Shear Force Weapon System Analysis

CFD drag torque and spin-up model for the angled drisk weapon

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September 2026 (CFD runs completed 21 March 2026)

Abstract

Shear Force is a 30 lb combat robot with an angled drisk weapon. I used Ansys Fluent to predict the aerodynamic torque that opposes the weapon's rotation, then combined that torque with a motor and pulley model in a spreadsheet time-step simulation to predict the weapon's top speed and spin-up time. The CFD used a steady rotating reference frame with the SST k-ω turbulence model on an 80,261-node, 412,013-element mesh, solved at 15 speeds from 8,000 to 15,000 rpm plus a 0 rpm check. The drag torque rose from 0.612 N·m at 8,000 rpm to 2.171 N·m at 15,000 rpm and follows $T_d = k \cdot N^2$ with $k = 9.717 \times 10^{-9}$ N·m/rpm^2 to within 1.7 % at every point. The system model predicts a maximum weapon speed of 10,444.71 rpm, a maximum tip speed of 244.67 mph, and 2.56 s from rest to 90 % of that tip speed (220.20 mph) for a weapon inertia of 0.00919 kg·m^2. The motor model neglects voltage sag, internal resistance, belt losses and bearing friction, and the mesh was not checked for independence, so the top speed and spin-up time are optimistic estimates rather than measured values.

Contents

1. Introduction

1.1 Background

Shear Force uses an angled drisk: a spinning weapon whose blades are angled to the plane of rotation rather than flat. Our specification for the weapon's top tip speed was about 240 mph, which keeps the design under the 250 mph tip-speed limit in the SCAR rules.

A hand calculation can estimate the top speed from the motor's no-load speed and the pulley reduction, but it ignores the aerodynamic torque on the spinning weapon. The weapon generates drag and, because the blades are angled, also lift (similar to a ceiling fan). Together these produce a net aerodynamic torque that opposes the rotation. Not every local surface contribution opposes the rotation at every point, but the integrated moment about the spin axis does, and that integrated value is what Fluent reports.

1.2 Objective and requirements

The objective was to find how fast the weapon spins. The quantities of interest are:

- the maximum (steady-state) weapon speed in rpm and the corresponding tip speed in mph, compared against the 240 mph target and the 250 mph limit;
- the time from rest to 90 % of the maximum tip speed, as a measure of spin-up.

A comparison between weapon types was considered at the start of this work but is not part of this report.

1.3 Approach

The motor's torque-speed (τ-ω) curve is straightforward to obtain, and so is the weapon-side curve for a given reduction. If the aerodynamic torque is also known as a function of speed, the top speed is where the weapon torque curve meets the aerodynamic torque curve. Section 2 describes the CFD that provides the aerodynamic torque curve, Section 3 gives its results, and Section 4 combines it with the motor and pulley model to simulate the spin-up.

2. CFD method

2.1 Software

I used Ansys Workbench and Fluent 2025 R2, with a Workbench parameter set to run the speed sweep as design points and a CFD-Post report template to produce the same figures for every design point.

2.2 Geometry and domain

I loaded the weapon assembly CAD into the geometry component of a Fluent (Fluid Flow) system and combined the assembly into a single body, so that the weapon surface becomes one boundary for the later named selections and boundary conditions. The model contains the weapon assembly only; the chassis and arena floor are not included.

I then used the Enclosure feature to create a cylindrical fluid domain around the assembly, with its axis on the weapon's spin axis and a size of about 300 % of the assembly (Figure 1). The Enclosure feature subtracts the weapon body from the fluid volume automatically.

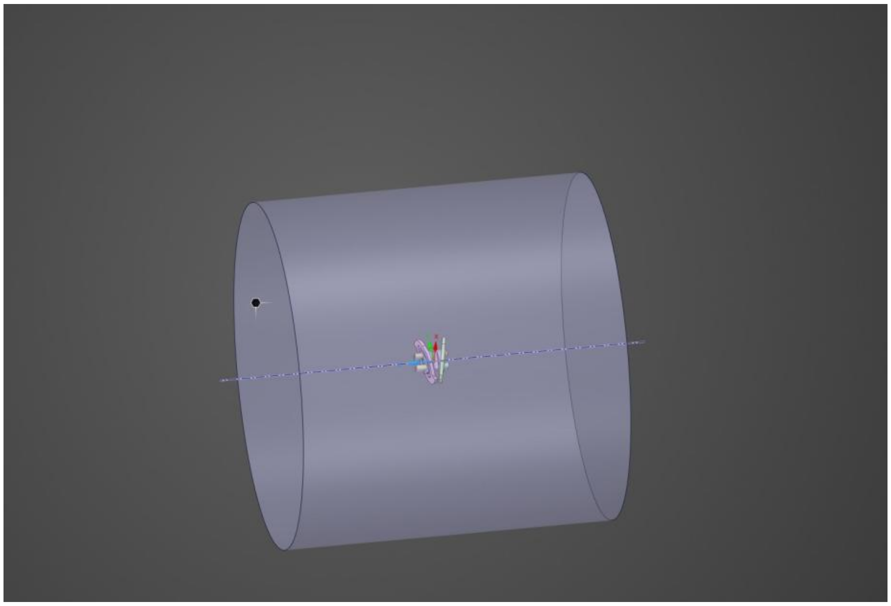

Figure 1. Cylindrical enclosure (fluid domain) around the weapon assembly, with the spin axis along the cylinder axis.

2.3 Mesh

I meshed only the enclosure (fluid) body, with the weapon body suppressed, and created named selections for the three boundaries: weapon_wall (the weapon surface left by the subtraction), outer_wall (the curved wall of the cylinder) and symmetry (the two end caps). The mesh has **80,261 nodes and 412,013 elements** in a single fluid zone (enclosure_enclosure), and every design point used the same mesh. Element type and quality statistics were not saved with the reports, and I did not run a mesh independence study (Section 5).

