betaflight defaults and slider extents were design around a 6S - 5" quad.
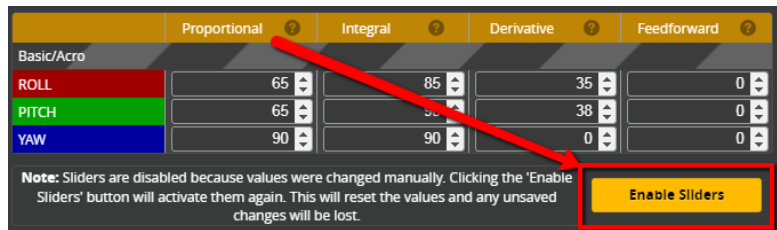
As we are doing the flips, rolls, and half rate moves (as show in the above video) we are drawing out the Stepped Response in the PID controller. **THIS IS HOW YOU TUN A PID CONTROLLER; period!** See Figure 5 for how the different terms impact the quads performance and Figure 7 for a description of what a "Critically damped" Stepped Reponses looks like.

PID Tuning Principles

A Deeper understanding of Stepped Response tuning:

Figure 5 below, shows a summary for what increasing one term will do when keeping the other two constant. For example looking at the top row in the table, holding I-term and D-term constant and Increasing P-term will:

1. Decrease Rise Time (speed of quad moving to match the stick commands);
2. Increase Overshoot (if excessive);
3. Small Increase of Settling Time (if excessive);
4. Decrease Steady-State Error (when optimal);
5. Degrade Stability (if excessive).

THE KEY is to have the right balance of P and D term to get a "Critically damped" Stepped Response (see Figure 7). The CLI paste in Step #2 above helps us isolate P & D gains **to find the perfect balance!**

Effects of Independent P, I, D, and FF tuning					
PID Term to Change	**Rise Time**	**Overshoot**	**Settling Time**	**Steady-State Error**	**Stability**
Increasing P-term	Decrease	Increase	Small Increase	Decrease	Degrade
Increasing I-Term	Small Increase	Increase	Increase	Large Decrease	Degrade
Increasing Dmax-term*	Small Increase	Decrease	Small Decrease	No Impact	Small Improve
Increasing Dmin-term*	Increase	Decrease	Decrease	Minor Change	Improve
Increasing FF-term	Large Decrease	Minor Increase	No Impact	Can Increase**	No Impact

* when D_min is enabled, it is the D-term in the PID controller. Only on sharp inputs does the active D-gain go to Dmax. See "FF induced overshoot:" in Step #4 for more details.

** through unstable RX signal (Cross Fire, R9 and all FrSky rx's)

Figure 5: Effect of PID changes (source: http://eprints.gla.ac.uk/3815/1/IEEE_CS_PID_01580152.pdf)

Figure 7 outlines the above terms. As we are doing flips and rolls we are changing the "Command" (*what we know as the Setpoint in the quad world [a.k.a. the sticks]*), causing the PID loop to react so we can see how it manages the change (the Stepped change Response). We want to do this with **both** full rate and half rate moves to see how it manages these two things to optimize the tune.

Again, the CLI paste helps us to isolate the P and D terms (turns off FF and getting I-term out of the way) so we can adjust P-term to determine the optimal P/D Balance (ratio); looking for the "Critically Damped" PID response. **This means the highest P/D Balance possible without overshoot!**
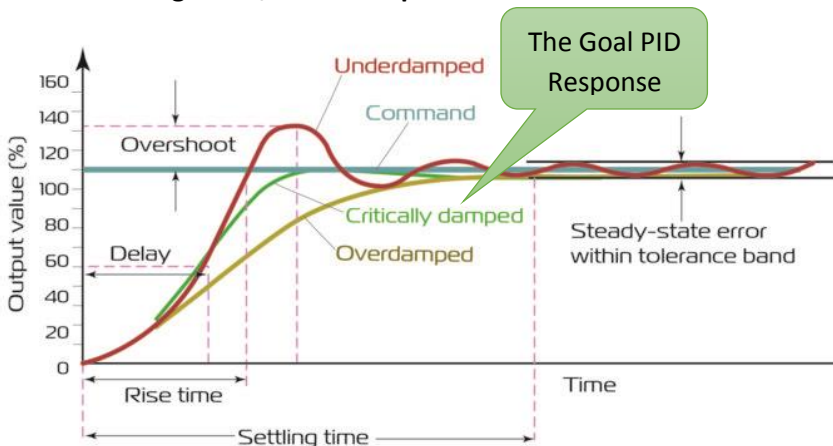

Figure 6: Analog of PID terms

Think of the PID controller like a strut on your car.

