Helicopter Duration Model Descent Stability

NARAM 53 Research & Development

Pacific Flying Machines T-736

Bob Parks NAR 7871

Ryan G. Coleman NAR 59361

LUNAR Section 534

Autorotating helicopter models have been popular since the introduction of the NAR competition event. A frustrating failure mode is when a model descends in the opposite orientation as it was designed, since the rotors may have much higher sink rates in this orientation, the results suffer. The cause of this upside-down descent orientation has never been investigated.

Both authors have had issues with this before, as have many other modelers. The hypothesis was that the rotors could be modeled as an equivalent fin and that from that, standard Center of Mass and Center of Pressure relationships could be used to determine which was a model would descend, so that these design principles could be used in future designs.

Drop tests were conducted, varying many parameters including Center of Mass location, fin size, blade angle, cone angle and blade span. All cases were observed 1) models that descend tail-first, as this particular design intended 2) models that flipped to descend nose-first 3) models that were bistable, and would descend in the orientation they were released at and 4) models that would descend nose-first or tail-first when release horizontally.

From these tests, we concluded that the stability of these models is very dependent on things like the rocket fin area, and the descent center of mass location, but there are also rotor stability effects which result in stability in both tail first and nose first descent orientations. The rotor stability effects are quite complicated and not amenable to being modeled as an "equivalent fin". However, the nose down stability mode can be quite robust and it may be better to actually design models to descend nose first.

Introduction

Ever since the beginning of the NAR Helicopter Duration event, contestants have been perplexed by the descent stability of the models. Most designs are intended to descend “tail down” or "tail first". Some of them do this just fine, but others persist in descending “nose down”. So, this could be a function of the design, but there are cases where the same design, as built by different modelers, will descend with different ends down! And there have been a few cases where sometimes a given model will descend nicely one way, and other times, it will be nice and stable, but pointing the other way!

One of the authors (Parks) first ran into this problem with FAI class S9 helicopter models intended for the World Championship in 2006. These models are required to have very large body sizes by the rules (500mm long, 40mm minimum diameter for A type motors, roughly the size of the Estes “Big Bertha” kit!). These models almost always stow the rotors inside the large body, and eject the rotor assembly, which then unfolds, and (hopefully) autorotates. The main body is attached by a shock cord to the rotor assembly. The design in question used high performance, molded, carbon fiber composite blades, with optimized airfoils, planform and twist. The ejectable rotor assembly worked extremely well when drop tested on its own, with good stability and rapid spinup, and extremely low descent rate, even when ballasted to include the mass of the body. However, once the body was attached, the combination insisted on dropping with both the body horizontal and the normal rotor spin axis horizontal.. 90 degrees away from what it should have been. As a result, the rotors would never spin up. It is believed that the large, but very light (about 9 grams with engine casing) body actually had more drag than the non-spinning rotor assembly. This problem was never fixed, and the models were never flown in competition.

The other author (Coleman) first ran into this problem when flying kits for NAR Helicopter Duration, probably around the late 1990s. Either by some combination of making the rotor too heavy or the fins too big, he made a very nice helicopter that would only come down nose-first (the wrong way for this model). After fixing it by adding rear weight by using clay for fin fillets, the model would recover in the correct orientation, but the added weight made it a very poor performer. This model is shown in Picture 1, you can see the red clay in the fin fillets.

Picture 1. An early model made by Coleman at left, showing evidence of fin fillets made of clay in attempt to cause tail-first descent.

At the last NARAM (52), the PFM team made an NAR D HD model with molded blade technology, but as a more typical NAR external rotor design. Again, it had outstanding spin up and descent rate performance, but, the full vehicle, in a normal flight, persisted in descending nose first. This meant that the very optimized airfoils on the rotor blades were working upside down, with a huge loss of performance due to the extra blade drag and loss of lift. A quick series of experiments were done to help understand the problem, and they indicated that the descent was strongly a function of the rocket fin size and Center of Mass (CM) location. Thus, it had fundamental similarities with the normal rocket stability problem. Over the years, experience and research have led to the commonly accepted rule of thumb of “keep the Center of Pressure (CP) at least one caliber aft of the CM” as well as methods like the Barrowman Equations for estimating the CP of “normal” rockets (which are used in all of the common modern rocket design programs).

This has been a common problem for other modelers as well. We cite one example posted on the yahoo group ContestRoc (or cRoc), message 29852, by Wolfram von Kiparski on June 13, 2011:

> "I wish I did [some test flights] with the Rose-a-roc in the original post.
>
> ...
>
> It descended upside down and rotating very slowly - almost like a parachute.
>
> Basically, it flew like crap."

So, was it possible to develop similar equations, or at least some “Rules of Thumb” for predicting the descent stability of Helicopter Duration models? We decided to attempt it, and the result is this report.

Background

First of all, why do we care which end of the model is pointed down? The rules (at various times) have specified that the model cannot tumble, or swap ends during the descent. The FAI rules still specify this, but the current NAR rules are more liberal, and allow some swapping of ends during the descent. (some RSO interpretations of the rules have not allowed nose down descents at all, even though this was never explicitly stated in the written rules!). So, at least for NAR competion, the rules don’t really care which end is first.