2.4 Rotating reference frame

Rotating the weapon mesh through time (a sliding mesh) would resolve the unsteady flow, but it needs a transient solution and much more computation. Instead I kept the weapon stationary and rotated the reference frame of the fluid zone about the spin axis (Fluent frame motion, also called the moving or rotating reference frame approach). This turns the problem into a steady one: in the weapon's frame, the air moves past a stationary weapon at the frame's rotational speed. I set frame motion on the enclosure fluid zone, aligned the rotation axis with the weapon's spin axis, and linked the rotational velocity to a Workbench input parameter, P1 Weapon_Rotation_Speed (rpm), so the sweep could run as design points.

2.5 Boundary conditions

Table 1. Boundary conditions.

Boundary	Fluent type	Condition
weapon_wall	Wall	Stationary no-slip wall (at rest in the rotating frame, so it turns with the weapon)
outer_wall	Wall	Slip wall (zero shear)
symmetry	Symmetry	The two end caps of the cylinder

The exported Fluent reports record only the boundary types (Wall, Symmetry). The slip condition on outer_wall is from my setup notes; Section 5 discusses what the velocity results suggest about it.

2.6 Physics and solver settings

- Turbulence model: SST k-ω, a standard model for external flows with separation around complex geometry. The saved residual monitors (continuity, three momentum components, k and ω) confirm it.
- Initialisation: hybrid initialisation.
- Iterations: 500 per run (Run Calculation setting).
- Output: a moment report definition (drag-torque) on weapon_wall about the spin axis, published as the Workbench output parameter P2 drag-torque-op. Workbench labels this parameter's unit J, which is dimensionally equal to N·m. A monitor plot of this moment against iteration was saved for every run.

2.7 Design point sweep and automated reports

I first ran a single design point to set up the post-processing: the contours, streamlines, torque chart and units I wanted in each report. I then set up automated report generation from that template, so each design point saved its own report, and set every design point to retain its data. Appendix B contains the torque histories for every speed.

The sweep covered 15 speeds from 8,000 to 15,000 rpm in 500 rpm steps (DP 0 to DP 14), plus 0 rpm (DP 15) as a check that the torque is zero without rotation (Table 2). DP 0 (8,000 rpm) ran 529 iterations from the hybrid initialisation. Each later design point started from the DP 0 solution and ran 500 further iterations, ending at iteration 1,029. The design point results were saved about 6 minutes apart on 21 March 2026.

2.8 Convergence

I monitored the residuals during each run with a target of 10^{-3} to 10^{-4}. At the final iteration of every design point, the scaled momentum residuals were between 2.5×10^{-6} and 1.2×10^{-4}, the k and ω residuals were between 7.9×10^{-5} and 2.7×10^{-4}, and the continuity residual had fallen to between 3.9×10^{-4} and 6.0×10^{-4} of its peak value (Table A1 in Appendix A). The torque monitor (Figures B1 and B2) settles within about 100 iterations of each speed change, then varies by up to about ±2 % before settling to within about 1.5 % over the last 200 iterations; the variation is largest at the highest speeds.

3. CFD results

3.1 Drag torque against speed

Table 2 lists the drag torque from every design point. Fluent reports the moment as negative because it opposes the rotation; the table and the system model use its magnitude. The tip speed column uses the 0.1 m tip radius.

Table 2. CFD drag torque magnitude at each speed, with the quadratic fit of Equation (1).

Design point	Speed (rpm)	ω (rad/s)	Tip speed (mph)	CFD drag torque (N·m)	Fit, Eq. (1) (N·m)	Fit minus CFD (%)
DP 15	0	0.0	0.0	0	0.0000	0
DP 0	8,000	837.8	187.4	0.61176	0.6219	+1.7
DP 1	8,500	890.1	199.1	0.70524	0.7021	-0.5
DP 2	9,000	942.5	210.8	0.78930	0.7871	-0.3
DP 3	9,500	994.8	222.5	0.87815	0.8770	-0.1
DP 4	10,000	1,047.2	234.3	0.97709	0.9717	-0.6
DP 5	10,500	1,099.6	246.0	1.0712	1.0713	+0.0
DP 6	11,000	1,151.9	257.7	1.1719	1.1758	+0.3
DP 7	11,500	1,204.3	269.4	1.2867	1.2851	-0.1
DP 8	12,000	1,256.6	281.1	1.4020	1.3993	-0.2
DP 9	12,500	1,309.0	292.8	1.5206	1.5183	-0.2
DP 10	13,000	1,361.4	304.5	1.6518	1.6422	-0.6
DP 11	13,500	1,413.7	316.2	1.7811	1.7709	-0.6
DP 12	14,000	1,466.1	328.0	1.9025	1.9045	+0.1
DP 13	14,500	1,518.4	339.7	2.0403	2.0430	+0.1
DP 14	15,000	1,570.8	351.4	2.1712	2.1863	+0.7

From 8,000 to 15,000 rpm the torque increases by a factor of 3.55 for a speed increase of 1.875 times ($1.875^2 = 3.52$), close to the square law expected for aerodynamic drag. The 0 rpm design point returned exactly zero torque, as expected.