In this example, "Command" goes from 0 to 110% at time zero. The PID loop then reacts to move the machine - in our case the quad - to the new value. The Command line is our sticks. The red, green, and yellow lines are different gyro (quad movement) responses based on different PID tunes.

You want a tune that produces a "Critically damped" quad movement response (measured by the gyro feedback to the PID loop).

Figure 7: Stepped Response diagram.

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Step #3 – Tune 'PD Gain' gain:

With the "P/D Balance" for your specific rig figured out **WE NEVER WANT TO DO ANYTHING TO CHANGE THAT** as we increase gains or reintroduce the advance PID controller parameters (FF, D_min, etc…). The PID sliders are built with that fundamental in mind and are there to help speed things up. With this understood, this step is to increase both P-gains and D-gains <u>TOGETHER</u> to get better prop wash handling and closer tracking to the stick inputs (Setpoint).
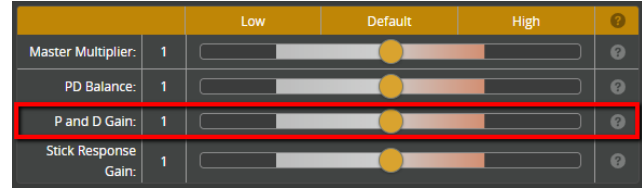

*Figure 8: **P and D Gain** slider in PIDs tab*

"P/D Balance" = P-gain ÷ D-gain.
e.g.: 60 (P-gain) / 35 (D-gain) = 1.71 (P/D Balance)

In the above example we have a 1.71 P/D Balance ratio. Therefore, if you increase D-gain from 35 to 40, you need to increase P-gain from 60 to 68 (40 (new D-gain) x 1.71 = 68 (new P-gain)). If you use the P and D Gain slider to move up the terms, it holds the PD Balance automatically.

Do prop wash inducing moves (180 turns or split-S moves). Push up your P and D gains to reduce prop wash. As you are moving up P and D gains, you will get to a point where the higher D-gains could start to cause motor heat or vibrations in smooth forward flight (typically gains of 40 to 60 on a 4s 5-inch OR 30 to 40 on a 6s 5-inch). Also, you will hit a point where prop wash will not get better. **This point is called "motor saturation" and is due to motor/prop mechanical limitations.** You can see this in flight just by things not getting any better or by looking at the Motor Command traces in a blackbox log (they hit 100% for 1 or 2ms). **THIS IS THE POINT YOU WANT TO BE AT** for the best tune you can have on your quads specific mechanical setup. The ONLY way to improve prop wash handling from this point is making mechanical changes. The cheapest way is finding the best (lightest) props to match your motors (not under or over propped), your desired response curve/feel, and your durability preference. So if you can't shake that last big of prop wash to your desired liking and you have followed these practices to a tee, <u>it is</u> a mechanical limitation; not the firmware.

Step #4 – Tune FeedForward ("FF"):

Step #4 is ONLY important if you want to sharpen up stick responsiveness (typically for racing). Maybe freestyle pilots like FF = 0 for smoother feel.

Once you have the P and D gain strengths to a point where you are getting motor saturation when trying to induce prop wash, you can still push the PID controller further with Betaflight's advanced PID controller features. FeedForward ("FF") will provide an additional *push* (alongside P-term) to

Figure 9: Stick Response Gain slider (FF slider) in PIDs tab

get the quad moving for sharp stick commands. FF-terms are based on the speed of your stick moves; like the mouse accelerator on your PC or Mac. FF is similar to a D-gain, except it is based on the sticks (not the gyro like the D-term) and pushes the quad (instead of dampens like the D-term). FF is mostly about *feel,* so increase as you see fit (or don't) to get the desired *feel*.