However, to achieve good rotor aerodynamic performance, the use of a good blade airfoil is critical, and cambered airfoils always have better lift to drag ratio than symmetric airfoils (at similar Reynolds Numbers). Also, a really good blade design involves the use of a twisted blade. And really careful aerodynamic design of the rotor means including the required angle of attack for the airfoil into the blade pitch distribution. All of these factors mean that the rotor blade has to be designed and manufactured for a specific direction of flight. If you design for tail first descent, and the model comes down nose first, the duration could be reduced by by over 50%, depending on how well the rotor design was optimized for a particular descent direction.

Traditionally, people have tried for a tail first descent, although its very unclear to the authors about why this is so. We suspect that it was partly due to a common misconception about “pendulum stability”. i.e, like a parachute, where the mass WILL be below the parachute. This concept works for pendulums swinging on fixed pivots, and it obviously works for parachutes. Unfortunately, the helicopter rotor behaves very differently from a parachute. With the typical rocket type parachute, if the model pitches a bit away from vertical, the drag force on the chute is still nearly vertical and nearly centered on the chute. If the suspended mass swings off to the side, the canopy drag force now has an offset from the mass, and there is a rotational moment produced by the drag force about the center of mass, causing the chute to swing back to vertical.

However, this does not apply to a helicopter rotor, just as it does not apply to a fixed wing aircraft in normal flight. With both the wing and the rotor, the dominant force is lift, which is always perpendicular to the direction of motion. For an aircraft it’s the forward flight motion, but for the rotor, it’s predominantly the speed due to the spin of the rotor, which is many times faster than the descent rate. Thus, if a rotor is tilted, the spin motion and the lift force is tilted with the rotor. For a helicopter with a rigid body, the tilted lift force still has zero moment about the center of mass, and thus no stability effect.

As we have seen in practice, HD models are stable, but they can be stable either nose up or nose down, with the rotor at the top or at the bottom. Pendulum stability is not the answer, so what is?

Propeller effects on Aircraft Stability

Helicopter rotor dynamics is a very complicated subject, usually taught at the graduate school level, so well beyond the scope of a relatively simple stability estimation that could be of use to the typical HD competitor. However, there is a somewhat similar situation with respect to the stability effects of aircraft propellers, and, in that case there is a simple way of approximating the stability effect of a prop. Our goal was to see if something similar could be done for HD models.

There was a substantial amount of aerodynamic research on propeller stability effects, mostly done 60 to 80 years ago. In that era, all aircraft were driven by propellers, and the engine power was increasing rapidly. With larger and higher powered propellers, it became obvious that the yaw stability of the airplanes was being reduced by some sort of propeller stability effect.

A lot of wind tunnel testing was done. Typical reports of the results are given in References 1-4. There was also work on reducing the experimental results into a form that was easily usable by aircraft designers. Two very good reports on this are given in References 5 and 6 by Ribner, both published in 1943. (Originally as classified reports during World War II). The best summary of the results, and a method which is still commonly used by designers of propeller driven aircraft, is, in Ribner's own words from the conclusion of the reports:

> "In developing side force, the propeller acts like a fin of which the area is the projected side area of tile propeller, the effective aspect ratio is of the order of 8, and the effective dynamic pressure is roughly that at the propeller disk as augmented by the inflow. The variation of the inflow velocity, for a fixed-pitch propeller, accounts for most of the variation of side-force with advance-diameter ratio."

This certainly satisfies the " simple" criteria. Just take the HD rotor, scale the area by some factor (equivalent to converting the propeller blade area into a projected side view), and just insert it into a typical rocket stability method, such as Barrowman or Center of Lateral Area. There are a lot of differences between an aircraft propeller and an HD rotor, so we did not expect to directly apply the Ribner method, but the thought was that we could do some drop tests, empirically find the CM locations for "neutral" stability, and then fit a "rotor area to fin area" scaling factor to the data.

HD model stability

The propeller data says is plausible to consider a spinning HD rotor as having a stability effect (i.e. side force due to "angle of attack" of its spin axis) that can be modeled by an "equivalent fin". If this is true in for our models, then we have a good explanation of the descent stability. We have these big rotor blades on one end, and, if they act at all like propeller blades, then they act like large fins at that end of the model. If the CM is far enough "upstream" of the blades, then we have typical weathervane stability.

The situation is complicated by the fact that we also have fins on the model to stabilize it during the rocket boosted ascent and coast phases. With a typical HD model design, the deployed rotor is at one end of the model, while the fins are at the other. As we all know, fins at the back of a rocket increase stability, while fins at the front decrease it. If the rotor "equivalent fin" is big enough, and the CM is close enough to the aft end of the model, then it is stable in a "tail first" descent. If the CM is too close to the rotor, or the rotor "equivalent fin" area is too small compared to the rocket fins, then the model is stable in the nose down configuration for descent. This type of model certainly has a chance to explain the observed HD model behavior.

Now, the prior art is all related to propellers which are driven by shaft power. This means that the air enters from the front at some airspeed, and is accelerated to a higher airspeed as is passes through the propeller disc. And, it was common for these propellers to have variable and sometimes rather large pitch angles, which resulted in substantial projected side area.

