

Betaflight PID Tuning Using Blackbox

(Betaflight v4.1; Betaflight Configurator v10.6.0; Blackbox Explorer v3.5.0)



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Step 0: Level Setting Expectations

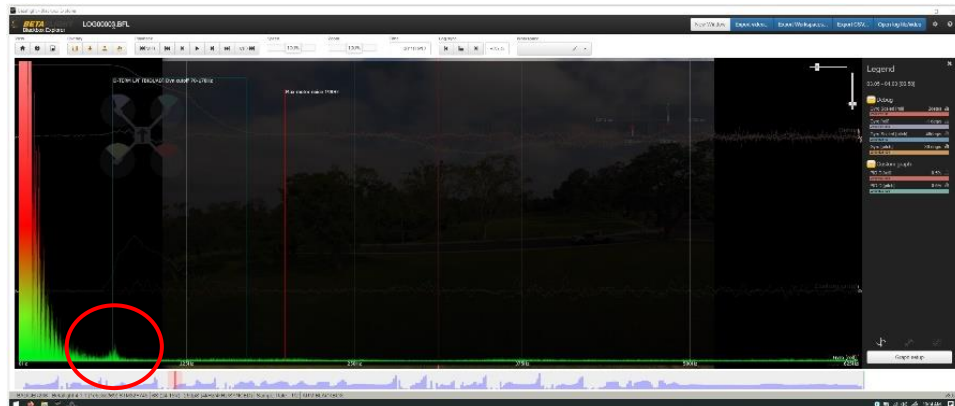
Why do we tune? We tune to get more responsiveness out of our quad. What does responsiveness mean? It means getting our quad to do what we want as accurately and as quickly as possible. Therefore, the goal of tuning is (i) ensure the accuracy of and (ii) minimize the timing lag between our radio stick commands (“setpoint”) and what our quad is doing (“gyro”). In blackbox speak, we want our gyro to track setpoint as closely as possible.

This process assumes you are using Betaflight and are familiar with both Betaflight Configurator and Blackbox Explorer. This process was based primarily on *UAV Tech’s PID Tuning Principals* in addition to research conducted by *Joshua Bardwell* and *Pawel Spychalski* as well as invaluable feedback from the phenomenal community at *IntoFPV.com*.

Step 1: Mitigating Noise

Before we even begin PID tuning, we need to eliminate as much excessive noise as possible. The D term is a noise amplifier therefore noise mitigation is key to establishing the proper term.

The following blackbox spectrogram reflects filtered gyro noise for the roll axis.

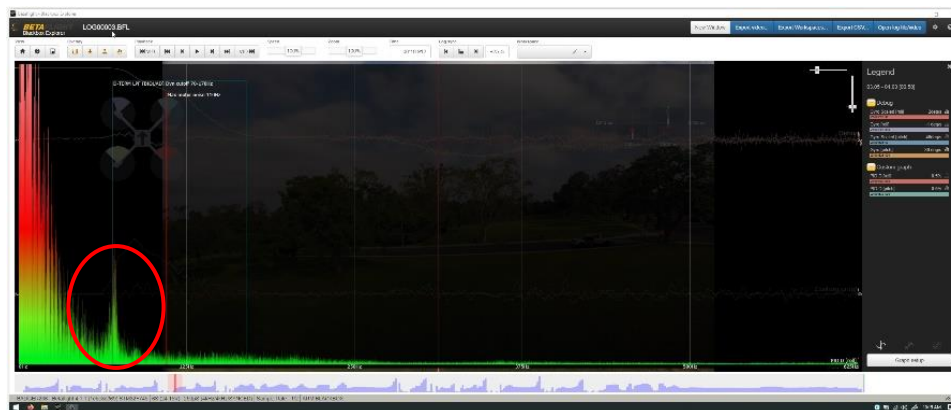


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The following shows the roll axis D-Term spectrogram amplifying the noise from the gyro roll axis.

