The Effect of Wing Stiffness and Centre of Gravity on the Glide Performance of Paper Airplanes

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Abstract. This study investigates how wing stiffness and center of gravity (CG) affect the glide performance of paper airplanes, which serve as simplified physical models for micro air vehicles (MAVs) operating at low Reynolds numbers. To examine these effects, three distinct wing stiffness levels and two CG positions were tested across 29 indoor free-flight trials. Each flight was recorded and analyzed using Tracker software to measure glide ratio, glide angle, and flight stability. The results revealed that a forward CG consistently enhanced stability, helping to prevent pitching oscillations and erratic descents. Increased wing stiffness contributed to more predictable and repeatable flight paths, yet did not necessarily improve glide efficiency, highlighting that rigidity alone cannot guarantee better aerodynamic performance. Notably, the low-stiffness mid-CG configuration failed to produce any stable flights, underscoring the destabilizing interaction between flexible wings and aft CG. These findings emphasis the intrinsic trade-off between stability and efficiency in low-Reynolds-number flight. They offer valuable insights into MAV design, suggesting that careful balancing of structural flexibility and mass distribution is crucial for achieving both controlled flight and optimal glide performance.

Keywords: Paper airplanes, MAVs, Reynolds number, Stiffness, Glide performance.

1. Introduction

The study of flight performance significantly depends on aerodynamic efficiency and stability. Aerodynamic efficiency is usually expressed as the lift-to-drag ratio, which describes how much lift can be generated for a given drag. Stability is also important because it affects whether the airplane can keep a smooth trajectory. A stable aircraft can maintain its posture more easily when experiencing disturbances such as turbulence or crosswinds, reducing the risks of losing control. For performance, a stable aircraft also keeps an optimal aerodynamic condition, which improves and allows engines to operate more efficiently, therefore consuming less fuel.

Beyond large-scale aircraft, the importance of aerodynamic efficiency and stability also extends to small-scale flyers, particularly micro air vehicles (MAVs). Unlike normal airplanes, MAVs move at lower speeds and have smaller wings and bodies, which are typically defined as extremely small, ultra-lightweight air vehicles with wingspans below 15 cm and weights under 20 g [1]. This makes them more sensitive to disturbances. MAVs are in increasing demand for navigating through confined spaces that are inaccessible for humans, for example in exploration tasks and rescue missions in complex environments.

Paper airplanes operate at low Reynolds numbers because of their small characteristic length and low velocity. This makes them suitable physical models for studying aerodynamic performance and stability for MAVs. At low Reynolds numbers, flows are highly viscous, with early boundary-layer separation and lower aerodynamic efficiency. The airflow also tends to become unstable, with effects such as vortex shedding and premature stall, which complicate the glide prediction.

Previous studies have shown that wing planform, aspect ratio and geometric modifications can significantly affect the glide efficiency in MAVs. However, these studies mainly emphasized the role of geometry and typically assumed rigid wings and fixed mass distributions. MAVs often use thin or flexible wing materials that deform under aerodynamic loads, and payloads such as batteries or sensors which shift the center of gravity (CG) during flight. Because these components usually account for a large fraction of the total mass, variations in CG position can have a substantial impact on stability and performance. Therefore, both stiffness and CG are critical to understand.

This aerodynamic regime can also be described using the Reynolds number (Re), which is a dimensionless parameter that represents the ratio of inertial forces to viscous forces in a flow:

$$\mathrm{Re} = \frac{\rho VL}{\mu} \tag{1}$$

Where ρ is the air density is, V is a characteristic velocity, L is a characteristic length and is the dynamic viscosity. The Reynolds number is one of the most important parameters in fluid dynamics because it shows whether viscous effects are negligible or dominant [2]. All real flows are viscous, showing friction and diffusion effects, while inviscid flows are only idealized approximations. At high Reynolds numbers, flows can often be approximated as inviscid, but at low Reynolds numbers of viscous effects dominate, and the inviscid assumption breaks down.

Viscous flows can be divided into laminar and turbulent regimes. In laminar flow, the streamlines are smooth and orderly, while in turbulent flow the motion is irregular and mixed. Low Reynolds number flows are more likely to remain laminar, but they are also prone to early separation of the boundary layer and unsteady vortices, which reduce aerodynamic efficiency and stability [3]. Paper airplanes operate in the range of 103–105, which makes them good analogues for MAVs. Their low structural stiffness and sensitivity to mass distribution also make them useful models for investigating how stiffness and CG affect glide efficiency and stability under low-Reynolds-number conditions.