However, the HD rotor works similar to a parachute in that it decelerates a mass of air in the process of providing its retarding force. The air enters the rotor at a higher speed (and smaller diameter streamtube) and exits as a lower speed (and larger diameter) stream tube. This is called "induced flow" effect. This means that in a nose down descent, the rocket fins see a lower airspeed flow than they do in a tail down descent. It is hard to tell the speed ratio for typical HD models, but there has been extensive research into this induced behavior for windmills. It turns out that the maximum energy is extracted when the inflow and outflow speeds conform to the Betz Limit (Reference 7). In practice, a good rotor will have an exit airspeed of about 1/3 of the inflow speed. However, this means that the aft fins might only have 1/9 the effect that they do in tail first descent.

At this point, we should discuss the effect of rotor "cone angle", sometimes called "dihedral". It is commonly thought that rotor blade "dihedral" is critical for descent stability. If the model comes down nose first, add more "dihedral". However, rotor cone angle is not the same as dihedral on a fixed wing aircraft.

Dihedral on a fixed wing aircraft works by the following method:

Roll disturbance causes a component of wing lift to the side

This causes an acceleration of the aircraft to the side

Resulting lateral velocity combines with forward flight velocity to give a non zero yaw angle

The yaw angle combines with the dihedral to increase angle of attack and thus increase lift on the lower side of the wing, while decreasing angle of attack and lift on the other wing

Resulting lift difference rolls the airplane back to level flight

On a spinning helicopter rotor the aerodynamics are quite different:

First, pitch or roll moments result in a rotor tilt response approximately 90 degrees later in the rotation. This is commonly, but mistakenly, called "precession". It is actually a case where the spinning rotor is a resonant system with an undamped natural frequency of 1/rev. As is typical in a resonant system, periodic excitation at the resonant frequency results in a 90 degree phase lag (and possibly an exaggerated amplitude) in the response. (In reality, the rotor has aerodynamic damping and blade flexibiltiy and the phase lag is not quite 90 deg.) But, the key here is that an increase in lift on a rotor blade in one position in the rotation results in the rotor blade actually rising up to its maximum deflection about 90 degrees later in the rotation.

If the rotor is tilted, the lift vector tilts also, and the helicopter will accelerate to the side, similar to a fixed wing airplane. This sideways speed will result in a change of rotor blade lift which depends on the phase angle of the blade relative to the sideways velocity.

If the rotor blade spanwise axis is perpendicular to the sideways velocity, the advancing blade has increased airspeed, and thus increased lift. Similarly, the retreating blade has decreased lift. This change in lift distribution results in a moment about the hub, but, as mentioned above, the response is delayed by 90 degrees of rotation, resulting in maximum deflection when the blade axis is aligned with the sideways velocity. Thus there is a stability effect to correct for a sideways velocity. (Normal helicopters use cyclic pitch controls to overcome this effect and allow the helicopter to actually go somewhere!) HOWEVER, this stability effect does not depend on cone angle, aside from "dihedral" producing a very slight change in moment arm of the lift force about the CM. Also note that this effect is stabilizing regardless of the location of the rotor on the model!

When the rotor blades are aligned with the sideways velocity, it just produces a spanwise flow on the blade. In normal aerodynamics of high aspect ratio wings, this is considered to have no effect, although there may be slight effects on the *flow at the blade tips. But, a change in the lift of the blades in this position would result in the rotor tilting about an axis parallel to the sideways velocity vector, which would not correct the initial upset.*

It should be noted that the cone angle often seen on full scale helicopter blades is actually a structural effect. Even though the blades are very light compared to the helicopter, the tip speed is very high and there are large centrifugal loads, much larger than the lift loads on the blades. In many helicopter hubs, the blades are actually attached with hinges at the root that allow the blades to freely pivot up and down. When spinning, the blades just deflect on their hinges until the only loads on the blades are along the spanwise axis of the blade, thus minimizing the structural loads.

Thus, it does not appear that blade cone angle is a significant stability effect on our models. There is a stability effect which tends to compensate for sideways movement, but it is only a function of the spinning rotor, and not cone angle.

So, this leads us to our hypothesis:

Hypothesis

It is possible to predict the descent stability of a HD model using a normal ascent stability calculation by modeling the rotor blades as an “equivalent fin”. The stability will also be a function of the Center of mass location and the size and location of the rocket fins used for boost stability.

Description of test program

Since there are a lot of unknowns here, and there are no simple ways to combine the spinning rotor aerodynamics with the rocket fin aerodynamics, we decided to do a drop test program to determine stability of various HD model configurations.

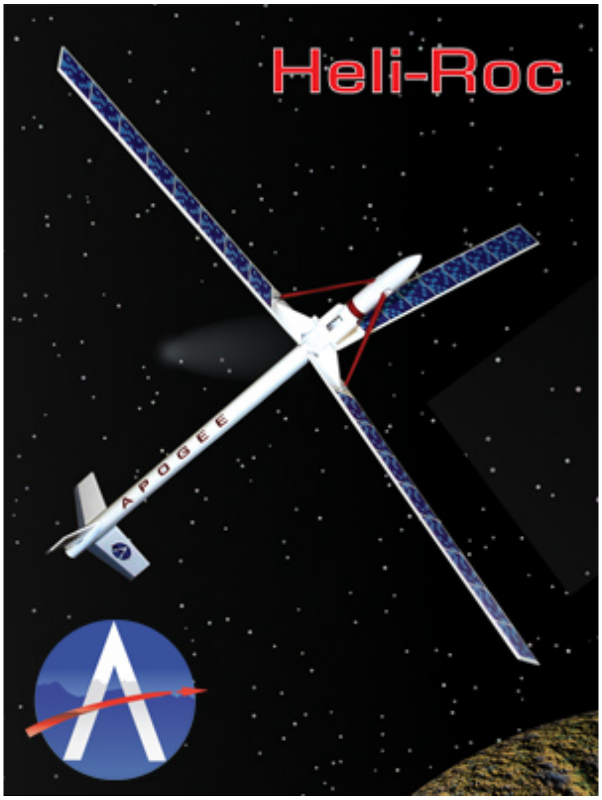
It should be noted that modern Computational Fluid Dynamics analysis could probably give a good solution to this stabilty problem, however, this kind of analysis requires a professional aerodynamicist to run it, software costing hundreds of dollars per day to lease and a high performance computer cluster to run it, and it may take a month of effort to get an answer. And, in our experience with such analysis, you still need some experimental data to validate the analysis! Maybe in another decade or two, this will become feasible to a dedicated hobbyist!

