A Comprehensive Analysis of the Mahogany Aerodynamic High-Altitude Stabilizer (MAHAS): First-Principles Aeromechanical Modeling, Scaling Boundaries, and High-Altitude Deployment Applications

Gowtham Krishna R

Independent Researcher

Abstract

This paper presents the aeromechanical modelling, first-principles mathematical derivations, and engineering applications of the Mahogany Aerodynamic High-Altitude Stabilizer (MAHAS), a novel bio-inspired passive descent modulator. Designed as an engine-less stabilization mechanism for payload drops and ejecting capsules, MAHAS mimics the highly optimized passive autorotation of *Swietenia* (mahogany) seeds. Traditional deceleration systems, such as parachutes, frequently suffer from structural collapse, chaotic tumbling, or deployment failure in thin, low-density high-altitude environments. MAHAS overcomes these challenges by exploiting an asymmetric mass offset and twisted air foil morphology to convert gravitational potential energy into rotational kinetic energy, establishing a stable vertical descent trajectory without active propulsion. This investigation details the mathematical formulation of the center-of-mass offset using a Dual-Mass Point (DMP) representation, the integration of aerodynamic torque through Blade Element Momentum Theory (BEMT), and the vertical force balance under the Yasuda–Azuma multi-axis equilibrium. Additionally, stereoscopic Digital Particle Image Velocimetry (DPIV) and Direct Numerical Simulation (DNS) validate the attachment of a leading-edge vortex (LEV) stabilized by centripetal and Coriolis accelerations. Aeromechanical scaling limits are analysed, identifying a critical performance boundary at an 8:1 scale ratio where high-Reynolds-number turbulent transitions necessitate strict wing-loading and spin-rate constraints. Finally, the paper demonstrates the integration of the MAHAS architecture into high-altitude environmental sensor drops, fighter jet emergency ejection seats, planetary re-entry capsules, and urban high-rise rescue pods.

I.INTRODUCTION

High-altitude payload drops, planetary atmospheric re-entry, and emergency crew ejection systems present severe aeromechanical challenges. In thin, low-density upper-atmospheric environments, conventional drag-based deceleration systems—such as parachutes—frequently experience catastrophic failures, including canopy collapse, fabric tearing, and chaotic tumbling due to insufficient dynamic pressure. Furthermore, active propulsion and powered stabilization thrusters introduce significant weight, complexity, and mechanical failure points, limiting their viability for lightweight or zero-power recovery operations.

To overcome these constraints, bio-inspired passive flight mechanics offer a highly efficient alternative. In nature, winged samaras—specifically seeds belonging to the genus *Swietenia* (mahogany)—utilize uniaxial passive autorotation to slow their rate of descent and maximize dispersal distance. By converting gravitational potential energy into rotational kinetic energy, *Swietenia* samaras establish a stable, non-tumbling helical descent trajectory. This rapid autorotation generates a stably attached Leading-Edge Vortex (LEV) across the wing span, producing high lift coefficients at extreme angles of attack without experiencing aerodynamic stall.