In existing studies of paper planes or MAVs, the focus is mostly on planform shapes or aspect ratios, but fewer studies have investigated the combined effects of structural stiffness and center of gravity on glide performance at low Reynolds numbers. A scoping search using Google Scholar (2021–2025) illustrates this difference. About 17,000 records were found relating to MAVs at low Reynolds numbers. Narrowing the search to fixed-wing stiffness produced about 11,900 records and adding center-of-gravity and glide performance gave 239 records. Among these, only 154 considered stiffness and CG together, and just 14 explicitly examined free-flight conditions. This sharp reduction across these stages highlights a research gap: very few free-flight studies have quantified the combined effects of wing stiffness and CG on glide efficiency and stability at low Reynolds numbers.

Investigating these two variables together is important because stiffness and CG are not independent in practice. Increasing stiffness often means adding material, which changes mass distribution, while CG location can shift dynamically as components move. Therefore, a controlled study using paper airplanes provides a simple but informative model for examining how these interacting factors influence glide efficiency and stability.

The aim of this study is to systematically investigate how wing stiffness and center of gravity (CG) influence the glide performance and stability of paper airplanes under free-flight, low-Reynolds-number conditions, as a simplified analogue for MAVs. Specifically, the study seeks to:

1. Quantify whether increased structural stiffness improves glide efficiency, as measured by glide ratio ($\frac{L}{D}$) and glide angle (γ).
2. Evaluate how different CG positions affect longitudinal stability and overall trajectory behavior during free flight.
3. Explore the interaction between stiffness and CG, since changes in stiffness often involve changes in mass distribution, and assess their combined effects on glide performance.

2. Methodology

2.1. Materials

Three stiffness levels were implemented using three paper types: printing paper for low stiffness, printing paper reinforced with a single layer of 10 mm wide adhesive tape along the wing edge for medium stiffness, and card paper for high stiffness. There were two different CG points, such as attaching a paper clip at either the nose or the midpoint of the plane. Tracker software was used to do motion tracking. Additional equipment including scissors and a ruler for folding, a digital scale for recording mass, and an iPhone camera (240 fps, 1080p) for video recording in slow motion.

2.2. Plane Preparation

All paper airplanes were folded in the dart configuration following a standard procedure [4]. The folding procedures were kept as consistent as possible to control the aerodynamics performance. Previous work has also used similarly folded paper airplanes to explore aerodynamic efficiency and stability [5] and could therefore support the feasibility of my experiment. Mass differences caused by different materials were recorded but not corrected. Black ink was painted on the front tip and the midpoint of the plane for tracking, and finding the handhold position.

2.3. Flight Launching and Recording

The flights were performed indoors to avoid wind, and the planes were launched by the same person, from the same height, at the same position every time. Each plane was launched five times, with runs with obvious yaw (>10°), collisions, or tracking loss discarded, and the films were taken by an iPhone with slow motion mode at the same position held by a stand. Launch transients were removed to avoid abstractions during the analysis stage, and analysis was restricted to steady segments in the stability section. A calibration tape was placed in the field of view to convert pixel distances into millimetres.

2.4. Motion Tracking and Data Analysis

The videos were motion tracked in tracker software. To facilitate accurate tracking, the noses of the plane marked with black ink were selected as tracking points. Calibration was performed in the scene by using a 25cm strip of adhesive tape. Tracking was performed manually using the Point Mass tool. The nose of the plane was marked frame by frame. The horizontal displacement and vertical displacement were measured since flights exhibited continuous gliding motion, which was between 0.5 seconds after launching and before landing. Glide angle was calculated as $\gamma = \arctan(\frac{|\Delta y|}{\Delta x})$, and lift-to-drag ratio as $\frac{L}{D} = \frac{\Delta x}{|\Delta y|}$. Stability was classified into two categories: stable (smooth glide) and unstable (rollover or stall). Unstable flights were excluded from efficiency calculations.