We could have also done wind tunnel testing, but that requires a wind tunnel! That would give much better quality data, but was not an option available to us.

The first task was to define the test models. We decided to limit tests to the “RotaRoc” type. This is the simplest, and most common HD model (ignoring low performance “Tasmanian Devil” types). It is a conventional rocket body tube, with nose cone in front and fins in the back. Typically there are 3 fins, and 3 rotor blades. The rotor blades are hinged at the nose, and fold aft along the body for boost. At ejection, they are released by a burn through thread retainer, and pulled to deployment position by rubber bands. The whole rocket then rotates (hopefully!) as a unit, and descends (hopefully!) tail first.

This simple configuration was easy to make as test models, and it was easy to make interchangeable rotor, body tube and fin units which slipped together and could be retained by a bit of masking tape. The rotors were additionally simplified because they did not need to fold for our testing.

We chose to base our test model on the Apogee Components “Heli-Roc” design. (Picture 2) We have built and flown these in the past and they work well. We also used one for our preliminary stability tests when trying to debug our NARAM 52 HD model.



Picture 2: The Apogee Heliroc, which the test models were based on

The Heli-Roc is designed for 13mm motors, so we scaled it up to 18mm size for our tests. At 18mm, we could use both T-20 tube and the larger TT-20 tube which telescopes over the T-20. This allowed “plug together” modularity. We also defined a “nominal rotor” and then looked at variations of parameters relative to that.

The drop test models were made with the following components.

The 3 aft “fin cans” with different size fins. The fin sizes are shown in Table 8. The fins were laser cut from “lite ply” (for durability). Each fin can was then ballasted so they were the same mass within .5 grams. This allowed swapping fins with no change of CM of the model. The fin units were made from TT-20 tube to slip on the outside of main body.

The body tubes were cut from T-20 tubing, each 10” long (to allow cutting 3 tubes from one 30” length of body tube with no waste). A standard balsa bulkhead was installed, with a ¼” bolt and nut through the bulkhead. These were glued into the body tubes, at 0, 1, 2, 3, 4 and 5” from the end. Any one of the six tubes could be installed in the model with either end forward, allowing 11 possible CM locations.

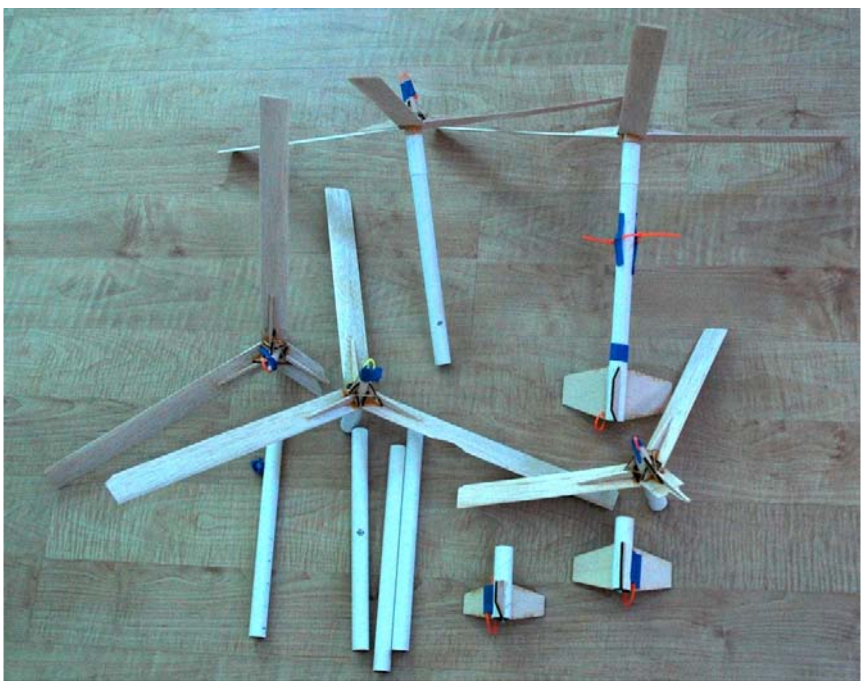
There were 5 rotor assemblies constructed. The core was a short TT-20 tube to slip over the T-20 bodies. We then added a TT-20 nose cone, which is roughly conical for most of its length. This made it easy to attach the blade hub assemblies. The balsa wood blades were all 1.25” chord (3 blades out of 4” wide wood with a bit of trimming margin) and 3/32” thick. The blades were hand carved to a 7.5% thick flat bottomed airfoil section (typical for most NAR HD models) on all but the inner 1” of blade, which was left square for ease of accurate attachment to the hub. 4 sets of blades were made with 12” radius, while one set was cut down to 8.25” radius.