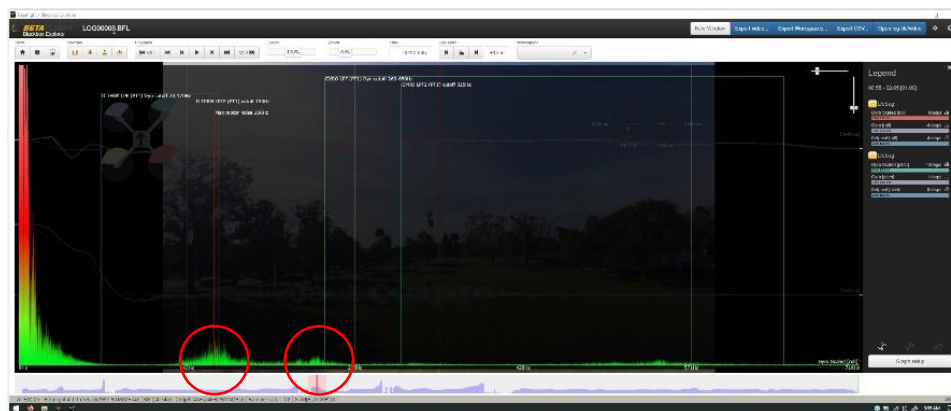


Noise primarily stems from three sources:

1. Motors and propellers
2. Air from propellers passing over arms
3. Harmonics (2nd harmonic at +100 Hz and sometimes 3rd at +200 Hz)

Additional noise that needs to be addressed may come from a poorly mounted flight controller, wires rubbing against the gyro, or a damaged motor to name just a few examples. These are usually low frequency noise that occur in the 60 Hz - 200 Hz range. We will be using spectrograph traces in blackbox to observe noise frequencies and amplitudes and address any mechanical or electrical noise.

The following spectrograph shows the unfiltered gyro noise (gyro_scale) for the roll axis showing motor noise at around 150 Hz and the first harmonic showing at around 250 Hz.



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Use Betaflight default PIDs and filtering with the following changes (use rates you are comfortable with):

- [Configuration tab] Set ESC / Motor protocol = DSHOT600
- [Configuration tab] Set Gyro and PID loops to 4 kHz
- [PID tab] Set I Term Relax (mitigates I term induced bounce back with lower cutoff)
 - Axes = RP
 - Type = Gyro
 - Cutoff = 10
- [Blackbox tab] Set minimum of 2 kHz recording
- [CLI] Enter code
 - `set debug_mode = gyro_scale` (enabling you to see unfiltered gyro in blackbox)
 - `rc_smoothing_auto_smoothness = 50` (optional if you are seeing step inputs in blackbox)

Test Flight #1: Perform test flights including snappy flips, rolls, and prop-wash inducing sharp turns. Check motor temps after each run for excessive heat.

Check noise spectrographs for Gyro Scale versus Gyro for each of pitch and roll observing noticeable noise traces.

- The thick band of low frequency noise on the left side is normal flight noise.
- Depending on motor size, motor noise typically propagates in the 150 Hz - 200 Hz range.
 - Motor noise harmonics may show in +100 Hz increments up to the 3rd harmonic.
- Observe any high amplitude noise in the 60 Hz – 200 Hz range and try to identify and mitigate the sources of this noise.
 - Broad spectrum (lacking defined peaks) noise is much more difficult to track with dynamic notch filtering.
 - Low amplitude noise can be ignored since filtering will effectively address those.

Once any unwanted noise has been identified and mitigated, we can move onto setting up optimal filtering.

Step 2: Optimal Filtering

While extremely effective, any manner of filtering results in additional phase delay which means more lag between setpoint and gyro. Therefore, we will be relying primarily on RPM Filtering and Dynamic Notch Filtering (extremely effective filters) and disabling the bulk of other filtering to minimize phase delay.

- [Configuration tab] Enable RPM Filtering
 - ESC / Motor protocol = DSHOT600
 - Bidirectional DShot = On
 - Gyro update frequency = 4 kHz
 - PID loop frequency = 4 kHz
 - Note that this requires BLHeli firmware 3.27