2.5. Reasons

Stiffness manipulation: For the three sets of stiffness levels, printing paper was used for the low-stiffness condition because it is lightweight, and flexible, therefore it is more sensitive to aerodynamic loads. For the intermediate stiffness set, this research has selected printing paper reinforced with a single layer of adhesive tape along the edges. This could improve stiffness slightly while keeping the shape of the wings and body unchanged. Card paper was used for the high stiffness set, regarding its greater thickness and high resistance to bending.

Stiffness can be defined as the ability of a material to maintain its geometric parameters within acceptable limits under external actions [6]. Composite materials typically consist of a stiff reinforcing phase (filler) embedded in a softer phase (matrix), and their improved mechanical performance arises from this combination. In the present study, applying adhesive tape to the wings of a paper airplane effectively created a simple composite material. The paper functioned as the matrix and the polymer tape functioned as the reinforcing component. The tape increases the local thickness and provides a higher modulus material along critical stress-bearing regions, thereby enhancing bending stiffness. As a result, reinforced wings resisted deformation under aerodynamic loads more effectively than unreinforced ones, helping the airplane maintain its intended geometry during flight.

2.6. Centre of Gravity Manipulation

Two center-of-gravity (CG) configurations were implemented to investigate how mass distribution affects glide stability and efficiency. Dedicated airframes were prepared for each CG condition: a small, identical paper clip was attached either at the nose (forward-CG condition) or at the mid-fuselage (central-CG condition). Using separate airframes avoided cumulative handling damage and ensured that each configuration maintained a constant mass distribution across all flights. Identical clips that had the same mass weighted by the digital scale were used; the total mass of each airframe (including clip) was recorded.

From a flight-dynamics perspective, the CG is the point at which the aircraft's weight effectively acts, and its location strongly influences longitudinal stability and pitch response. A forward CG generally increases static stability by providing a larger restoring moment, but it can increase trim/induced drag and reduce glide efficiency. A more aft CG reduces static margin and can promote oscillatory behavior or stall if pushed too far. Testing forward and central CG positions therefore probed the expected trade-off between stability and glide ratio.

2.7. Flight Launching and Recording

Flights were launched indoors to avoid unpredictable wind and weather conditions. This made the testing environment consistent and reduced the risk of external factors affecting the results. Launching was always done by the same person, from the same position (The launcher's back was kept against the wall) and height (the release point aligned with the chin, and the forearm and upper arm forming a right angle at the moment of release. The launcher's height was 180 cm.), in order to minimise variation in throwing technique. Each airplane was launched five times to improve reliability, and any flights with obvious yaw, collisions, or tracking failures were discarded. Video recording was done using an iPhone in slow-motion mode at 240 fps. The high frame rate increased the number of data points for each flight and reduced motion blur, which was especially important for short, fast flights. This made the motion tracking more precise. The same person held the phone during filming in order to maintain a constant recording height and angle as much as possible.

2.8. Motion Tracking and Calibration

The motion tracking was done in Tracker software [7], which allows accurate frame-by-frame analysis of displacement. Black ink was marked on the airplane nose to provide a strong contrast with the white background, so the tracking point could be clearly identified in every frame. A 25 cm adhesive tape strip was fixed in the background as a calibration scale, which made it possible to convert pixel measurements into millimetres. By doing so, the recorded displacements of the airplane can be calculated using Axes tools in the tracker software. Manual tracking was chosen instead of automatic tracking because paper airplanes are small and can move quickly, and automatic tracking often fails under such conditions. Although slower, manual digitisation ensured more consistent and reliable data across all flights.

3. Data Analysis

From the trajectories, horizontal (Δx) and vertical (Δy) displacements were extracted to calculate glide angle ($\gamma = \arctan(\frac{|\Delta y|}{\Delta x})$) and glide ratio ($\frac{L}{D} = \frac{\Delta x}{|\Delta y|}$). These two metrics are widely used to describe aerodynamic efficiency and descent behaviour, and they directly address the first research aim: whether stiffness improves glide performance. Stability was classified as either stable (smooth glide) or unstable (stall, rollover). This addressed the second research aim: how CG position affects stability. Unstable flights were excluded from efficiency calculations to avoid skewing the results. Data points were analysed between 0.5 s after launch and 0.5 s before landing, in order to exclude transient effects of the release and ground contact. Trajectories tracked in Tracker were exported as .csv files and imported into Excel for further processing, including calculation of horizontal and vertical displacements, glide angle, and glide ratio. Together, these analysis choices ensured that the collected data were directly linked to the research questions while minimising confounding variables.