We made laser cut hub parts from 1/8” lite ply to accurately set the blade angles, both the pitch angle and the cone (“dihedral”) angle.

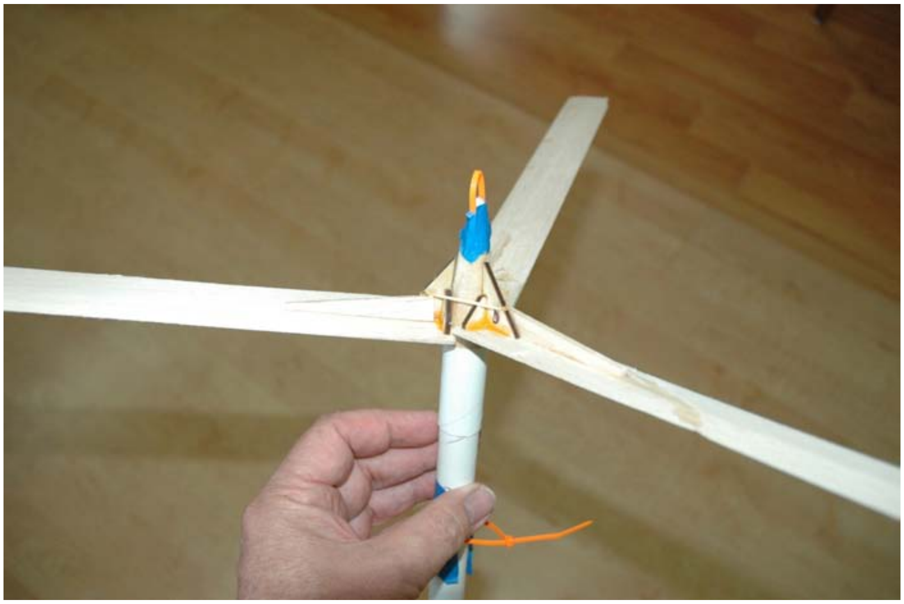
There were 3 cone angles, 3, 7 and 11 degrees from plane of rotation, all with -7 deg pitch and 12” radius blades

There were 2 pitch angles, -7 deg and -4 deg, both with 7 deg cone angle and 12” radius blades

Finally, as mentioned above, there were 2 blade spans, 8.25 and 12 “ radius from centerline, both with -7 deg pitch and 7 deg cone angle. The models are shown in Picture 3, a close-up of the rotor head is shown in Picture 4.



Picture 3. Several of the modular model parts, one completed model at right. Pictures are post-testing, so some breaks are obvious.



Picture 4. Close up photo of a typical rotor hub assembly the pitch and cone angles were each set by a laser cut plywood piece, and the two pieces fit each other with laser cut notches to ensure consistent alignment. The rotor blade root was left square to mate precisely with the laser cut parts. After initial breakage, the balsa extension and kevlar wrap were added.

After the first test drops, it was obvious that the blade hubs were not strong enough, so the hubs were reinforced with extra balsa strips to distribute load spanwise out onto the blades and the hubs were wrapped with Kevlar thread to prevent the blades from peeling off the nose cones. Even with this, we still had significant blade breakage. Most often it was with a nose down descent where the spinning blade it the floor at high tip speed, but occasionally it was when a model fell sideways or otherwise did not yet spin up, and hit at much higher speed. In the end, blade damage limited the amount of tests we could accomplish in the time we had access to our drop test facility.

Drop Test method

The testing location was an open indoor atrium, a 5-story building called Genentech Hall, part of the University of California San Francisco where one author (Coleman) is employed. On weekends and holidays, the heating/cooling is minimal to save money, which decreases airflow to very little. Each story is roughly 20 feet high, except for the first story which was 26 feet from balcony to floor. After a few preliminary tests, the first story height was sufficient to see all the transitions we needed to see, and avoided problems with a drop test drifting into a lower balcony. One view is shown in Picture 5. All tests were performed on July 4th, 2011.

Picture 5. View of the test facility, taken from the second story. All tests were conducted from the first story to the floor.

We used a fishing pole with reel to hoist models between flights. This had several advantages, it allowed a short time between drops and allowed models to be dropped 2 meters away from the sides of the atrium. This was first done in reference 8.

A model release mechanism was developed. This is shown Pictures 6 & 7, it was attached to the end of the fishing line. It was modified from standard "releasable tow hook" from radio control sailplanes, attached to fishing pole so the reel and release was all in the same mechanism. The mechanism contained a standard RC receiver, battery and servo connected to the releasable tow hook. An RC transmitter was used to activate the tow hook release. By attaching zip ties to the nose, fin root, or CM, any of 3 drop positions was available (tail-first, nose-first, sideways). This was a vast improvement over the release mechanism in reference 8.

Picture 6. Closeup of the release mechanism, top of one test model.

Picture 7. The release mechanism shown with a complete test model.

The testing setup consisted of two people, one on upper floor with fishing pole and radio transmitter. The other person is on the ground floor to attach model, modify model setup, attempt to catch model, and record results.