DON'T BE AFRAID TO USE HIGH FF GAINS (300+)! In my experience, a 4S - 650g - 5" quad may need FF gains as high as 300 to have the Gyro completely track the Setpoint for rates that top out at 1020 deg/sec.

For a video guide on this step, see:

PID Tuning Principles: Step #4 - Tuning FeedForward and D_min to Track Setpoint

FF induced overshoot: As you increase FF-gains, the quad may start to get some minor overshooting. This is much less of an issue in BF 4.1+ than ever before because some code was added to detect and shut

off the pushing of FF as it saw it was approaching the target. **However,** if you do have some overshooting, re-enabling D_min can address the overshooting by the added push of FF.

Figure 10: D_min Activation

Once D_min is activated the "D_min" column adds to the PID gains grid (Figure 10). **The D_min column is now your base D-gains in normal forward flight!** The quad will spend most of the time flying at the D_min value. The "Derivative" column is the boosted D-gains in sharp stick input and during prop wash (aka "D_max").
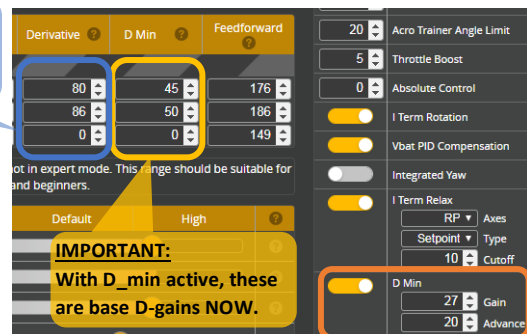
A typical D_max setting that addresses any FF overshooting is approximately equal to your P-gains. If you are using the sliders, they automatically keep an appropriate ratio.

A deeper understanding of D_min:

Once you activate D_min, the quad will fly with D = D_min. If the quad needs more D-gain due to sharp moves, prop wash, etc, it will ramp up to D_max (the value in "Derivative" column) in order to combat the move / induced error. D_min boosts the active D-gains during prop wash detection as well. You can raise the "D_min Gain" value (shown as "27" in Figure 10) to increase the sensitivity of prop wash detection. Default is 27 but you can increase as high as 50 to make D_min raise the active D-gains sooner and stay higher longer. However, this will increase Rise Time for stick moves as the active D-gain will boost sooner in sharp stick moves. See the below videos for more on the D_min feature:

D_min Details and use for Noisy rigs to reduce filtering: https://youtu.be/n8iwIcJSuWs
D_min as "D_Boost" for a high performance tune (what we want): https://youtu.be/RtsQwGVTHg4

Once you are all done, you should have a tune that the Gyro completely tracks the sticks (the most DIRECT feel possible) and combats prop wash, wind, wobble, bobbles, etc… up to your quad's mechanical limits.

Step #5 – Yaw tuning: yaw is a very slow axis to respond to stick commands (Setpoint) when compared to roll or pitch. Most of the influence for yaw is through motor/prop inertia shifts (2 motors speed up and 2 slow down). Therefore, it typically doesn't overshoot Setpoint and hence D-gains in BF for yaw are defaulted to 0 negating the D-term opposition to P-gains on yaw (but is a gain you can adjust if desired). To increase the initial push of yaw, like other axis's, increase your P-gains. If you add in Yaw D-gain, it will oppose that push requiring higher P-gains. This will give yaw an initial jump to get things moving. However, since so slow to react, yaw requires a much higher I-gain to keep it tracking Setpoint. Like with I-term tuning in Step #6, it is best to tune yaw through blackbox and looking at how well the yaw axis gyro reading is tracking the yaw axis Setpoint as you do sharp yaw moves. Then apply the principles of Step #2 to the yaw axis. I find you need a **HIGH** P-gain and I-gain on yaw (P = 80 / 90 and default I-gains). For a video guide on this step, see: PID Tuning Principles: Step #5 - Yaw Axis Tuning