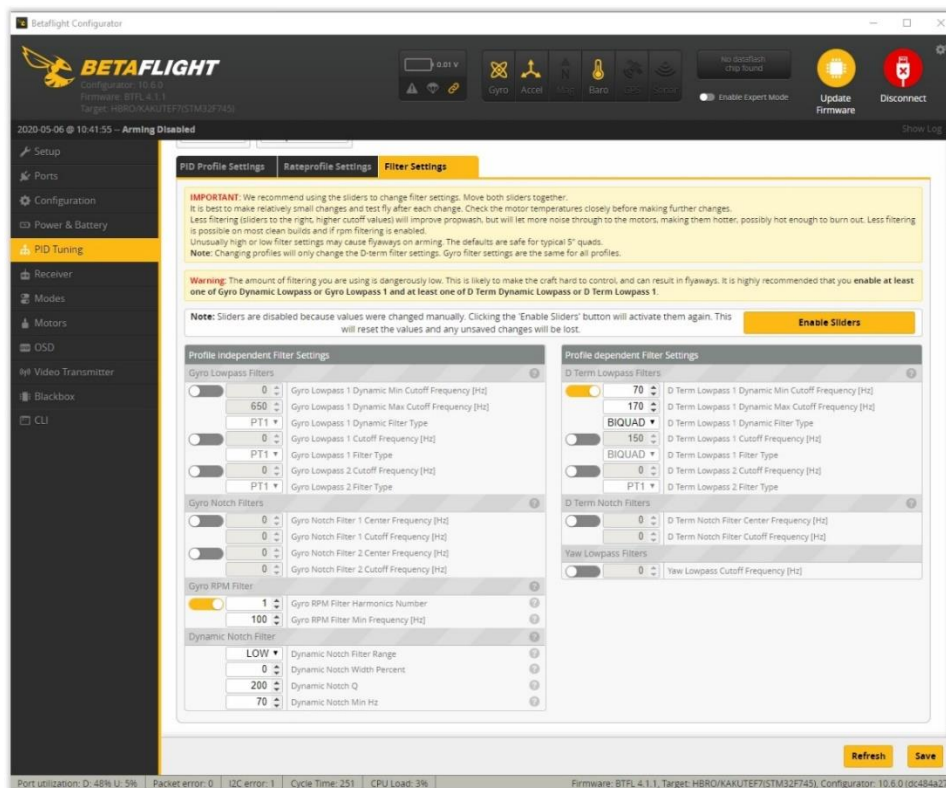
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- [Configuration tab] Enable Dynamic Filtering
 - Dynamic_Filter = On
- [Filter tab] Set D Term Lowpass 1 Dynamic Filter
 - Min Cutoff Frequency = 70 kHz
 - Max Cutoff Frequency = 170 kHz
 - Filter Type = BIQUAD
- [Filter tab] Set Gyro RPM Filter
 - Harmonics Number = 1
 - Min Frequency = 100 kHz
- [Filter tab] Dynamic Notch Filter
 - Range = LOW
 - Width Percent = 0
 - Notch Q = 200
 - Min Hz = 70
- [Filter tab] Turn off all other filters (note including the remaining D Term Lowpass filters)

Your Filter tab should look like this.



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Note that in addition to the active filters, there is an onboard gyro digital filter that effectively covers the 400 Hz - 1000 Hz range. The Dynamic Notch filter is meant to address any remaining peak noise including 200 Hz motor noise. Therefore, additional Lowpass Filters do not do much since the Dynamic Notch filtering is so effective. However, if you are unable to identify and mitigate some high amplitude noise source, use any additional filtering needed to address it.

Test Flight #2: Perform test flights including snappy flips, rolls, and prop-wash inducing sharp turns. Check motor temps after each run for excessive heat. IF MOTORS RUN TOO HOT TO THE TOUCH, STOP. In this case, the filtering strategy is too aggressive for your build. Either go back and try and fix any noise issues or begin turning on additional filters beginning with the Gyro Lowpass Filters. Otherwise, observe your traces using blackbox spectrographs to ensure proper noise levels.

Once the optimal filtering is in place, the next step is the actual PID tuning. More specifically, P and D tuning.

Step 3: The P-to-D Ratio

Rather than attempting to hone in on a specific set of P, I, and D Terms, we are just going to focus on P and D (and really mostly just P). We will begin with a (generally arbitrary) D Term and begin applying higher P's until we induce oscillations. Our starting D Terms will be a function of the voltage:

- **5S-6S: D term of 20-40**
- **3S-4S: D term of 40-60**

For the P Term starting point, begin at 1.5x the selected D which will almost always be too low. To isolate the impact of P and D on the gyro, we will disable a lot of functionality so we can focus on this ratio alone by issuing the following commands in the CLI:

#PID Gains Settings

set d_min_pitch = 0

set d_min_roll = 0

set f_pitch = 0

set f_roll = 0

set f_yaw = 0

#PID Controller Settings

Set pidsum_limit = 1000

set pidsum_limit_yaw = 1000

set feedforward_transition = 0

set abs_control_gain = 0

set use_integrated_yaw = OFF

set itemp_relax_cutoff = 10

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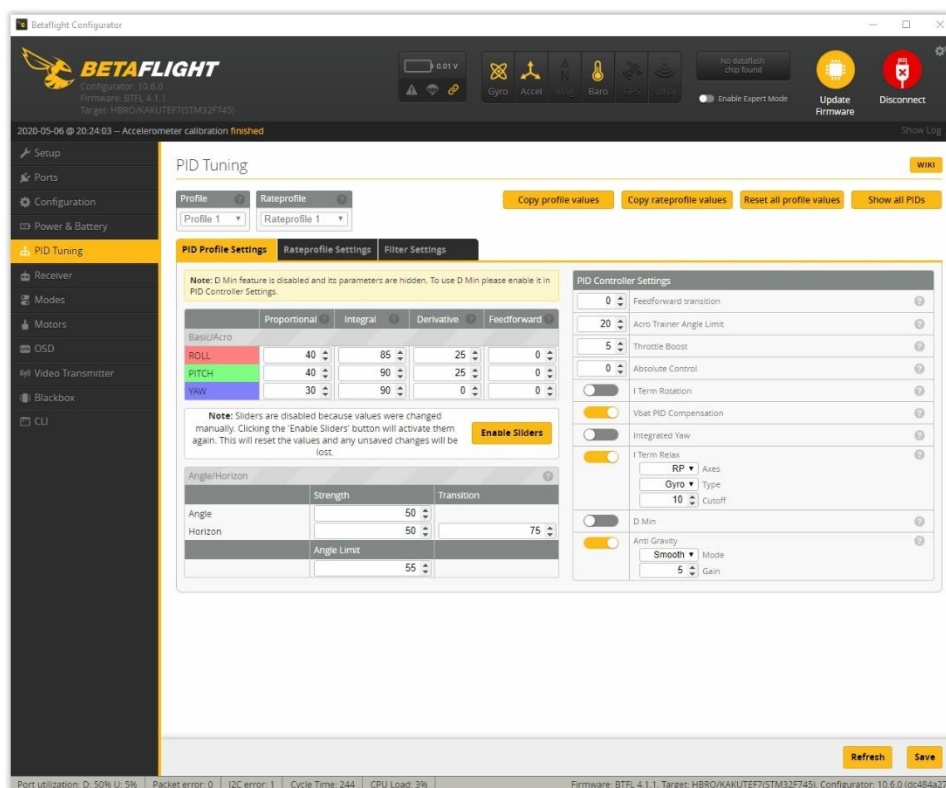
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On the PID tab, ensure that all of these features reflect the following.

- Feed Forward values are zero
- D-Min is disabled
- Feed Forward transition = 0
- Absolute Control = 0
- I-Term Relax
 - Axes = RP
 - Type = Gyro
- Vbat PID Compensation = On

Your PID tab should look like this with starting point P's and D's based on your power system.



Test Flight #3: Perform test flights including snappy flips, rolls, and prop-wash inducing sharp turns. Check motor temps after each run for excessive heat. IF MOTORS RUN TOO HOT TO THE TOUCH, STOP. You are likely running too high of a D Term. Begin again with a lower D Term (lower by 5 or 10) and / or turn additional filters incrementally (starting with the Gyro Lowpass Filters). Otherwise, after each flight, increase P by an increment of 5 or 10 until oscillations are observed. Note that you will experience two forms of oscillations whether your P/D Ratio is too low or too high.