3.2 Drag torque fit

For the system model I fitted a square law through the origin to the CFD points (least squares, including the 0 rpm point):

$$T_d = k\,N^2, \quad k = 9.717 \times 10^{-9}\ \text{N·m/rpm}^2 \tag{1}$$

where N is the weapon speed in rpm. The fit is within 1.7 % of every CFD point (Table 2). Figure 2 shows the CFD points with Equation (1). A full second-order trendline fitted in the spreadsheet, $T = 9.65 \times 10^{-9} N^2 + 9.53 \times 10^{-7} N - 1.78 \times 10^{-3}$ ($R^2 = 1$ at the displayed precision), gives nearly the same curve; the time-step simulation uses Equation (1).

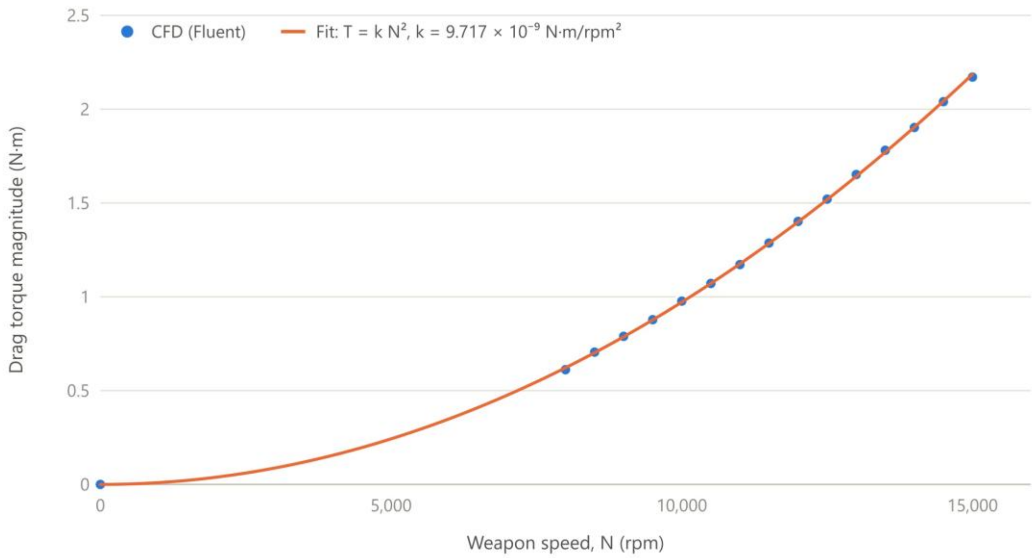

Figure 2. CFD drag torque magnitude against weapon speed, with the square-law fit of Equation (1).

3.3 Flow field

Each design point report also contains pressure contours on the weapon surface and air velocity streamlines. The velocity fields show an anomaly near the outer boundary (Section 5, limitation 4), so I read these plots only qualitatively and do not include them here.

The torque used in Section 4 is the integrated moment on weapon_wall and does not depend on these plots; I did not post-process the velocity fields to remove the anomaly.

4. System model (spin-up)

4.1 Motor, reduction and weapon inputs

The system model is a spreadsheet with three parts: the weapon and motor calculations (Tables 3 and 4), the CFD inputs and drag fit (Table 2 and Equation 1), and a time-step simulation (Table 5). The full spreadsheet is available here:

[Weapon Speed Analysis, Shear Force (Google Sheets)]

Table 3. System model inputs.

Parameter	Value	Units	Source or note
Weapon assembly moment of inertia, J	0.0091865073	$kg \cdot m^2$	From CAD: pulley and weapon assembly
Radius to tip, r	0.1	m	From CAD
Battery maximum voltage, V_{max}	50.4	V	12S (two 6S LiPo packs in series), 4.2 V per cell
Battery nominal voltage	44.4	V	12S, 3.7 V per cell
Motor K_v	950	rpm/V	Motor specification
No-load current, I_{nl}	5.1	A	Motor specification
Internal resistance	0.0049	Ω	Motor specification (not used in the model)
Maximum current, I_{max}	212	A	Limited by the motor
Pulley reduction, G	4	:1	Weapon pulley to motor pulley

4.2 Motor and weapon torque-speed curves

The motor torque constant follows from K_v:

$$K_t = \frac{60}{2\pi K_v} = 0.01005189 \text{ N·m/A} \tag{2}$$

The motor no-load speed and stall torque (current-limited at I_{max}) are:

$$N_{nl,m} = V_{max} K_v = 47{,}880 \text{ rpm} \tag{3}$$

$$T_{s,m} = (I_{max} - I_{nl}) K_t = 2.080 \text{ N·m} \tag{4}$$

Through the 4:1 pulley reduction, the weapon no-load speed and stall torque are:

$$N_{nl,w} = \frac{N_{nl,m}}{G} = 11{,}970 \text{ rpm} \tag{5}$$

$$T_{s,w} = G\, T_{s,m} = 8.319 \text{ N·m} \tag{6}$$

Treating the motor curve as linear, the torque available at the weapon at speed N is:

$$T_w(N) = T_{s,w} - s\,N, \quad s = \frac{T_{s,w}}{N_{nl,w}} = 0.00069498 \text{ N·m/rpm} \tag{7}$$

Table 4 lists the derived values at the spreadsheet's full precision.

Table 4. Derived motor and weapon values.