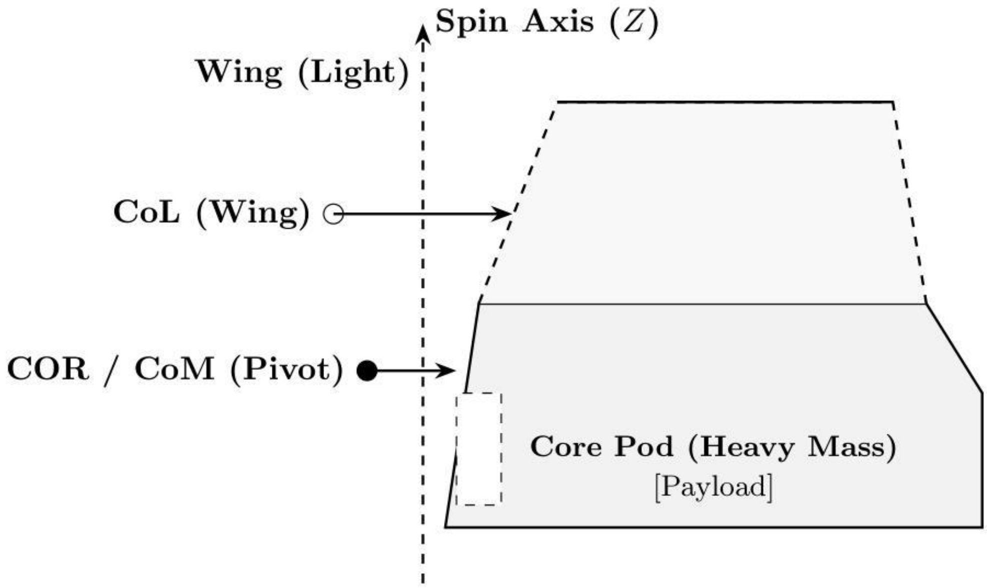
This paper introduces the Mahogany Aerodynamic High-Altitude Stabilizer (MAHAS), an engine-less, rigid stabilization architecture designed to scale the biomechanical mechanisms of *Swietenia* seeds into industrial and aerospace applications. The primary contributions of this work are fourfold:

1. **First-Principles Aeromechanical Modeling:** Formulating a Dual-Mass Point (DMP) framework to mathematically define the center of mass offset between the heavy payload pod and the light aerodynamic wing.
2. **Multi-Axis Equilibrium Integration:** Applying Blade Element Momentum Theory (BEMT) alongside the Yasuda-Azuma force and moment integrals to solve vertical force balance, rotational torque, and coning angle equilibrium.
3. **Fluid Dynamic Vortex Characterization:** Examining the spanwise flow and centripetal/Coriolis acceleration fields that stabilize the Leading-Edge Vortex (LEV) across varying wingspan regions.
4. **Fluid Dynamic Scaling Boundaries:** Defining critical Reynolds number (Re) transitions and identifying the operational limits up to an 8:1 scale ratio.

Finally, this investigation demonstrates the deployment of MAHAS across high-altitude environmental sensor drops, fighter jet emergency ejection systems, urban high-rise rescue pods, and planetary re-entry capsules.

II. **BIOMECHANICAL MORPHOLOGY OF THE *SWIETENIA* SAMARA**

The passive dispersal of winged seeds, or samaras, is a highly evolved botanical survival strategy designed to maximize the landing distance from the parent tree canopy. Unlike pappose diaspores that rely purely on drag-based deceleration, winged samaras utilize lift-generating aerodynamic structures to slow their rate of descent. The mahogany seed, belonging to the genus Swietenia (specifically Swietenia macrophylla and Swietenia mahagoni), is a premier biological model of uniaxial passive autorotation.