3.1. Potential Issues

Several limitations affected the accuracy and reliability of the data collected in this experiment.

Recording Environment: The motion tracking environment was not perfectly suitable. The videos were taken indoors with relatively poor lighting, and the wall color was similar to that of paper airplanes. As a result, the planes occasionally blended into the background, making it difficult for the software to distinguish the tracking point. This could cause missing data points or produce noisy, jagged trajectories, which would reduce smoothness of the data. In addition, even with slow-motion recording, some frames were affected by motion blur, especially during rapid rotations, which reduced the accuracy of the identified positions. Together, these issues may have introduced random error into the displacement data, affecting the calculation of glide angles and lift-to-drag ratios.

Precision Construction: The folding process of paper airplanes was not perfectly precise. Small variations in wing angle, crease sharpness, or nose symmetry were unavoidable, even though folding steps were kept consistent. These slight asymmetries may have altered the lift and drag forces experienced by each airplane. This means that part of the variability in the data could be due to construction differences rather than stiffness or center-of-gravity manipulations, reducing the reliability of comparisons across groups.

Manual Launching: All airplanes were launched manually, and it was difficult to maintain the same release angle, height, and velocity for every trial. Even small changes in the way the plane left the hand could affect its trajectory. As a result, unwanted variation was introduced into glide angles and lift-to-drag ratios, which made it harder to isolate the effects of stiffness and CG. Inconsistent launches could also create borderline cases where a stable plane appeared unstable.

Airframe durability: When the same airplane was launched repeatedly, the nose section frequently hit the ground on landing. Over time, these repeated impacts caused the nose to bend or crease. This deformation changed the geometry of the airplane and could alter its aerodynamic characteristics, meaning that later flights of the same airframe might perform differently from earlier flights.

Structural Flexibility: The wings made from thin printing paper were relatively flexible and sometimes became floppy during flight. This structural property meant that the wing geometry could change under aerodynamic loads, altering the lift and dragging characteristics in ways that were not consistent across flights. Consequently, the measured glide performance may not always match theoretical predictions based on rigid wings, limiting the reliability of comparisons with aerodynamic theory. The FAA highlights a similar concern in real glider design, noting that “due to the flexibility of a glider wing design, the wing may oscillate rapidly or flutter at high airspeeds” and that prolonged flutter can even cause structural failure [8]. While the paper airplanes in this study did not reach such speeds, the principle remains relevant: wing flexibility can lead to oscillations and inconsistent aerodynamic behavior, reducing the repeatability of glide performance.

Approximated stiffness and mass effects: Finally, stiffness was only approximated through material choices, printing paper, reinforced paper, and card. This approach did not provide a direct, quantitative measurement of stiffness, and the manipulations also changed the mass of the airplanes. For example, adding tape increased both stiffness and weight, and attaching paper clips shifted the CG but also increased the total mass. As a result, stiffness and mass effects were not fully isolated, and part of the observed differences in glide performance could have been caused by changes in weight rather than stiffness or CG location alone. Although these factors were considered qualitatively in the design of the experiment, no quantitative data on stiffness or mass distribution were incorporated into the calculations, which limits the accuracy of the analysis.

3.2. Strategies

To reduce the influence of these problems, several measures were adopted:

1. Recording environment. Flights were conducted indoors to remove wind effects. A plain white wall was used as the background, and black ink markings were drawn on the airplane nose to provide strong contrast. This reduced the chance of the plane blending into the background. Slow-motion recording at 240 fps was chosen to minimize motion blur and increase the number of frames available for tracking.
2. Construction precision. Care was taken during folding to align both sides of each crease as accurately as possible, ensuring better wing symmetry.
3. Manual launching. The same person launched all flights, with a fixed posture: back against the wall, release point aligned with the chin, and arms forming a right angle at the elbow. This helped to keep release angle and velocity more consistent across trials.
4. Structural flexibility. To reduce the impact of deformation during flight, each airplane was reinforced at critical points (e.g. with tape for the medium-stiffness group). Furthermore, only the stable glide segments (0.5 s after launch until just before landing) were selected for analysis, so transient instabilities did not distort the results.
5. Airframe damage. Since repeated landings sometimes bent the nose, the nose was manually straightened before each flight to restore the original geometry as closely as possible. This reduced variability between early and later trials of the same airframe.
6. Approximated stiffness and mass effects. For CG manipulation, paper clips were weighed on a digital scale, and only clips with mass differences within ±0.05 g were selected. This ensured consistency across airplanes. The total mass of each airplane was also recorded. Although stiffness itself was not measured quantitatively, using consistent materials and controlled reinforcement helped to keep the differences systematic.