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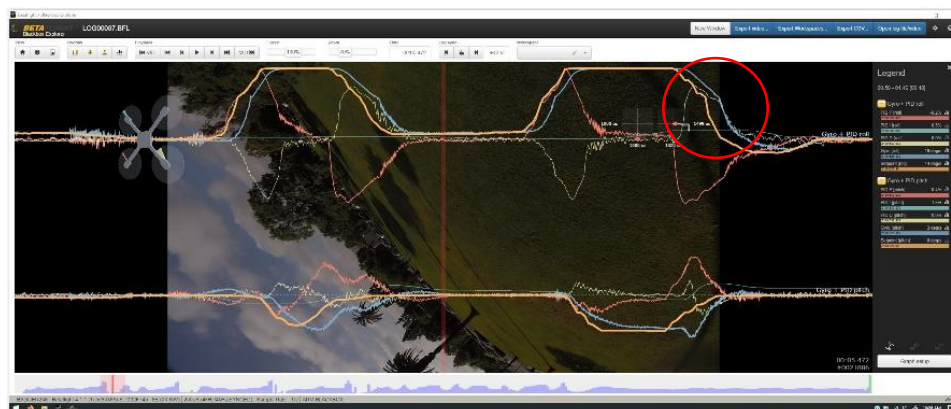
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- Too low results in slow oscillations as a result of the I Term taking over to make up for the lack of P Term.
 - Note that mistaking slow bounceback for too high of a P Term thereby compensating with more D Term will only increase the PID error making this worse.
- Too high results in quick oscillations as a result of the P Term overshooting its target due to the lack of offsetting D Term.
 - In blackbox trace, look for otherwise good setpoint tracking with an overshoot at the apex of a hard move or constant P Term or gyro oscillation during cruising flight.
 - On sharp prop-wash inducing terms, you may here brief motor trill at the apex.
 - Note that Betaflight has gotten very good at addressing high P oscillations therefore it is best observed in blackbox traces; for typical 6S 5-inch quads, P's of 50-80 are not uncommon.

In blackbox, observe your setpoint versus your gyro traces for each of the pitch and roll axis in particular at the start and termination of hard maneuvers and at the end of prop-wash inducing turns. Look for overshoots in gyro to setpoint which would suggest too high of P Term.

In the following traces, the thick orange line is Setpoint and the thick blue line is Gyro. In this view, we have some room to increase P given the lag to setpoint at the start and end of this roll. More importantly, note that gyro is not overshooting setpoint (i.e., oscillations).

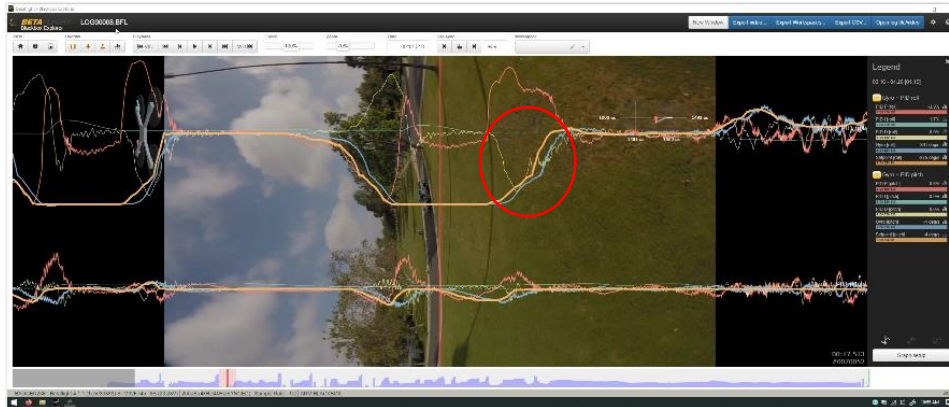


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In this view, gyro is now overshooting setpoint in this roll. Note also the improved tracking to setpoint. We will want a P Term between these two views.



Once you have arrived at your optimal P Term and D Term for each of the pitch and roll axis, note these figures and the ratio for each axis. For the remainder of this process and at any time going forward, you can change your P's and D's to address noise or performance as long as you maintain the P-to-D ratio.

In the next step, we will address the remaining I Term and Yaw tuning. As explained in the next step, these are generally very high error margin terms and therefore very difficult to “break” or mess up.

Step 4: I Term & Yaw Tuning

Both the I Term and Yaw have relatively large margins of error compared to the other terms and axes.

- The I Term is meant as a backup for P when unexpected movement from the gyro is observed like wind or other externalities.
 - Use Betaflight defaults and change as needed.
- Yaw relies on motor inertia rather than propeller thrust to effect quad movement. Therefore, it is very slow to react and typically never overshoots setpoint. Any D Term used on Yaw would typically be a waste and only result in added noise (remember D Term is a noise amplifier). The following is a general good starting point for Yaw.
 - Set P = 100
 - Set I = 100
 - Set D = 0
 - Set Feed Forward = 100

That is really it for I Term and Yaw. The last step will be to tighten the remaining gap between gyro and setpoint at the beginning and ends of sharp maneuvers and during recovery from prop-wash inducing turns by using Feed Forward and D-Min.