Quantity	Value	Units	Relation
Motor torque constant, K_t	0.01005189114	N·m/A	Equation (2)
Motor no-load speed, $N_{nl,m}$	47,880	rpm	Equation (3)
Motor stall torque, $T_{s,m}$	2.079736277	N·m	Equation (4)
Weapon no-load speed, $N_{nl,w}$	11,970	rpm	Equation (5)
Weapon stall torque, $T_{s,w}$	8.31894511	N·m	Equation (6)
Weapon torque-speed slope, s	0.000694982883	N·m/rpm	Equation (7)
Drag coefficient, k	$9.717054733 \times 10^{-9}$	N·m/rpm^2	Equation (1)

4.3 Time-step simulation

The simulation steps the weapon from rest (Table 5). At each step, the net torque is the weapon torque minus the drag torque, and the angular acceleration is the net torque divided by the inertia:

$$T_{net} = T_w(N) - T_d(N) \tag{8}$$

$$\alpha = \frac{T_{net}}{J} \tag{9}$$

I integrated with an explicit (Euler) step of Δt = 0.04 s for 500 steps (20 s):

$$\omega_{i+1} = \omega_i + \alpha_i \, \Delta t, \quad N = \frac{60\,\omega}{2\pi}, \quad v_{tip} = \omega\, r \tag{10}$$

Table 5 shows selected steps. At t = 0 the net torque equals the weapon stall torque, 8.319 N·m, which gives an initial angular acceleration of 8.319 / 0.00919 = 905.6 rad/s^2. The tip speed first reaches 220.20 mph at step 64 (t = 2.56 s).

Table 5. Time-step simulation, selected steps (Δt = 0.04 s; the full 500 steps are in the spreadsheet).

Step	t (s)	ω (rad/s)	Tip speed (mph)	Weapon speed (rpm)	Weapon torque (N·m)	Drag torque (N·m)	Net torque (N·m)	α (rad/s²)
0	0.00	0.0	0.00	0	8.319	0.000	8.319	905.6
1	0.04	36.2	8.10	346	8.079	0.001	8.077	879.3
2	0.08	71.4	15.97	682	7.845	0.005	7.841	853.5
5	0.20	170.8	38.21	1,631	7.185	0.026	7.160	779.4
10	0.40	317.4	71.01	3,031	6.212	0.089	6.123	666.5
20	0.80	548.8	122.76	5,241	4.677	0.267	4.410	480.0
30	1.20	714.3	159.78	6,821	3.579	0.452	3.127	340.3
40	1.60	831.0	185.89	7,935	2.804	0.612	2.192	238.6
50	2.00	912.5	204.13	8,714	2.263	0.738	1.525	166.0
63	2.52	982.4	219.76	9,381	1.799	0.855	0.944	102.7
64	2.56	986.5	220.68	9,421	1.772	0.862	0.909	99.0
75	3.00	1,022.9	228.82	9,768	1.530	0.927	0.603	65.6

Step	t (s)	ω (rad/s)	Tip speed (mph)	Weapon speed (rpm)	Weapon torque (N·m)	Drag torque (N·m)	Net torque (N·m)	α (rad/s²)
100	4.00	1,066.3	238.52	10,182	1.242	1.007	0.235	25.6
150	6.00	1,089.7	243.75	10,405	1.087	1.052	0.035	3.8
200	8.00	1,093.2	244.53	10,439	1.064	1.059	0.005	0.6
250	10.00	1,093.7	244.65	10,444	1.061	1.060	7.8×10^{-4}	0.1
500	20.00	1,093.8	244.67	10,445	1.060	1.060	5.8×10^{-8}	6.3×10^{-6}

4.4 Steady state

The weapon stops accelerating when the weapon torque equals the drag torque, $T_w(N) = T_d(N)$. With Equation (1) this is a quadratic in N:

$$N_{max} = \frac{-s + \sqrt{s^2 + 4\,k\,T_{s,w}}}{2k} = 10{,}444.71 \text{ rpm} \tag{11}$$

Without aerodynamic torque the weapon would reach its no-load speed of 11,970 rpm (280.40 mph at the tip); the drag lowers the top speed by 12.7 %.

4.5 Results

Table 6. System model results (J = 0.00919 kg·m², Δt = 0.04 s).

Quantity	Value	Units	Definition
Maximum tip speed	244.67	mph	Steady-state tip speed at N_{max} (109.38 m/s)
90 % of maximum tip speed	220.20	mph	0.9 × 244.67 mph
Time to 90 % of maximum tip speed	2.56	s	Time from rest until the tip speed first reaches 220.20 mph
Maximum weapon speed	10,444.71	rpm	Equation (11)

The spin-up time is quantised to the 0.04 s step. Repeating the integration with a 0.001 s step gives 2.58 s, so the step size changes the result by about 0.02 s. The spin-up time is directly proportional to the inertia J (the net torque is divided by J at every step), while the top speed does not depend on J. An earlier preliminary CAD inertia of 0.00576 kg·m^2 gave 1.60 s.

Figures 3 to 5 show the tip speed, angular acceleration and net torque against time for the first 10 s of the 20 s simulation. The tip speed rises like a first-order response, approximately

$$v_{tip}(t) \approx C_1\,(1 - e^{-C_2 t}) \tag{12}$$

although it is not exactly first order because the drag term is quadratic in speed. The net torque falls below 1 % of its initial value after 5.1 s.

