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Steadier Drone Payloads for Gimbal and UAV Engineers

A finite-element modal study of a drone gimbal yoke shows that the line-of-sight mode is a torsion mode, and that section shape beats added material.

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Method
Three-dimensional frame finite-element modal analysis

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Abstract

Structural modes of a drone gimbal's payload yoke limit how hard the stabilization loop can be pushed. We model a representative aluminum U-yoke carrying a 0.3 kg payload with three-dimensional frame finite elements, classify modes by their effect on the line of sight, and compare design changes within a 15 g budget. The model reproduces exact cantilever bending and torsion frequencies to better than 0.01 %.

The first line-of-sight mode is a 166 Hz fore-aft pitch swing governed by crossbar torsion. Corner gussets of 15 g raise it to 191 Hz and a thicker crossbar of the same added mass to 197 Hz, while a closed box crossbar of unchanged mass reaches 237 Hz. A heavier 0.45 kg payload lowers the baseline mode to 136 Hz. Section shape, not added material, is the efficient lever.

Keywords: gimbal, payload yoke, modal analysis, finite element, line of sight, torsion

1. Introduction

A two-axis drone gimbal holds its camera in a U-shaped yoke: a crossbar on the pan motor and two arms carrying the payload on the tilt axis. The yoke's lowest structural modes sit inside or near the bandwidth that a stabilization loop needs, and a mode that rotates the line of sight limits how hard the loop can be pushed [1]. Designers usually respond by adding material where the yoke looks weak, typically gussets at the corners. This paper uses a finite-element model of a representative yoke to ask which mode limits line-of-sight stability and which change raises it most for a fixed mass budget.

2. Model and Method

The yoke (Figure 1) is aluminum 6061-T6 ($E = 68.9$ GPa, $G = 26$ GPa, 2,700 kg/m^3). The crossbar spans 110 mm and is a 22 × 8.73 mm flat bar, clamped at its center by the pan motor. The arms are 75 mm long, 16 mm fore-aft by 4 mm thick. The payload (0.3 kg, moments of inertia 4.5, 3.0 and 3.0 × 10^{-4} kg·m² about the roll, pitch and yaw axes) is a rigid body joined to both arm tips, with the tilt motor treated as locked. Each member is meshed with 12 three-dimensional Euler–Bernoulli frame elements (12 degrees of freedom each) with consistent mass [2]; torsion constants follow Roark for rectangular and thin-walled closed sections [4]. Natural frequencies and mode shapes come from the generalized eigenproblem

$$K\varphi = \omega^2 M\varphi \tag{1}$$

and modes are classified by the payload motion they produce: rotation about the pitch axis moves the line of sight, while lateral sway with roll tilts the horizon. Five design variants are compared, all within 15 g of the 83 g baseline yoke: corner gussets (modeled as four times the bending and torsional stiffness over 15 mm of each member at each corner, plus 7.5 g per corner); a thicker flat-bar crossbar using the same 15 g; a closed box crossbar (22 × 21.4 mm, 2.5 mm wall) of the same mass as the flat bar; and the same box with 15 g more wall material.