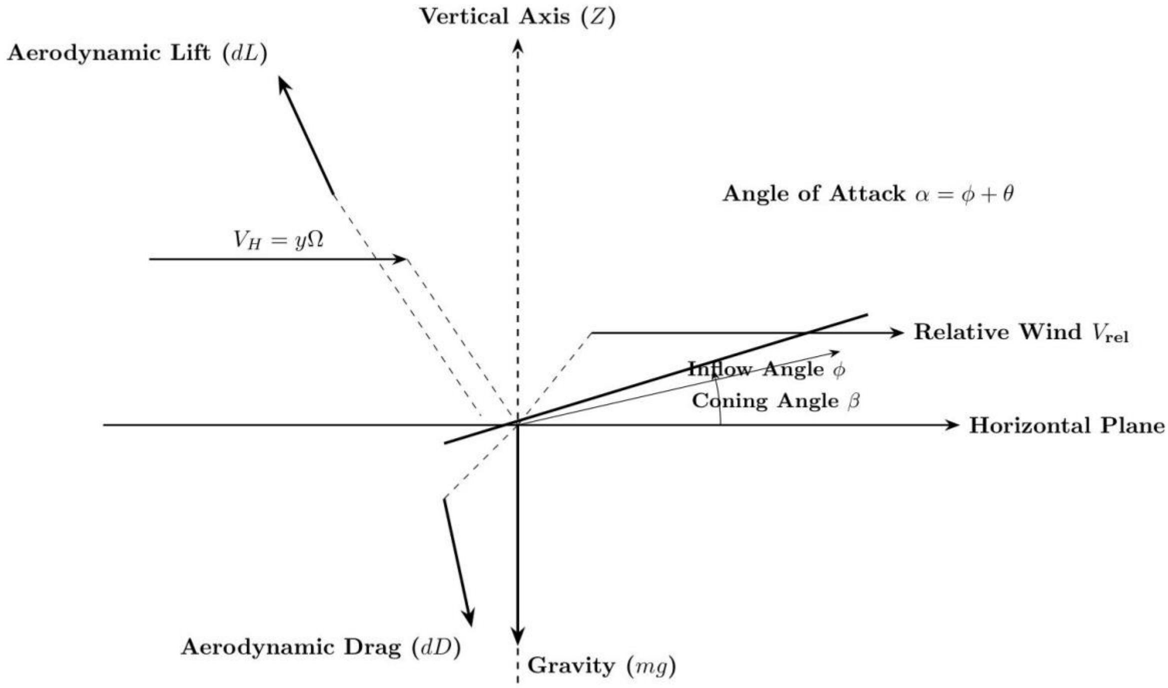
The morphological structure of the *Swietenia* samara is characterized by pronounced physical asymmetry. It consists of a dense, compact basal seed core containing the embryo and an elongated, papery, twisted wing extending laterally from the core. This asymmetrical layout concentrates the majority of the seed's mass at the base, shifting the center of gravity (CG) far from the geometric centroid of the wing. This mass distribution creates a dual-mass system, which can be analytically modeled using a Dual-Mass Point (DMP) framework. Within this framework, the concentrated seed core acts as the primary mass point, while the leading edge of the wing represents a secondary distributed mass line.

During descent, the *Swietenia* samara does not tumble randomly. Instead, it establishes a stable gyration about a vertical spin axis that passes very close to its center of mass, slightly displaced toward the left. This displacement generates a centrifugal force acting horizontally, which is balanced by the horizontal aerodynamic forces acting on the wing. The wing maintains a nearly constant inclination relative to the horizontal plane, known as the coning angle (β), which averages approximately 16° in natural mahogany seeds.

The wing of the *Swietenia* samara is not flat. It possesses a distinct camber and a twist that varies continuously from the root to the tip, forming an aerodynamic blade with a downwardly convex mean camber line near the wing root. This downwardly convex camber near the center of gravity is critical for generating the initial aerodynamic driving torque, enabling rapid rotational initiation while maintaining a low rate of descent.

III.CORE PHYSICS AND MATHEMATICAL FRAMEWORK

To translate the passive biomechanical flight of the Swietenia seed into a viable engineering platform (MAHAS), the physical parameters must be derived from first principles. The dynamic model is developed using rigid-body rotational mechanics and fluid dynamics.



3.1. Center of Mass Offset

The center of mass offset is the primary driver of rotational torque and gyroscopic stability in the MAHAS system. Let the system be represented by a Dual-Mass Point (DMP) model, where the heavy, compact core pod of mass $M_{po}d$ is centered at the coordinate origin ($x_{po}d = 0$), and the lightweight aerodynamic wing of mass $M_{(wing)}$ extends along the x-axis with its geometric centroid located at $x_{(centroid)} = \frac{R}{2}$, where R is the total wingspan.