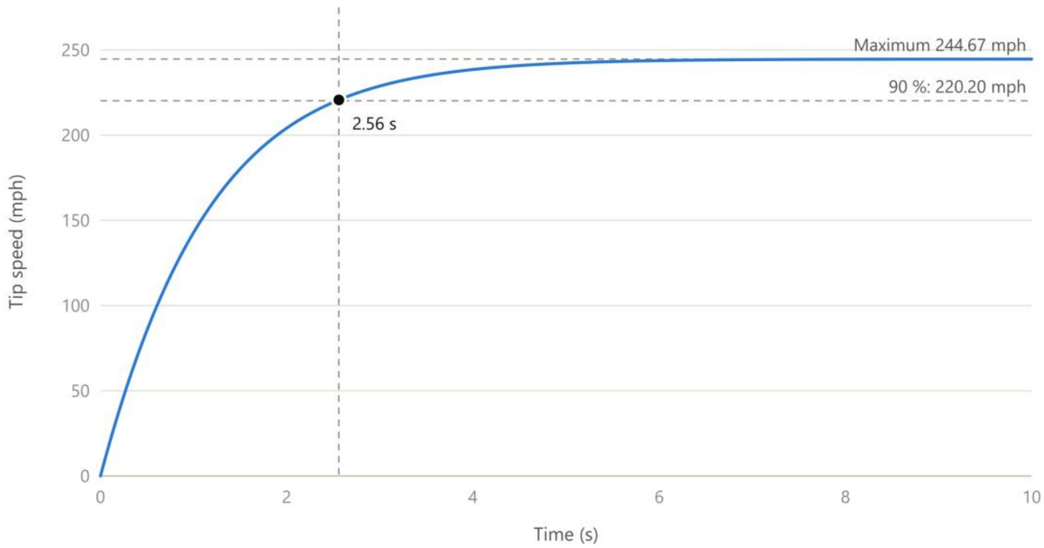

Figure 3. Tip speed against time, with the maximum (244.67 mph) and 90 % (220.20 mph) levels.

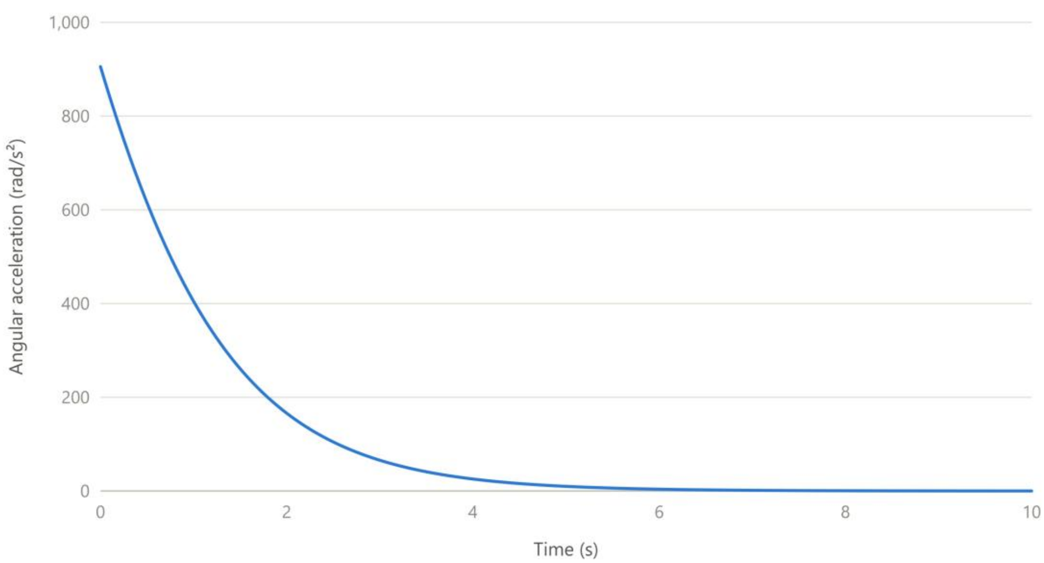

Figure 4. Weapon angular acceleration against time.

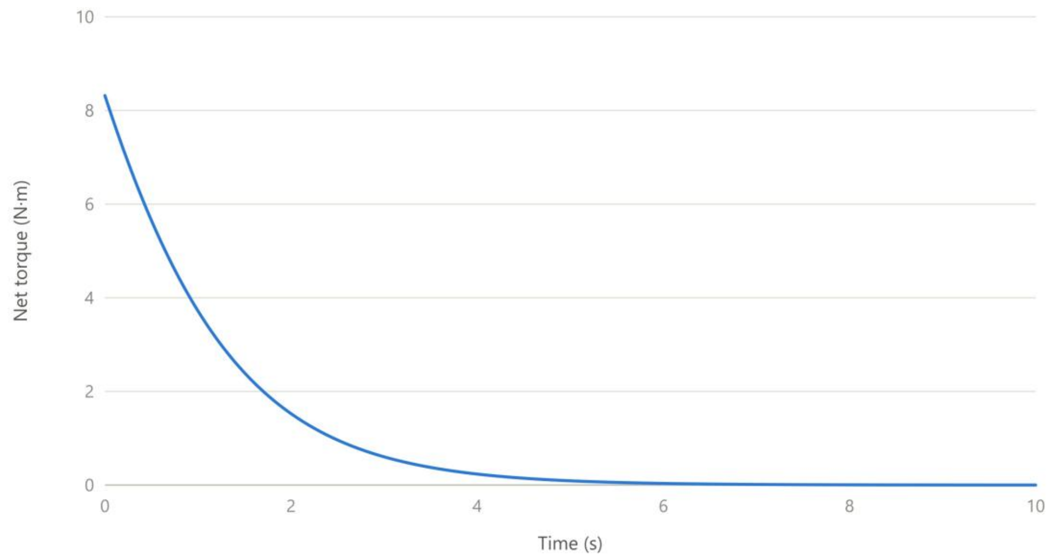

Figure 5. Net torque on the weapon against time.

As a check on the steady state, I plotted the weapon torque line (Equation 7) and the magnitude of the drag torque against angular velocity (Figure 6). The two curves meet at 1,093.8 rad/s, which is 10,444.71 rpm, matching Equation (11).