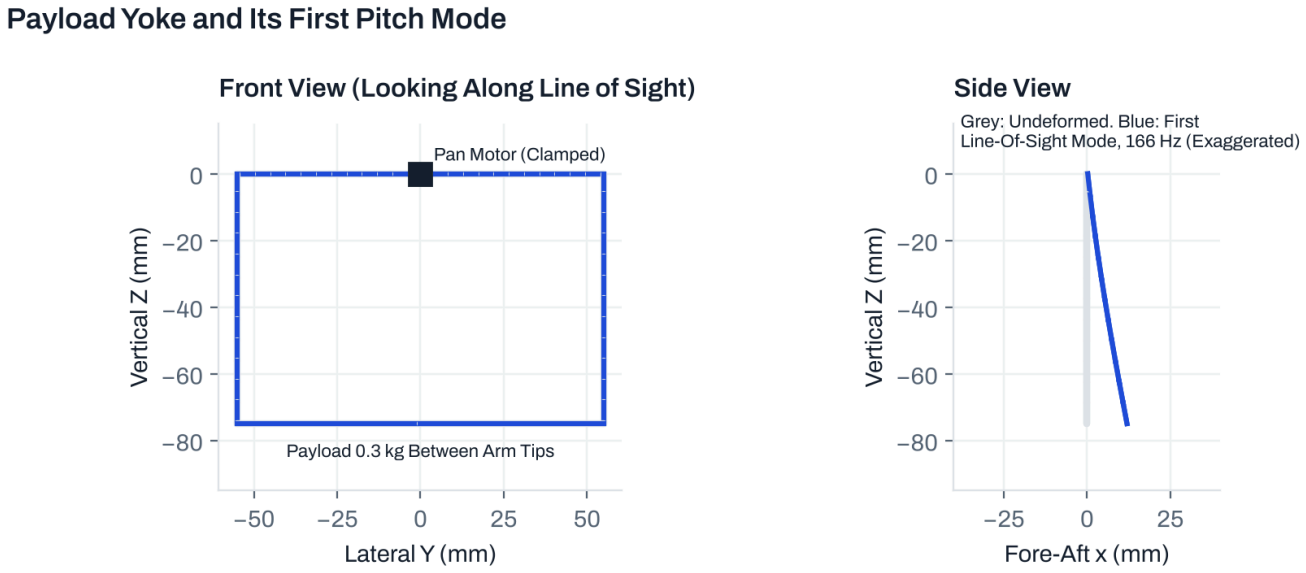

Figure 1. Reference payload yoke and its first line-of-sight mode at 166 Hz. Grey: undeformed; blue: mode shape (exaggerated). The payload swings fore-aft as the crossbar twists, which the gyro sees as pitch.

3. Verification

Check	Reference	Result
Cantilever, first two bending modes	Exact $(1.875)^2$ and $(4.694)^2$ solutions [3]	102.00 / 639.2 Hz against 102.00 / 639.2 Hz
Torsion of a bar with tip inertia	$\sqrt{(GJ/(LI_p))}/2\pi$ [5]	525.8 against 525.8 Hz
Mesh convergence, pitch mode	6, 12 and 24 elements per member	166.0, 166.0, 166.0 Hz

Table 1. Verification of the frame finite-element model.

4. Results

4.1 Baseline Modes

The baseline yoke's two lowest modes are a lateral sway with roll at 141 Hz and a fore-aft pitch swing at 166 Hz (Figure 1). The pitch mode is the one a pitch-rate gyro sees; it is governed by crossbar torsion, with the arms bending fore-aft about their roots. The pan (yaw) mode is much higher, 695 Hz.

Variant	Yoke mass (g)	Sway and roll (Hz)	Pitch, line of sight (Hz)	Yaw (Hz)
Flat-bar crossbar (baseline)	83	141	166	695
Corner gussets, +15 g	98	164	191	732
Thicker flat bar, +15 g	98	152	197	770
Box crossbar, same mass	83	162	237	885
Box crossbar, +15 g	98	164	253	956
Heavier payload, 0.45 kg	83	116	136	579

Table 2. Natural frequencies of the yoke variants with a 0.3 kg payload (0.45 kg in the last row).

4.2 Design Variants Within a 15 g Budget

Fifteen grams of corner gussets raise the pitch mode by 15 %, to 191 Hz, and spending the same mass on a thicker crossbar does slightly better, 197 Hz (Figure 2). Changing the crossbar from a flat bar to a closed box of the same mass raises it by 42 %, to 237 Hz, because the box's torsion constant is 4.8 times that of the flat bar. Adding the 15 g to the box gives 253 Hz. The box also lifts the sway mode to 162 Hz. Because the gusset model represents a stiffened corner by a stiffness factor, we varied it: the pitch mode is 181 Hz at twice the corner stiffness, 191 Hz at four times (the value used) and 199 Hz for an effectively rigid 15 mm corner. Rigid corners extending 25 mm, about 42 g of gusset plate if area scales with leg length squared, reach 232 Hz, still below the box crossbar at no added mass.

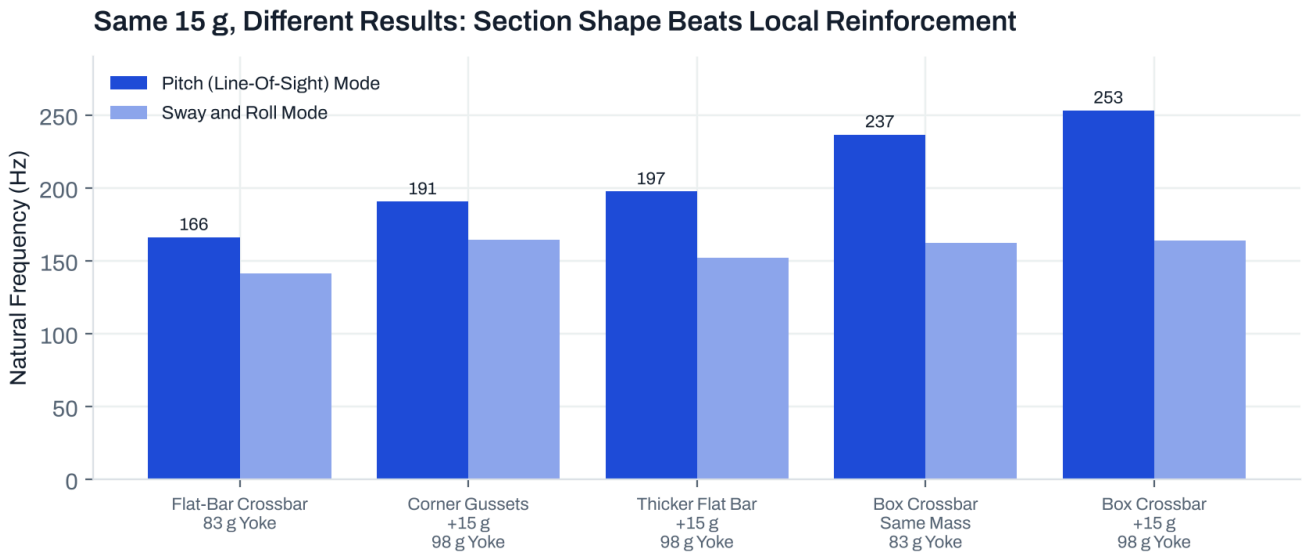

Figure 2. Pitch (line-of-sight) and sway modes for the baseline yoke and four variants, with yoke mass. Corner gussets and a thicker bar spend 15 g; the box crossbar of the same mass changes only the section shape.