3.3. Improvements for Future Research

To improve accuracy in future work, flights could be recorded in a better controlled environment with sufficient lighting and higher frame-rate cameras, which would make motion tracking more precise. A background with a colour in strong contrast to the paper airplanes could also be used, such as a dark cloth behind white planes, to reduce visual interference and make motion tracking easier. Mechanical launchers could be used to provide consistent release velocity and angle, removing human variability. Independent mechanical tests, such as three-point bending ($\delta = \frac{FL^3}{48EI}$), could be used to quantify stiffness directly and separate it from mass differences. In addition, the mass of each airplane and the exact CG position could be measured quantitatively and incorporated into the calculations, rather than being treated only as categorical factors. This would allow the effects of mass distribution and weight to be modelled explicitly, and would make it possible to explore correlations between stiffness, mass, CG, and glide performance. Exploring more CG positions rather than only forward and central would provide a clearer picture of the relationship between stability and efficiency. Beyond this study, such improvements would make the results more applicable to the design of small-scale gliders or unmanned aerial vehicles, where balancing stiffness, mass, and CG is crucial.

4. Results

29 flights were conducted in total across 6 configurations(L-F, L-M, M-F, M-M, H-F, H-M). 19 of them were stable, and 10 of them were unstable. Average glide ratios($\frac{L}{D}$) varied between ~0.76 and ~0.98 among the stable flights, and the average glide angle(γ) ranged from ~45° to ~53°.

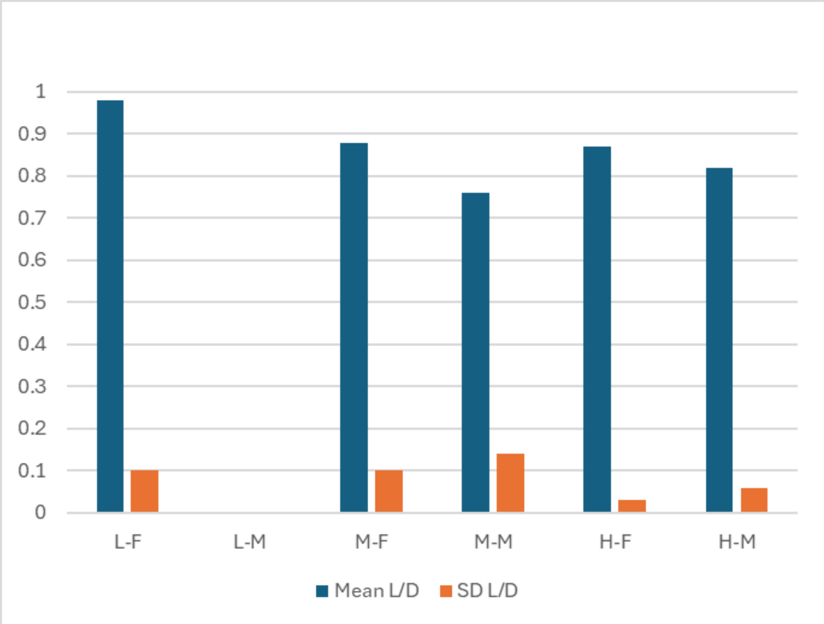

Figure 1. Mean and standard deviation of the Lift-to-Drag ratio.

As shown in Fig.1, in terms of the efficiency, configuration L-F had achieved the highest glide ratio ($\frac{L}{D}$) of ~0.98 ± 0.10, while having a glide angle (γ) of ~45.6° ± 3.0°. In contrast, M-M had the lowest glide ratio of ~0.76 ± 0.14, with the highest glide ratio of ~52.9° ± 5.1°. Intermediate values were obtained for M-F (0.88 ± 0.10, γ = 48.7° ± 3.3°), H-F (0.87 ± 0.03, γ = 48.9° ± 1.0°), and H-M (0.82 ± 0.06, γ = 50.8° ± 2.1°). For the configuration L-M, no stable flight was achieved, resulting in no meaningful averages obtained.