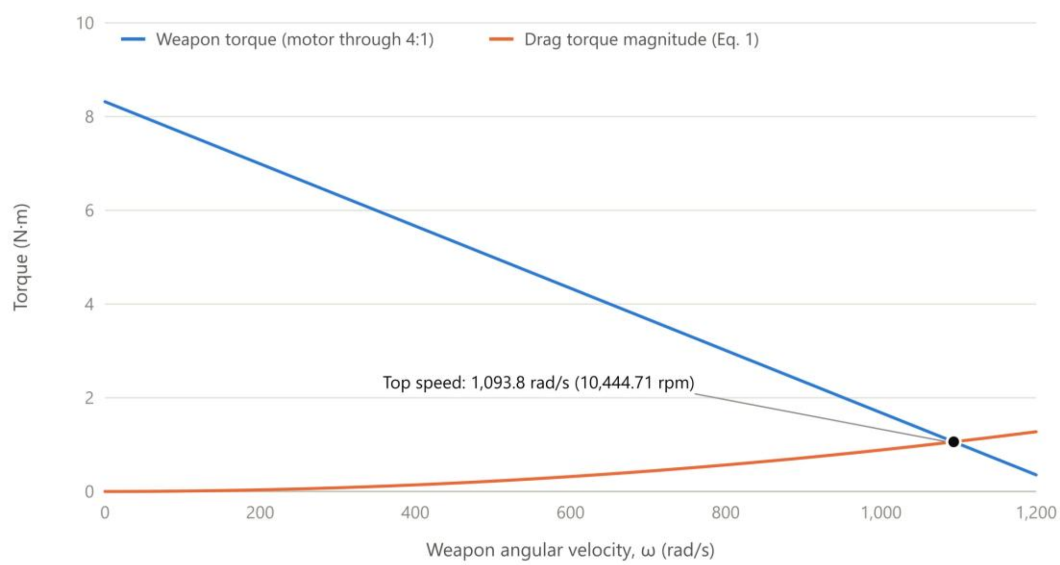

Figure 6. Torque against angular velocity: weapon torque (motor τ-ω curve through the 4:1 reduction) and drag torque magnitude. The crossing is the top speed.

5. Discussion and limitations

The predicted top tip speed of 244.67 mph is above the 240 mph target and below the 250 mph limit. The margin to the limit is 5.33 mph (2.2 %). The limitations below are not quantified, and a 2.2 % margin is too small to rely on the model alone, so the weapon's real top speed needs to be measured. The main limitations are:

1. **Steady rotating frame.** The frame-motion model treats the flow as steady in the weapon's frame. It does not resolve unsteady effects such as vortex shedding from the blades or the wake interacting with the next blade. I did not run a transient (sliding mesh) case to check the steady result.
2. **Mesh.** All results come from one mesh of 412,013 elements. I did not run a mesh independence study, and the element quality and near-wall resolution were not recorded, so I cannot quantify the discretisation error in the torque.
3. **Convergence.** The residuals met the 10^{-3} target, but the torque monitor still varies by up to about 1.5 % over the last 200 iterations at the highest speeds (Section 2.8). This is small compared with the other limitations here.
4. **Domain and outer wall.** The model contains the weapon assembly alone in a cylindrical enclosure, without the chassis, the arena floor or walls, all of which would change the flow around a real robot. In every design point report, the peak air speed on the velocity plots is exactly proportional to rotation speed (0.1403 mph per rpm, from 1,192.6 mph at 8,500 rpm to 2,104.6 mph at 15,000 rpm). That equals rigid rotation at a radius of about 0.60 m, far outside the 0.1 m weapon tip, so the peak sits at the enclosure boundary rather than near the weapon (Figure 1 shows the size of the weapon relative to the domain). This is consistent with the outer wall moving with the rotating frame, which the exported reports cannot confirm or rule out. If the outer wall does rotate with the frame, it drives the surrounding air into rotation, which would likely reduce the computed drag torque; I have not quantified this.
5. **Forces not evaluated.** Only the moment about the spin axis was extracted. The angled blades also produce an axial force (lift), which the model does not report.
6. **Drag fit range.** The CFD covers 8,000 to 15,000 rpm; below 8,000 rpm the fit of Equation (1) is anchored only by the 0 rpm point. The weapon is below 8,000 rpm for about the first 1.6 s of the spin-up, where the drag torque is at most about 0.62 N·m against a weapon torque of 2.7 N·m or more, so the error from extrapolation has a limited effect on the spin-up time.
7. **Motor model.** The motor curve is a straight line between the current-limited stall torque and the no-load speed at the full-charge voltage of 50.4 V. The model does not include voltage sag, battery or motor internal resistance (0.0049 Ω is listed but not used), ESC current limits, belt and pulley losses or bearing friction. Each of these reduces the torque available, so the predicted top speed and spin-up time are both optimistic.
8. **Inertia.** The inertia of 0.00919 kg·m^2 comes from the CAD model of the pulley and weapon assembly and has not been checked against the built parts. The spin-up time of 2.56 s scales in direct proportion to the inertia (a 10 % higher inertia gives a 10 % longer spin-up), while the top speed is unaffected.

6. Conclusions and recommendations

6.1 Conclusions

- The CFD drag torque on the angled drisk rises from 0.612 N·m at 8,000 rpm to 2.171 N·m at 15,000 rpm and follows a square law, $T_d = 9.717 \times 10^{-9} N^2$ (N in rpm), to within 1.7 %.
- With the 4:1 reduction and a 950 rpm/V motor at 50.4 V, the predicted top speed is 10,444.71 rpm, a tip speed of 244.67 mph. Aerodynamic torque reduces the top speed by 12.7 % from the 11,970 rpm no-load weapon speed.
- The predicted time from rest to 90 % of the maximum tip speed (220.20 mph) is 2.56 s for an inertia of 0.00919 kg·m^2.
- The predicted top speed meets the 240 mph target and is under the 250 mph limit, but the 2.2 % margin to the limit is small compared with the unquantified modelling errors in Section 5.