Drop distance was about 26 feet, which allowed most transitions to be seen (switching from tail-first to nose-first). It was not high enough to observe the repetitive flipping behavior that has been sometimes observed in the field, but that was not the main focus of this report. Complete drop results are contained at the end of the report, each section of tests has a brief table summarizing the tests relevant to that experiment.

Problems with the testing

The main issue is that the models were a bit heavy, and, when they fell sideways or did not spin, they hit the ground hard enough to break the rotor blades, even when only dropped from 26 feet. We made quite a few repairs during testing, but some of the blades shattered into many pieces, so it was impossible to continue the tests without a major rebuild. Thus there were some tests that we would have liked to accomplish, but which were not done. Attempting to catch models proved somewhat successful, but models could still break on impacting an author, or missing the catch and hitting the floor.

Center of mass tests

The first tests done were a range of CM locations with our "nominal" rotor with a 7 deg cone angle, 7 deg pitch and 12" radius. We also did this with the medium size fins. We then swapped body tubes to change center of mass locations. In all cases the CM was measured from the tail of the model, since it was much easier to measure without having the rotor in the way of the measurement.

We did tests with the CM 6.5" from tail to 8.25" from tail, which was the farthest forward we could get with our ballasted tubes. We did both nose first and tail first drops, although not all models were dropped nose first (due to higher incidence of rotor breakage in nose first drops). These are shown in Table 1.

In all cases, the models descended in the orientation they were dropped. A nose first drop resulted in a nose first descent, while a tail first drop gave a tail first descent. This was true over the entire range from 7.0 to 8.25" CM locations. While we expected some range of CM locations where the model could be stable either nose up or nose down, this range was much greater than we expected. (i.e. the models were "bistable" or had at least two stable orientations in descent.) But it also starts to offer an explanation of why some HD models can descend nose first some times, and tail first at other times.

Given the large CM range that was bistable, we also did one side drop of the 8.25 CM configuration, and it pitched into a nose first descent. We did not try more aft CM configurations in the initial series, because of concerns of destroying blades and having to skip other tests we wanted to do. Based on these tests, we picked the 8.25 CM location as baseline for the remaining comparison tests.

Table 1. CM test, Medium Fins, Large Rotor, -7 pitch, 7 deg cone

Test #	CM from rear	Dropped	Landed
3	6.5	tail first	tail first
1	7	tail first	tail first coning
2	7	nose first	nose first
4	7.25	tail first	tail first
5	7.5	tail first	tail first
6	8	tail first	tail first
7	8	nose first	nose first
8	8.25	tail first	tail first
9	8.25	nose first	nose first coning
10	8.25	sideways	nose first

Cone angle tests

We tested 3 different rotor cone angles, all with full span, 12” radius, blades, and -7 deg pitch angle, and the CM at 8.25” from the tail. The results are shown in Table 2.

The 3 deg and 7 deg rotors were both bistable and fell nose or tail first, as dropped but both would go to nose first if dropped sideways

The 11 deg rotor would go to tail first if dropped sideways, so that much cone angle did make a difference.

Note that a 5 deg change in coning angle results in approximately .5” of axial shift of the centroid of the rotor blade area so there is at least some mechanism for the cone angle changing the stability.

Table 2. Cone Angle Tests, -7 deg pitch, Large Rotor

Test #	CM from rear	Cone Angle	Fins	Dropped	Landed
18	8.25	3	m	nose first	nose first
9	8.25	7	m	nose first	nose first
16	8.25	3	m	sideways	nose first
10	8.25	7	m	sideways	nose first
19	8.25	11	m	sideways	tail first
12	8.25	7	l	sideways	nose first
20	8.25	11	l	sideways	sideways
17	8.25	3	m	tail first	tail first
8	8.25	7	m	tail first	tail first

Rotor Diameter tests

To assess the effect of rotor size on stability, we tested a range of CM locations with a smaller, 8.25" radius, rotor. With the smaller, lighter rotor, the farthest forward we could get the CM was 8" from the tail. At that CM, it fell nose first, even from a tail first drop. We shifted the CM aft to 7.5" and again, it would fall nose first regardless of release orientation. With the CM at 6.5", the model was gradually rotating towards nose first from a tail first drop. Finally, at 5.5" CM we had similar bistable results as the large rotor a 8.5" CM. So, from this test, it appears that the rotor size has a large effect on stability.

Table 3. CM test, Medium Fins, Small Rotor, -7 pitch, 7 cone

Test #	CM from rear	Dropped	Landed
25	5.5	tail first	marginal but tail first
26	5.5	nose first	nose first
27	5.5	sideways	side towards nose first
24	6.25	tail first	side tending nose first
23	7.5	tail first	nose first
21	8	sideways	nose first- marginal
22	8	tail first	nose first

Fin Size tests

Starting from the baseline rotor, and with the 8.25 CM, we tested 3 different fin sizes. All of the models were dropped sideways. Remember that with the baseline medium fins, the model was bistable, depending on drop orientation, but when dropped sideways, it would rotate to a nose first attitude.

With the small fins, the model would rotate to tail first descent, while with the large fins, it would go nose first. With the small fins and a more aft 6” CM, and a nose down drop, it appeared marginally stable and like it was attempting to flip to tail first, and may have done so given more drop height.