The center of gravity ($x_{(CG)}$) of the combined system along the spanwise axis Is given by:

$$Xcg = \frac{Mpodxpod + Mwingxcentroid}{Mpod + Mwing}$$

$$= \frac{Mwing\left(\frac{R}{2}\right)}{Mpod + Mwing}$$

The center of mass offset ($r_{(offset)}$) is defined as the absolute physical distance between the geometric centroid of the wing ($x_{(centroid)}$) and the center of gravity ($x_{(CG)}$) of the combined system:

$$Roffset = xcentroid - xCG$$

$$Roffset = \frac{R}{2} - \frac{\left[Mwing\left(\frac{R}{2}\right)\right]}{Mpod + Mwing}$$

Factoring out the term representing the geometric centroid of the wing yields the final first-principles formulation for the center of mass offset:

$$Roffset = \left(\frac{R}{2}\right)\left[1 - \frac{Mwing}{Mpod + Mwing}\right]$$

$$= \left(\frac{R}{2}\right)\left[\frac{Mpod}{Mpod + Mwing}\right]$$

This derivation demonstrates that as the mass of the core pod increases relative to the wing ($M_{pod} \gg M_{(wing)}$), the center of mass offset ($r_{(offset)}$) approaches its maximum theoretical value of R/2. This larger offset increases the moment arm available for aerodynamic torque generation, thereby enhancing passive autorotation, gyroscopic stability, and descent control in the MAHAS system.

3.2 Aerodynamic Torque

The macro-scale aerodynamic torque (τ) acting on the rotating wing assembly about the vertical axis is modeled using a standard dimensionless torque coefficient (Cq):

$$T = ½\rho v^2 SCq$$

Where ρ is the local atmospheric density, v is the vertical descent velocity, S is the projected surface area of the wing, and Cq is the torque coefficient.

To bridge this macro-scale equation with the micro-scale physics of the wing, the net torque is also formulated by integrating the aerodynamic forces acting along the span. Let dL(y) and dD(y) represent the infinitesimal lift and drag forces acting on a wing section of width dy at a radial distance y from the spin axis. If the wing is inclined at a coning angle β and the relative wind is at an inflow angle φ, the net rotational driving force per unit span is:

$$dL \sin\varphi - dD \cos\varphi$$

The total aerodynamic torque is the spanwise integral of this driving force multiplied by the moment arm y cos β:

$$T = \int_{-Yb}^{Yt} (dLsin\,\varphi - dDcos\,\varphi)ycos\,\beta\,dy$$

Where $-Y_\beta$ is the root distance from the spin axis and Y_t is the tip distance, such that the total wing span $b_{(span)} = Y_\beta + Y_t$. At steady-state terminal descent, the accelerating torque generated by lift precisely balances the resisting torque generated by profile drag, yielding a net torque of zero ($\tau = 0$), which maintains a constant angular velocity (Ω).

3.3 Terminal Velocity Equilibrium

At terminal velocity, the gravitational force acting on the total mass ($Fg = mg$) is perfectly balanced by the vertical components of the aerodynamic lift and drag:

$$Fg = Lverticle +$$

$$mg = \int_{-Yb}^{Yt} (dL\,cos\varphi + dDsin\,\varphi)\cos\beta\,dy$$

This vertical force equilibrium can also be modeled macroscopically by treating the rotating wing as an actuator disk. Under steady wing-vortex theory, the vertical thrust (or vertical drag force) scales with the swept disk area: $S_{(disk)} = \pi R^2$ and a total thrust coefficient CT:

$$Mg = ½\rho V_{(terminal)}{}^2 \pi R^2 CT$$

Solving for the steady-state terminal velocity ($V_{(terminal)}$) yields:

$$V_{(terminal)} = \sqrt{(\frac{2mg}{\rho\pi R^2 CT})}$$

This equation highlights that terminal velocity is proportional to the square root of the wing loading ($mg/\pi R^2$), demonstrating how the sweeping motion of the single-winged stabilizer creates a large virtual disk area that slows descent as effectively as a conventional drag parachute.

IV .FLUID DYNAMICS OF THE LEADING-EDGE Vortex (LEV)

The exceptional lift-generating capability of the *Swietenia* samara is driven by an unusual, highly efficient aerodynamic phenomenon known as a stable Leading-Edge Vortex (LEV). In classical aeronautics, a leading-edge vortex is highly unstable; as a conventional wing translates at high angles of attack, the vortex forms, quickly detaches, and sheds into the wake, causing a severe aerodynamic stall. However, stereoscopic Digital Particle Image Velocimetry (DPIV) of autorotating mahogany seeds in vertical wind tunnels reveals that the LEV remains stably attached to the upper surface of the wing throughout the entire descent.