4.3 Effect of Payload Mass

Payload mass moves the mode as much as any of these changes (Figure 3). Going from 0.3 to 0.45 kg lowers the baseline pitch mode to 136 Hz; the box yoke with the heavier payload, 194 Hz, still sits above the baseline yoke with the original payload.

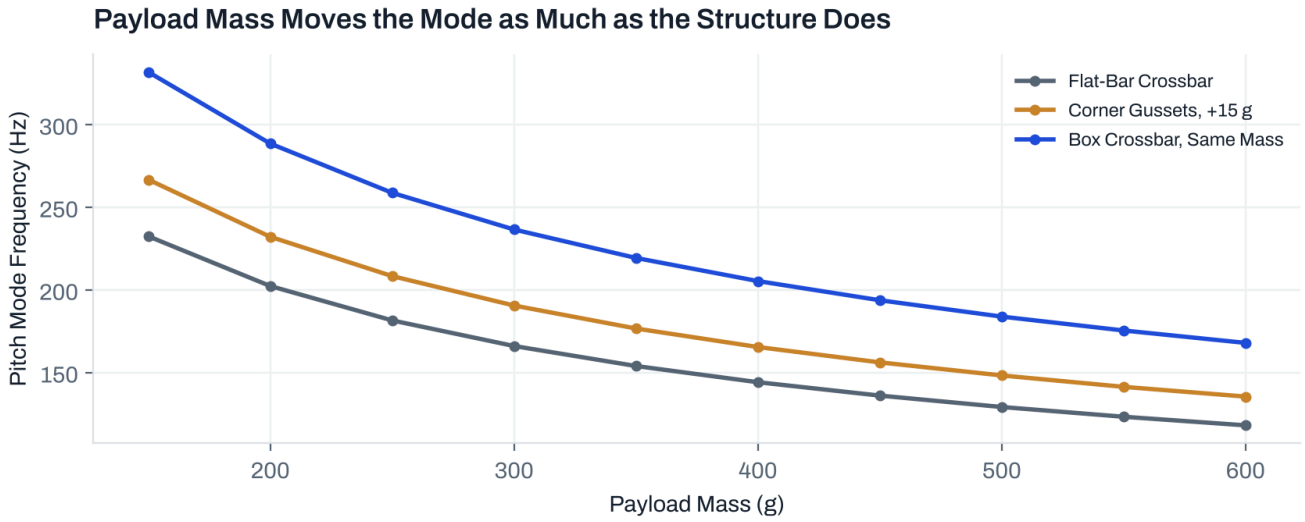

Figure 3. Pitch mode frequency against payload mass (inertia scaled with mass) for the flat-bar baseline, corner gussets and the box crossbar.

5. Discussion

The line-of-sight mode of this yoke is a torsion mode, and torsional stiffness of thin open sections is poor: it grows with the cube of the thin dimension, while a closed section carries torsion by shear flow around its perimeter. Local reinforcement at the corners treats the symptom where the yoke looks weak, not the member that actually twists. For a stabilization loop with a crossover of a few tens of hertz, a higher and cleaner mode means less reliance on notch filters, which lose effectiveness if the mode shifts with payload or temperature [1]. Our companion controls study [6] finds that, for a 50 Hz pointing loop, the box crossbar's 237 Hz mode is gain-stabilized and restores near rigid-body

margins, while the 191 Hz gusseted mode is not. The payload sweep shows why that matters: a gimbal sold for several payloads should be checked at the heaviest one.

Limitations. Beam elements represent the members; joints are rigid and fasteners, bearings and the motor's own compliance are not modeled. The tilt motor is locked, so the servo stiffness that sets the tilt-axis mode is not included. Gussets are represented by an equivalent stiffness factor rather than a shell model; the sensitivity in Section 4 bounds this choice. Damping, which sets mode peak height, is not computed. A modal test of a built yoke should confirm the ranking before the design is frozen.

6. Conclusions

1. The first line-of-sight mode of the reference yoke is a 166 Hz pitch swing governed by crossbar torsion.
2. Fifteen grams of corner gussets raise it to 191 Hz; a box crossbar of the same mass as the flat bar raises it to 237 Hz with no added mass.
3. Increasing payload from 0.3 to 0.45 kg lowers the baseline mode to 136 Hz, so modal checks should use the heaviest supported payload.

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