We did a similar test with the small rotor and a 5.5” CM. The medium fins were bistable, the small fins gave definite tail first stability with both tail first and sideways drops.

So, fin size is a critical parameter in descent stability.

Table 4. Varying fin size tests with large rotors, 7 deg cone, -7 deg pitch

Test #	CM from rear	Fins	Dropped	Landed
11	8.25	s	sideways	tail first
12	8.25	l	sideways	nose first
8	8.25	m	tail first	tail first
9	8.25	m	nose first	nose first coning
10	8.25	m	sideways	nose first
30	6	s	nose first	coning trying to flip

Table 5. Varying fin size tests with small rotors, 7 deg cone, -7 deg pitch

Test #	CM from rear	Fins	Dropped	Landed
25	5.5	m	tail first	marginal but tail first
26	5.5	m	nose first	nose first
27	5.5	m	sideways	side towards nose first
28	5.5	s	tail first	tail first
29	5.5	s	sideways	tail first stable

Blade Pitch Tests

In the Ribner method for propeller stability effects, the critical parameter is the blade projected side area, so high pitch blades result in larger stability effects. Propellor pitch angles can be quite large, well over 45 deg in the cases Ribner considered. Our HD models have much lower pitch angles, so we did 2 cases to check if there was a stability difference. Our nominal blades were -7 deg pitch angle, one that ensures a rapid, reliable rotor spin up. We made another rotor with blades at -4 degrees, which is a typical limit for HD models. Spin up is slower, and maybe less reliable, but, if it works, the descent rate can be slower. The results are shown in Table 3. As you can see, there was minimal difference in stability. As expected, the -4 deg rotor took much longer to spin up, but once it did, the descent rate was noticeably slower.

Table 6. Blade Pitch Tests, 7 deg Cone, Medium Fins

Test #	CM from rear	Pitch	Dropped	Landed
15	8.25	4	nose first	nose first
9	8.25	7	nose first	nose first coning
13	8.25	4	sideways	nose first slowly
10	8.25	7	sideways	nose first
14	8.25	4	tail first	tail first
8	8.25	7	tail first	tail first

Attempts at a stability estimation method

Once we had the drop test data, we attempted to determine if "an equivalent fin" type of analysis would replicate the results. The plan was to create analysis models, then scale either entire blades or the blade chord (replicating a projected lateral area type method) until we got the "CP" to match the neutral stability CM as determined by the testing. Of course, this was complicated by the large range of CM's that resulted in bistable behavior.

There are two main stability analysis methods used by rocketeers. The original classic method was the "cardboard cutout" method. Draw the side view of the rocket on a piece of uniform cardboard, cut it out, and then balance it to find the CM of the cardboard. This gives the "center of lateral area", which, for most rocket like shapes is a good approximation of the Center of Pressure when the rocket is at a 90 degree angle of attack. In almost all cases, this CP is ahead of the CP at small angles of attack and thus is a conservative (and safe!) estimate of rocket stability. In modern times, many computer aided drafting type programs will automatically calculate the center of lateral area of an arbitrary 2 dimensional shape. (It has never been clear how to handle this method for a 3 fin rocket, we chose to just treat it with a symmetric profile as if it had 4 fins. Aside from the lateral area of the body, it really does not matter.)

The other common method is the Barrowman Equations, as developed by former NAR President Jim Barrowman, as part of his graduate thesis. Originally intended to assess stability of sounding rockets, they have gained widespread usage in hobby rocketry as well. The currently available rocket design software programs like Open Rocket and RockSim appear to use something like the Barrowman equations to estimate CP location. The key feature of the Barrowman method is that it is specifically analyzing the small angles of attack typical in the flight of a stable rocket.

In our case for HD models, it was unclear which method might be better. CLA certainly applies to the body and fins when we did a sideways drop case, and maybe some projected area type scaling of the rotor would work. Barrowman certainly applies to the nose, body and fins of the rocket in nose first flight, and might even apply for tail first, but the deployed rotors are certainly not at low angle of attack. But, again, maybe some projected area factor would work.

So, we tried both methods. CLA was done in a CAD program (Shark FX) while Barrowman was done in Open Rocket. We did an appropriate model of the basic rocket, either side view or Barrowman, and then added rotor blades to the nose. We started with the baseline 12" radius rotor with 7 degree cone angle. We then tried scaling the blade chord (i.e. projected area type factor) and we tried scaling of both span and chord. Obviously, with just one data point, the 8.25" CM from the nominal rotor drop tests, its easy to get a match. For the CLA case, it was by scaling the rotor chord to about half the real value. For Open Rocket, we scaled the entire rotor to 45% of original size. For Open Rocket, we modeled it both tail first and nose first.

The Open Rocket results are in Figures 1 and 2.