This stable attachment is maintained by powerful spanwise flow and strain fields generated by centripetal and Coriolis accelerations within the rotating frame of reference. These accelerations scale with low Rossby numbers ($Ro \approx 1$), which are characteristic of the propeller-like sweep of the wing. The centrifugal force acts as a passive boundary-layer pump, driving a strong radial flow along the core of the vortex toward the wingtip. This spanwise flow drains excess vorticity from the leading edge, preventing the vortex from growing to an unstable size and detaching.

DPIV and flow-field analyses reveal that the LEV is highly structured and varies predictably along the span of the *Swietenia* wing:

1. **Root Region (0%–25% span)**: Near the wing base, local rotational velocities are low ($V(y) = y\Omega$). While the shear layers above the leading and trailing edges act as a source of vorticity, no coherent, stable LEV core is formed in this inboard region.
2. **Mid-Span Region (25%–75% span):** The LEV first appears as a distinct, stable structure at approximately 25% of the wingspan. Moving outboard, the vortex core increases in size and strength, forming a tight, stable, conical pattern.
3. **Peak Intensity Zone (75% span):** The LEV reaches its maximum stability and spanwise flow velocity at 75% of the wingspan, creating a powerful suction region that generates the majority of the wing's lift.
4. **Tip Region (90%–100% span):** As the flow approaches the wingtip, the stability of the vortex core begins to decrease. The LEV undergoes a structural re-orientation, merging with the primary tip vortex and shedding into the wake.

Because the LEV remains stably attached across the primary lifting surface, the wing can operate at extremely high angles of attack (*up to 40°–45°*) without stalling. This generates a large pressure differential between the upper and lower surfaces, which peaks near the wingtip and drives the stable, conical rotation of the stabilizer.

V.FORCE BALANCE AND AERODYNAMIC VECTOR ANALYSIS

A comprehensive force balance on the MAHAS wing requires modeling the velocity vectors and forces acting on an infinitesimal wing section (dy) at a radial distance y from the spin axis.The vertical descent velocity of the stabilizer is $V_{(d)}$, and the local horizontal rotational velocity is $V_{(H)}$ = yΩ. Because the wing is inclined upward at a coning angle β, the local vertical descent velocity component relative to the wing is $V_{(d)}$ cosβ. The resultant relative wind velocity ($V_{(rel)}$) perceived by the wing element is the vector sum of these velocities:

$$V_{(rel)}(y) = \sqrt{[(y\Omega)^2 + (V_d cos\beta)^2]}$$

The inflow angle (φ) is the angle between the relative wind vector $V_{(rel)}$ and the flight path plane:

$$\Phi(y) = tan^{-1}[\frac{(V_d\ cos\beta)}{y\Omega}]$$

If the local chord of the wing is set at a geometric pitch angle θ relative to the flight path plane, the local effective angle of attack (α) is:

$$\alpha(y) = \varphi(y) + \theta(y)$$

The infinitesimal lift (dL) and drag (dD) forces generated by a wing section of chord b(y) are formulated as:

$$dL = ½\rho V_{(rel)}(y)^2\ b(y)\ C_{(L)}(\alpha)\ dy$$

$$dD = ½\rho V_{(rel)}(y)^2\ b(y)\ C_{(D)}(\alpha)\ dy$$

These local aerodynamic forces must satisfy three coupled equilibrium integrals, as established by Yasuda and Azuma:

1. **Vertical Force Balance:** The total vertical aerodynamic force must precisely balance the total gravity force (weight W = mg) of the stabilizer:

$$\int_{-Yb}^{Yt} (dL\ cos\varphi +\ dD\ sin\varphi) cos\beta\ dy -\ W\ =\ 0$$

2. **Rotational Torque Balance:** The net driving aerodynamic torque must balance the resisting profile torque:

$$\int_{-Yb}^{Yt} (dL\ sin\varphi -\ dD\ cos\varphi) y\ cos\beta\ dy\ =\ 0$$

3. **Coning Moment Balance:** The coning angle β must achieve a stable equilibrium where the upward aerodynamic lift moment is balanced by the downward moments generated by centrifugal forces and the distributed weight of the wing:

$$\int_{-Yb}^{Yt} (dL\ cos\varphi +\ dD\ sin\varphi)\ y\ dy\ -\ \int_{-Yb}^{Yt} (\Omega^2 qycos\beta)(y\ sin\beta)\ dy\ -\int_{-Yb}^{Yt} gq\ cos\beta\ y\ dy =\ 0$$

Where $q = \rho_{(w)}\ b(_{y})\ t_{(w)}$ is the distributed mass per unit span of the wing, with $\rho_{(w)}$ representing the wing material density and $t_{(w)}$ its thickness.

This three-axis equilibrium ensures that the MAHAS system dynamically self-adjusts its spin rate and coning angle, providing a highly stable, non-tumbling vertical trajectory even in turbulent atmospheric conditions.

VI. ROTATIONAL INITIATION AND TRANSITION PHASES

The operational effectiveness of the MAHAS system depends heavily on its ability to rapidly transition from a state of rest to stable, high-RPM autorotation. This transitional behavior is highly sensitive to the initial release attitude and launch velocity.

When dropped from rest in still air, a natural *Swietenia* seed experiences a brief period of unstable free fall before initiating rotation. The length of this transitional "free-fall window" is determined by the drop orientation:

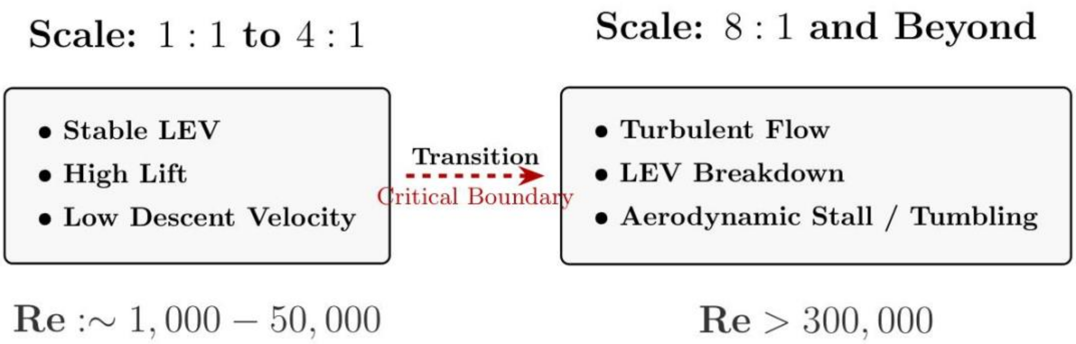
1. **Parallel Release:** If the stabilizer is released with the wing oriented horizontally (parallel to the ground), it falls through a relatively long free-fall distance (often exceeding 1.0 m) before the asymmetric wing camber generates sufficient aerodynamic torque to initiate rotation.
2. **Vertical Release:** If released with the heavy core pod pointing downward and the wing oriented vertically, the asymmetric airflow is engaged immediately, reducing the free-fall window to less than 0.3 m.
3. **Upward Launch or Ejection:** When the stabilizer is launched upward against the direction of gravity (e.g., during pilot ejection), the relative upward wind immediately drives a high rotational velocity. This completely eliminates the free-fall window, initiating stable autorotation instantly at the apex of the launch trajectory.

Furthermore, when the stabilizer is ejected or catapulted at high velocities (up to ten times its steady-state descent speed), its initial rotational frequency can reach up to four times its steady-state terminal RPM. In this transient, high-velocity regime ($Re \approx 10^4$), the wing generates exceptionally high lift forces that act as a powerful aerodynamic brake, rapidly decelerating the payload safely before settling into its stable, steady-state terminal descent. This rapid deceleration capability makes the MAHAS mechanism highly effective for high-speed ejection and drop missions.