As shown in Fig.2, stability rates varied substantially among groups. M-M reached 100% stability (5/5 flights), while both L-F and M-F showed ~80% stability. H-F and H-M achieved ~60% stable flights. In contrast, L-M exhibited 0% stability, with all flights rolling over before gliding. This indicates that the forward CG would usually improve stability, whereas increased stiffness improved consistency, however could not always lead to higher glide ratio.

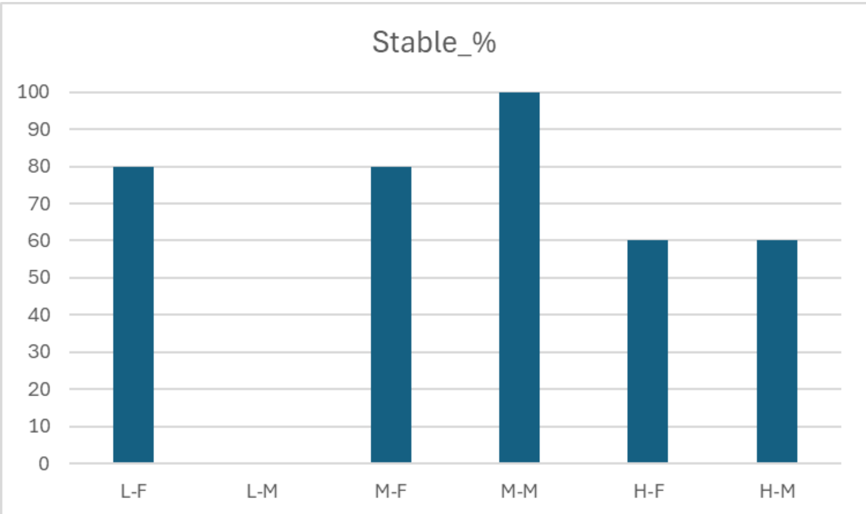

Figure 2. The percentage of stable flights.

These results suggest that a forward CG generally improves longitudinal stability, while increased stiffness tends to enhance flight consistency. However, higher stiffness did not always translate to better glide ratios, indicating a complex trade-off between efficiency and stability.

5. Discussion

The study indicated the significant impacts of stiffness and CG location on the performance of flights. Forward CG always enhances stability while stiffness improves consistency but cannot always improve glide ratio. In particular, the L-M configuration (low stiffness with mid-CG) produced no stable flights, emphasizing the strong destabilizing effect of combining flexible wings with an aft CG.

The observed trends followed the aerodynamic theory. A forward CG shifts the balance point ahead of the aerodynamic center, increasing longitudinal static stability and reducing the likelihood of pitching oscillations or rollover. In contrast, a more central or aft CG reduces static stability, making the aircraft more sensitive to disturbances, which results in rolling-overs more often. Similarly, wing stiffness plays a dual role: low stiffness allows structural deformation, leading to asymmetric lift and instability, whereas excessive stiffness increases mass and wing loading, which can reduce the lift-to-drag ratio. This could explain why the M-M configuration achieved the best stability, but a steeper glide angle and lower efficiency came along, while L-F produced the highest $\frac{L}{D}$ but with occasional instability.

The instability of a few configurations in this study, such as L-M, is consistent. For example, Bourdin, Gresham, and Triantafyllou found that aerodynamic force production in flapping wings strongly depends on Reynolds' number and wing geometry [9]. Similarly, the flexible wings in this study might affected their effective geometry during flight, amplifying the low-Re sensitivity and leading to unstable trajectories.

The trade-off between stability and efficiency my study echoes findings in MAV research. Mueller and DeLaurier reviewed aerodynamic challenges of small aerial vehicles, highlighting that low Reynolds number effects such as laminar separation bubbles make it difficult to optimise stability and efficiency simultaneously [10]. This supports the conclusion that depending on design priorities, stiffness and CG placement need to be balanced.

6. Conclusion

Overall, the results highlight a trade-off between stability and efficiency. Forward CG enhanced stability, while increased stiffness improved consistency but not always efficiency. These findings echo MAV research, where low-Reynolds-number effects make it difficult to optimise both stability and efficiency simultaneously.

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