Step 5: Feed Forward & D-Min Tuning

It is important to understand that while the P Term reacts to differences in setpoint and gyro, Feed Forward reacts to the change in stick rate itself. While the P Term has to wait for an error to occur, Feed Forward pays no attention to the error and only to the sticks themselves. By applying Feed Forward, we can tighten the gap between setpoint and gyro even further resulting in that flying-on-rails type feeling on the sticks.

However, in order to really tame this level of handling we need a more dynamic D Term. This is where D-Min comes in. By enabling D-Min, the “D-Min” values will be used for the majority of the flight scaling up to “Derivative” values on extreme maneuvers. This is basically like a Turbo-D.

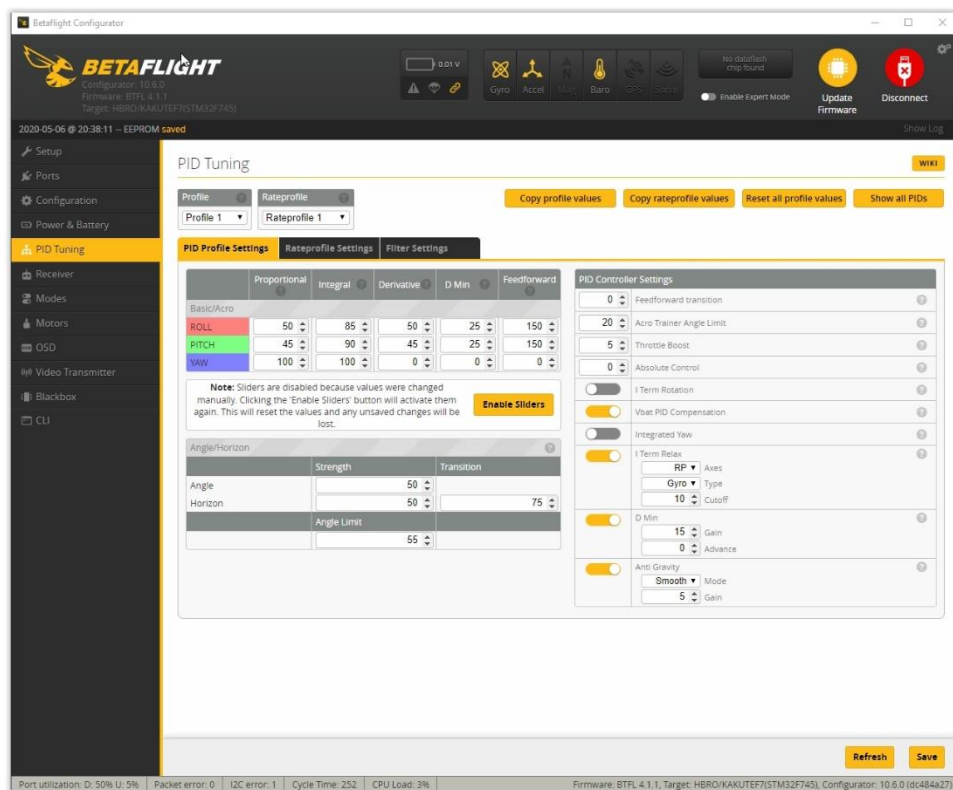
- [PIDs Tab] Set up D-Min
 - Toggle D-Min switch to On (note the new D-Min column that appears)
 - Set Gain = 15 (as a starting point)
 - Set Advance = 0
 - Copy the Derivative values to the corresponding D-Min column
 - Copy the Proportional values to the corresponding Derivative column
 - Remember that these “Turbo-D” terms will only be used on extreme movements.
 - Note that values copied to the D-Min column will be -1 since you cannot have the same value. After copying the P Terms, you can change these back.
- [PIDs Tab] Set Feed Forward
 - 150 for each of the pitch and roll axis as a starting point
- [Blackbox Tab] Set debug mode
 - Set debug mode to D-Min so that term can be observed in traces