VII. AEROMECHANICAL SCALING BOUNDARIES

To successfully scale the biological flight of the *Swietenia* seed (which weighs approximately 1.0 g) to industrial payload classes (weighing 5.0 to 50.0 kg), the designs must adhere strictly to fluid-dynamic scaling laws.The primary non-dimensional parameters governing this scale-up are the Reynolds number ($Re = \rho V_{(d)} c/\mu$) and the Rossby number ($Ro = V_{(d)}/\Omega R$), where c is the mean chord, R is the wingspan, and μ is the dynamic viscosity of air. Natural mahogany seeds operate at low Reynolds numbers ($Re \approx 10^3$–10^4) and low Rossby numbers ($Ro \approx 1$), where viscous forces are significant and help keep the LEV stably attached to the wing surface.

As the physical dimensions of the stabilizer are scaled up, the Reynolds number increases significantly into a highly turbulent regime ($Re \approx 10^5$–10^6). At these high Reynolds numbers, the flow over the wing transitions to a fully turbulent state, which can cause the LEV to break down and detach from the wing surface, resulting in aerodynamic stall and a severe loss of lift.



Experimental and wind tunnel testing of scaled Swietenia samara structures indicates a critical performance boundary:

1. **Scale Ratios up to 4:1**: The vertical descent remains highly stable. Scaling up the wing area within this range boosts the total thrust by approximately seven times, as the increased surface area effectively captures wind energy.
2. **Scale Ratios from 4:1 to 8:1**: The thrust increases by only four times, indicating diminishing returns as aerodynamic efficiency begins to degrade.
3. **Scale Ratios of 8:1 and Beyond**: The vertical aerodynamic performance degrades significantly. At this scale, the massive increase in centrifugal force and turbulent flow over the wing causes the LEV to separate and break down. The stabilizer becomes highly sensitive to lateral wind gusts and struggles to maintain a stable, vertical spin axis, frequently entering a chaotic tumbling state.

Additionally, numerical Moving Reference Frame (MRF) simulations demonstrate that while descent velocities and spin rates rise almost linearly with wing loading, the spin rate must be carefully controlled. If the spin rate exceeds 200 rad/s, the aerodynamic lift does not increase further due to compressibility effects and local flow separation. Therefore, for large-scale biomimetic applications, the spin rate should be kept below 200 rad/s.

The aeromechanical performance characteristics across different scale ratios are compiled in Table 1.

Scale Ratio (to Natural Seed)	**Flight Reynolds Number (Re)**	**Thrust Multi. Factor**	**System Vertical Stability Status**	**Kinematic Flight Behavior**
1:1	$\approx 1 \times 10^3$	1.0× (Baseline)	Exceptional	Pure vertical autorotation; highly :
2:1	$\approx 8 \times 10^3$	3.2×	High	Stable helical descent; minimal dri
4:1	$\approx 5 \times 10^4$	7.0×	Satisfactory	Steady rotation; handles light late
8:1	$\approx 3 \times 10^5$	11.0×	Degraded	Critical boundary; high risk of sep
12:1	$\approx 1 \times 10^6$	13.5×	Unstable*	Chaotic tumbling; severe LEV bre

VIII. HIGH-ALTITUDE AND CIVIL ENGINEERING APPLICATIONS

The MAHAS passive descent mechanism has several potential applications in aerospace, defense, and municipal safety systems where traditional deceleration methods are prone to failure.

8.1 High-Altitude Pre-Parachute Stabilization

During high-altitude drops or emergency space capsule re-entries, the extremely thin atmosphere makes traditional parachutes highly ineffective. Because there is insufficient air density to inflate the canopy, parachutes deployed at these altitudes frequently twist, tear, or collapse, leading to high-velocity free falls.

MAHAS addresses this issue by providing pre-parachute stabilization. Its rigid, asymmetric wing structure does not rely on inflation and initiates spin-up as soon as air molecules interact with the wing surface. This rapid autorotation stabilizes the payload's orientation and provides steady deceleration through the thin upper atmosphere, safely bridging the dangerous free-fall window until the air density becomes sufficient for reliable parachute deployment.