6.2 Recommendations

1. Run a mesh independence study at one speed near the predicted top speed (10,500 rpm), with at least two refinements, and record element quality.
2. Run one transient sliding-mesh case at the same speed to check the steady rotating-frame torque.
3. Confirm the outer wall condition, enlarge the domain, and add the chassis and floor to see how much they change the torque.
4. Check the CAD inertia against the built weapon assembly and rerun the spin-up if it differs.
5. Add battery and motor internal resistance, voltage sag, and belt efficiency to the motor model.
6. Measure the weapon's spin-up on the robot (for example, weapon speed against time from a tachometer or high-speed video) and compare it with Table 6.

6.3 Data

- Spreadsheet (motor model, CFD inputs and time-step simulation): Weapon Speed Analysis, Shear Force, Google Sheets (link in Section 4.1).
- Ansys Workbench and Fluent 2025 R2 project: design points DP 0 to DP 15, with a CFD-Post report and solution monitor for each, 21 March 2026.

Appendix A. Per-design-point results

Table 2 gives the torque at each speed. Table A1 gives the final residuals from the Fluent solution monitors. The momentum, k and ω values are the scaled residuals at the last iteration (for momentum, the largest of the three components). The continuity value is the residual at the last iteration divided by its peak value during the run.

Table A1. Iterations and final residuals for each design point.

Design point	Speed (rpm)	Final iteration	Continuity (relative to peak)	Momentum (max of x, y, z)	k	ω
DP 0	8,000	529	5.3×10^{-4}	1.2×10^{-4}	2.6×10^{-4}	1.7×10^{-4}
DP 1	8,500	1,029	3.9×10^{-4}	5.6×10^{-5}	1.3×10^{-4}	8.2×10^{-5}
DP 2	9,000	1,029	4.1×10^{-4}	5.8×10^{-5}	1.3×10^{-4}	8.2×10^{-5}
DP 3	9,500	1,029	4.7×10^{-4}	5.9×10^{-5}	1.4×10^{-4}	8.5×10^{-5}
DP 4	10,000	1,029	4.8×10^{-4}	6.1×10^{-5}	1.4×10^{-4}	8.3×10^{-5}
DP 5	10,500	1,029	5.0×10^{-4}	6.2×10^{-5}	1.5×10^{-4}	7.9×10^{-5}
DP 6	11,000	1,029	5.0×10^{-4}	6.3×10^{-5}	1.5×10^{-4}	8.3×10^{-5}
DP 7	11,500	1,029	5.1×10^{-4}	6.5×10^{-5}	1.6×10^{-4}	8.1×10^{-5}
DP 8	12,000	1,029	5.4×10^{-4}	6.6×10^{-5}	1.6×10^{-4}	8.5×10^{-5}
DP 9	12,500	1,029	5.8×10^{-4}	6.7×10^{-5}	1.7×10^{-4}	9.1×10^{-5}
DP 10	13,000	1,029	5.9×10^{-4}	6.8×10^{-5}	1.7×10^{-4}	9.6×10^{-5}
DP 11	13,500	1,029	6.0×10^{-4}	7.0×10^{-5}	1.7×10^{-4}	9.5×10^{-5}
DP 12	14,000	1,029	5.4×10^{-4}	7.1×10^{-5}	1.7×10^{-4}	9.5×10^{-5}
DP 13	14,500	1,029	5.1×10^{-4}	7.1×10^{-5}	1.8×10^{-4}	1.0×10^{-4}
DP 14	15,000	1,029	4.7×10^{-4}	7.2×10^{-5}	1.8×10^{-4}	9.3×10^{-5}

DP 0 ran from the hybrid initialisation to iteration 529. DP 1 to DP 14 each started from the DP 0 solution and ran to iteration 1,029. DP 15 (0 rpm) ran 5 iterations and returned zero torque.

Appendix B. Torque convergence histories

Figure B1 shows the torque monitor against iteration at 10,500 rpm (DP 5), the design point closest to the predicted top speed. Figure B2 shows the same monitor for every speed from 8,000 to 15,000 rpm.