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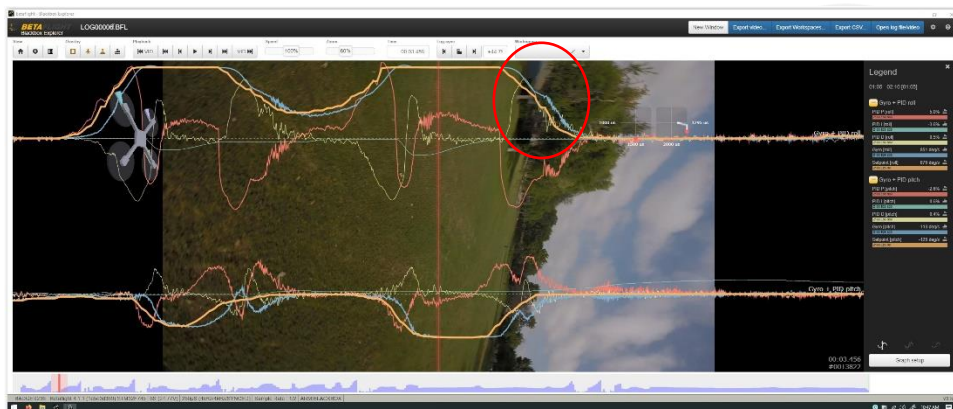


Your PID Tab may look something like this in preparation for Feed Forward and D-Min tuning.



Test Flight #4: Perform test flights including snappy flips, rolls, and prop-wash inducing sharp turns incrementing Feed Forward for pitch and roll by 50 on each flight until you begin to experience oscillations or bounce back. Check motor temps after each run for excessive heat.

The effect of Feed Forward in terms of setpoint tracking is very evident. This view shows gyro (thick blue) to setpoint (thick orange) tracking for a quad with optimal P-to-D but zero Feed Forward.

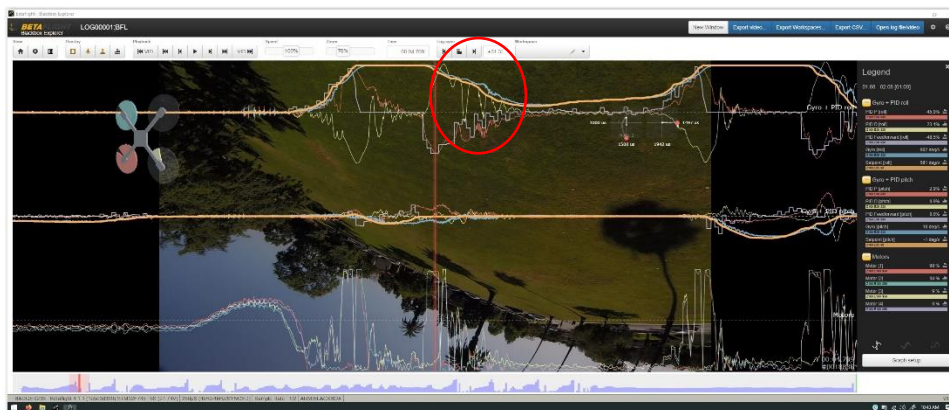


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This view shows setpoint tracking with minimal Feed Forward of 150.



Observe blackbox traces for gyro versus setpoint which should now be even tighter after the application of Feed Forward.

- At some point, you will see similar oscillations and bounce back particularly at the end of hard moves resulting from too much Feed Forward.
- Show Motor traces to observe motor saturation which can result in remaining overshoot.
- Note that remaining overshoot can be addressed with the following
 - Higher Derivative (Turbo-D) values
 - Higher D-Min Gain
 - Stronger motors

Once Feed Forward and D-Min tuning is completed, that is the end of this process. Enjoy your finely tuned quad! Just remember that you can change the P and D terms any time as long as the ratio is preserved.

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References:

- **the.ronin** YouTube channel: <https://www.youtube.com/channel/UCgye9lcXJMWusiAB0Z02HUw/>
- **UAV Tech** YouTube channel: <https://www.youtube.com/user/spatzengr>
- **Joshua Bardwell** YouTube channel: <https://www.youtube.com/user/loraan>
- **Pawel Spsychalski** YouTube channel: <https://www.youtube.com/user/dzikuvx>
- **intoFPV** multirotor forum: <https://intofpv.com/>