> *Note in BF 4.0+, the Yaw I-gains are multiplied by 2.5 in the code to give an even higher I-gain control on Yaw. So in earlier versions of BF (3.5 and lower) Yaw I-gains are way too low.*

> *Integrated Yaw feature in BF 4.0: If activated this changes the advice above. Note the paste in Step #2 disables Integrated Yaw for the time being until this new yaw tuning approach can be vetted (with Absolute Control) and this guide can be updated. If you want to play, knock yourself out. If you want to keep it simple, keep Integrated Yaw disabled.*

Step #6 – I-term tuning: With the addition of the i-Term Relax feature in BF, you can run very high I-gains without negative ramifications. The best way to tune I-term is through feel or blackbox. Higher I-gains will make the quad track the Setpoint more accurately in sweeping turns. It will also make your quad feel a little stiffer for entering sharp moves. In the end, it is not that touchy of a term/gain. So the best way is to get everything else set and then get a backbox log and see how well the quad is tracking the Setpoint through sweeping moves/turns.

If the Gyro trace seems to run high or low of the Setpoint for an extended period of time, you need higher I-gains. If you have very, very slow bouncing of the Gyro trace above and below the Setpoint trace, that means your I-term is too high (this would be very rare and require I-gains of 100+ in most cases – look for a 4-leaf clover that day and play the PowerBall!). In most cases, quads fall within the large window for decent I-gains set by the Defaults so typically little focus is placed on I-term tuning. But generally racers want higher I-gains for better tracking in broad and tight turns so try raising them up a bunch (20 or 30) and see how you like it for around the track. If you like a more loose feel for free style, try lower I-gains and maybe even FF = 0 for smoother molasses HD footage.

DEFINITIONS:

"Overshoot": is when you induce a change the desired roll, pitch or yaw rotation rate and the quad moves to match your new commanded rate (in deg/sec) but overshoots the target. This is also known as "bounceback" when referred to as motion seen in the FPV feed, LOS, or in blackbox logs <u>at the end</u> of sharp flip or roll. So the term "bounceback" is the quad overshooting the commanded change in motion and hence has to "bounce back" to the commanded rate. Looking at Figure 7 above, overshoot is a sign of an "Underdamped" PID controller; not a good PID tune.

"Bounceback": is the quad doing a small shutter (or shake) at the end of a sharp flip or roll. You can see bounceback in your FPV feed, HD footage or blackbox log. It is typically the quad going past the desired roll or flip rate (Setpoint) and bouncing back to the Setpoint. Looking at Figure 7 above, bounceback is a sign of an "Underdamped" PID controller; not a good PID tune.

          If the Bounceback **is fast**:
- If the quad seems to go past the Setpoint and bounce back to the Setpoint, that means your P/D Balance is too high. Either increase D-term or reduce P-term.

- If the quad seems to stop short of the Setpoint and then bounce further to hit the Setpoint (rare), that means your P/D Balance is too low (see Figure 7 – Overdamped condition). Either reduce D-term or increase P-term.

          If the Bounceback **is slow**:
- That is I-term windup causing the I-term to drag the quad past (or stop short) of the Setpoint and then it slowly adjusts back (or forward) to the Setpoint. HOWEVER, with the CLI paste in Step #2 above, setting the 'i-Term Relax' feature to a cutoff of "10" will prevent I-term windup from dragging the quad past the Setpoint. For more on the i-Term Relax feature, see: https://youtu.be/QfiGTG5LfCk

"Setpoint": is what you are telling the quad to do. For example: when you do a sharp roll, the Setpoint ramps from a rotation rate of 0 degrees/second roll rate to what you have your max roll rate set to in the Rates tab. We tell the quad the roll, pitch and yaw rates with our TX sticks (the rest is just throttle amount) and the PID loop controls the quad getting to and sustaining the commanded rates (Setpoint). You can see how close you are tracking to Setpoint through feel experience (lots of it) or more simply through looking at a blackbox log.