8.2 Emergency Pilot Ejection Systems

In high-speed fighter jet ejections, pilots are exposed to extreme wind shear and aerodynamic forces that can cause rapid, chaotic tumbling. This high-frequency rolling can subject the pilot to severe multi-axis G-forces, leading to disorientation, physical injury, or loss of consciousness.

Integrating a deployable MAHAS wing assembly directly into the ejection seat provides immediate stabilization. Once ejected, the seat acts as the heavy core mass, while the deployed wing utilizes the high relative air velocity to spin up. This high-speed rotation generates a powerful gyroscopic effect, similar to that of a satellite stabilizer, keeping the seat upright and stable during descent, preventing chaotic tumbling, and significantly improving pilot survivability.

8.3 Meteorological Sensor Drops and Payload Delivery

For climate research and atmospheric monitoring, scientific payloads and sensor packages (such as dropsondes) must be deployed into severe storm environments or high-altitude atmospheric layers. Parachutes deployed in these highly turbulent zones are easily shredded or blown far off course by strong winds.

A MAHAS-based sensor pod provides a durable alternative. The rigid wing assembly is highly resistant to wind shear and descends along a predictable vertical spiral path. This helps maintain sensor stability during descent, allowing high-quality atmospheric data collection with minimal wind-induced drift.

8.4 Urban Disaster Rescue and Municipal Safety

In dense, high-rise urban areas, fires, structural collapses, or emergency evacuations from skyscrapers present significant rescue challenges. Traditional parachute rescues are impractical from these heights because the available drop distance is too short to allow safe parachute deployment.

Compact MAHAS rescue pods can be launched directly from high-rise windows or rooftops. Because the wing's asymmetric geometry generates high rotational torque almost immediately, the system initiates stable autorotation within a short vertical distance. This enables the pod to descend safely to street level without requiring external power or specialized landing infrastructure.

8.5 Defense Logistics and Space Probe Recovery

In tactical defense operations, supplying ground forces requires highly accurate payload delivery. Traditional parachutes are easily detected and are susceptible to wind-induced drift, reducing delivery accuracy.

MAHAS-stabilized delivery pods can be released from high altitudes and descend along steep, controlled helical trajectories that minimize wind drift.

Additionally, planetary space probes and return capsules entering the atmospheres of Mars or Venus could employ scaled MAHAS stabilizers. The passive single-wing design is mechanically simple, inherently self-stabilizing, and has the potential to reduce dependence on complex attitude-control hardware during atmospheric descent.

IX. CONCLUSIONS

The **Mahogany Aerodynamic High-Altitude Stabilizer (MAHAS)** represents a highly effective translation of biological flight principles into a robust engineering solution for passive descent stabilization. By analyzing the autorotation of *Swietenia* seeds, this research establishes that asymmetric mass distribution coupled with specialized airfoil geometries can generate a stable, high-lift Leading-Edge Vortex (LEV). This fluid-structure interaction enables controlled vertical descent without the use of fuel, motors, or active electronics.

Mathematical modeling using Blade Element Momentum Theory (BEMT) and the Yasuda–Azuma force and torque integrations demonstrates that scaled-up MAHAS structures can maintain vertical stability and achieve reliable terminal velocities. However, fluid-dynamic scaling limits reveal a critical operational boundary at an 8:1 scale ratio, where transition to a highly turbulent, high-Reynolds-number regime can cause LEV breakdown and compromise flight stability.

To overcome this scale barrier, target designs should maintain low wing loading through the use of high-performance carbon composites, optimized trailing-edge microstructures, and flexible connective hinges. Implementing these bio-inspired design strategies enables MAHAS to serve as a reliable, zero-power stabilization system for high-altitude sensor recovery, emergency pilot ejection, and planetary probe landing missions, demonstrating how simple, bio-inspired structures can address complex aerospace engineering challenges.

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