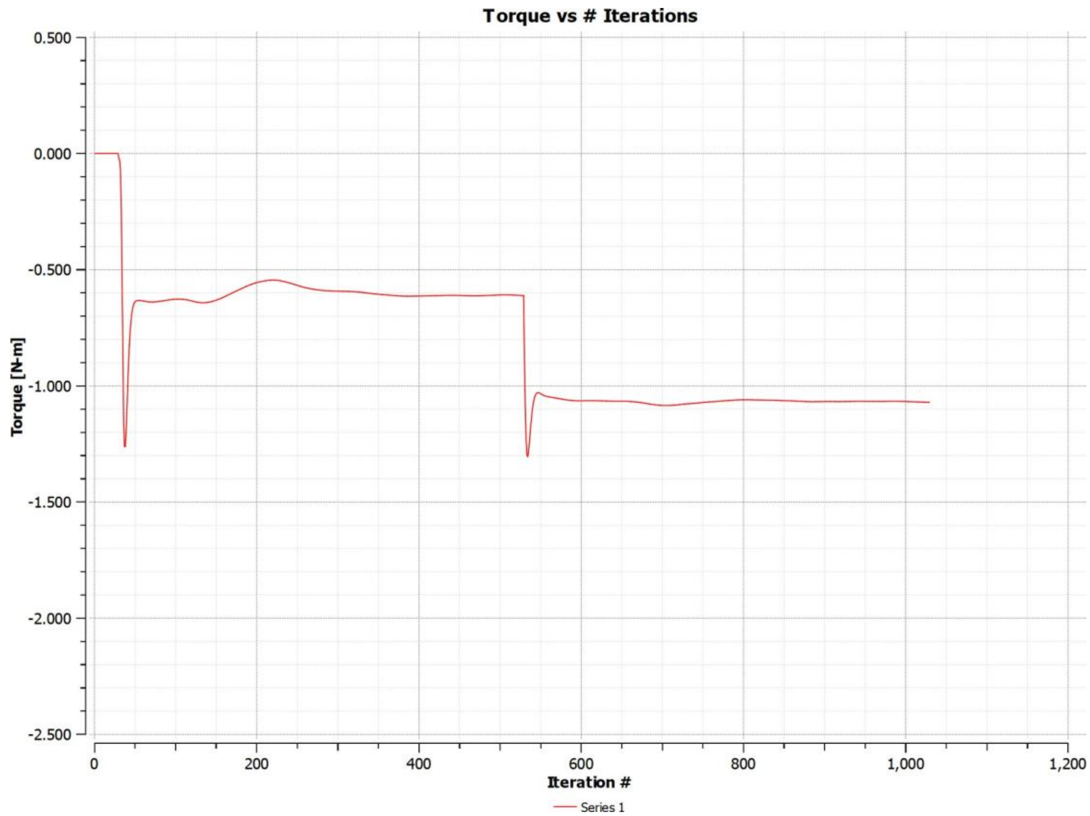

Figure B1. Torque monitor against iteration at 10,500 rpm. Iterations 1 to 529 are the DP 0 (8,000 rpm) solution this run started from.

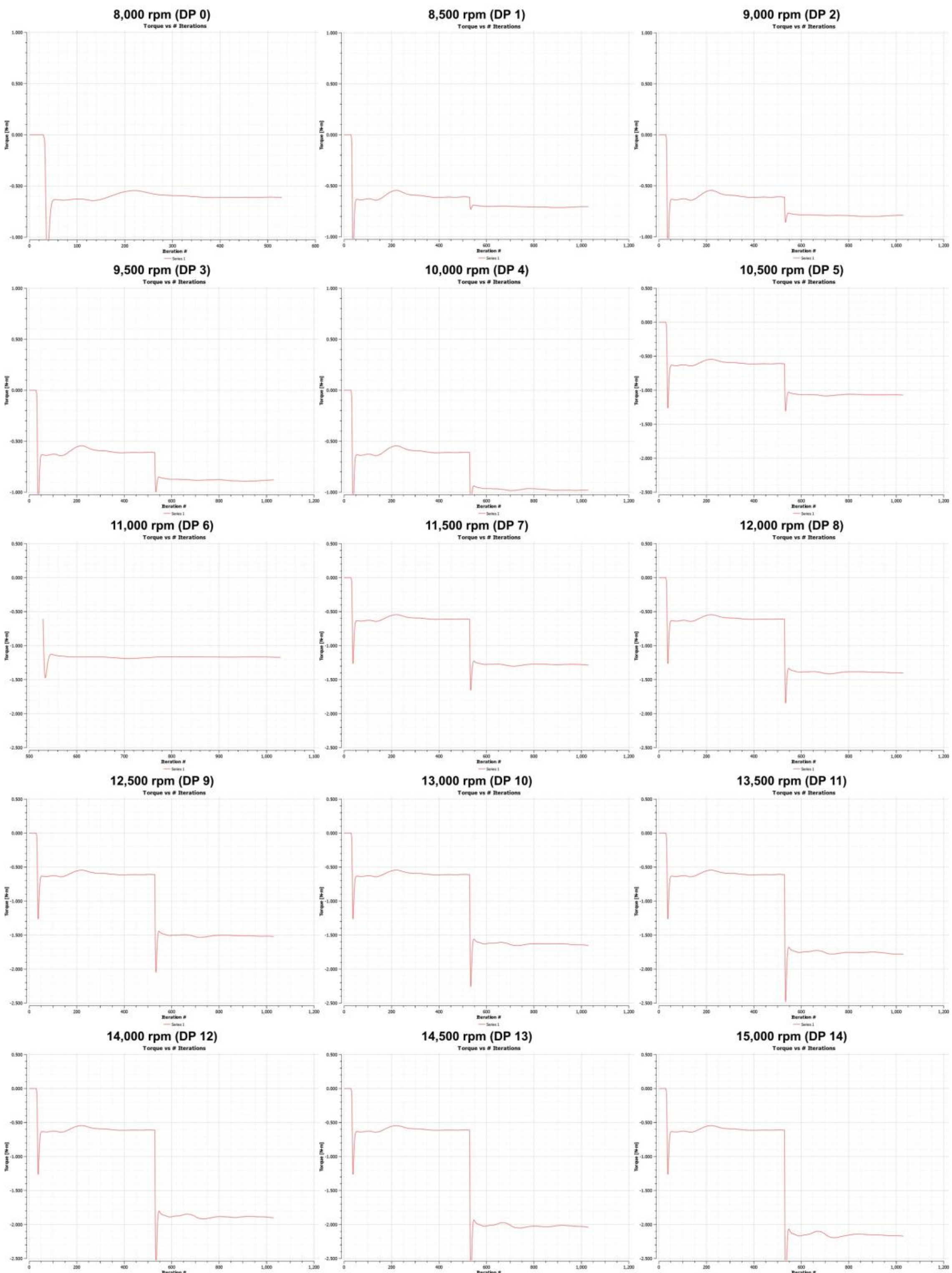

Figure B2. Torque monitor against iteration for every speed from 8,000 to 15,000 rpm. In each run after DP 0, the first 529 iterations are the DP 0 solution (the 11,000 rpm plot starts its axis at iteration 500).