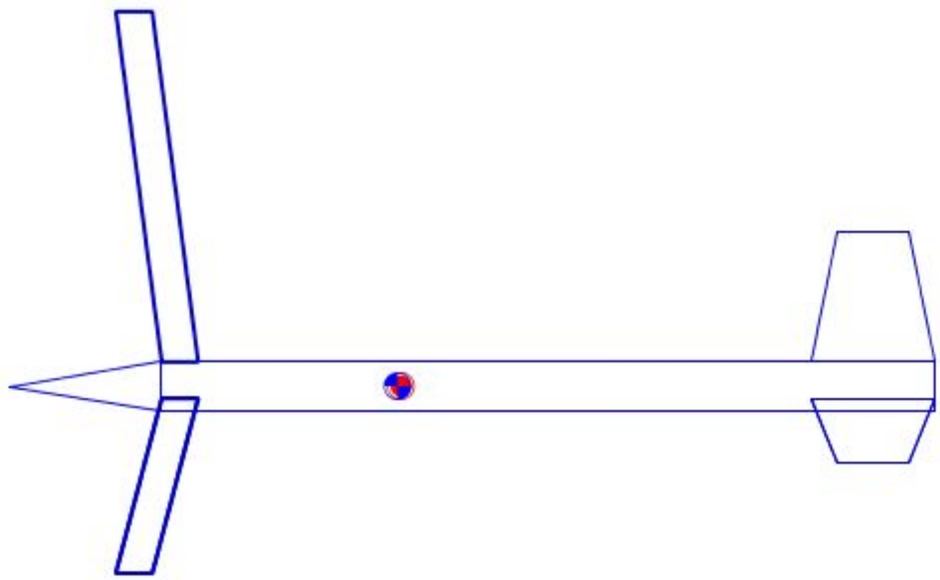


Figure 1 Open Rocket nose first case, with scaled 12" radius rotor. Scale adjusted to put CP on CM

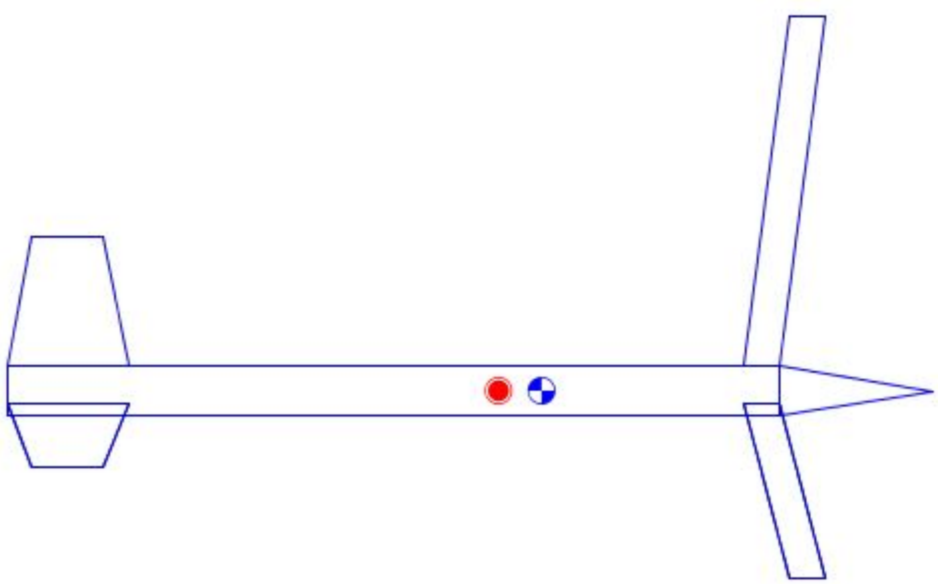


Figure 2 Same model in Open Rocket, but rotated to tail first orientation. Same scale factor on rotor as above. Note that this case shows a slight nose first stability

So, when we scaled the rotor for neutral stability in the nose first case, we got some positive nose first stability in the tail first case (CM closer to the nose than the CP). This seems reasonable, within the resolution of our drop tests.

Now, if we apply the same rotor scale factor to the small diameter rotor case, we get the results in Figures 3 and 4.

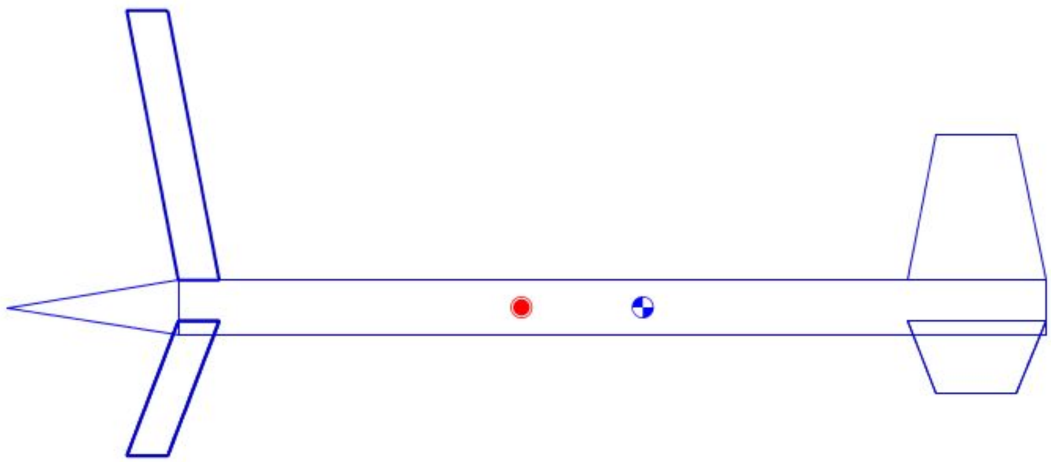


Figure 3 small rotor nose first case, same scale factor as above. Note that this case shows strong tail first stability

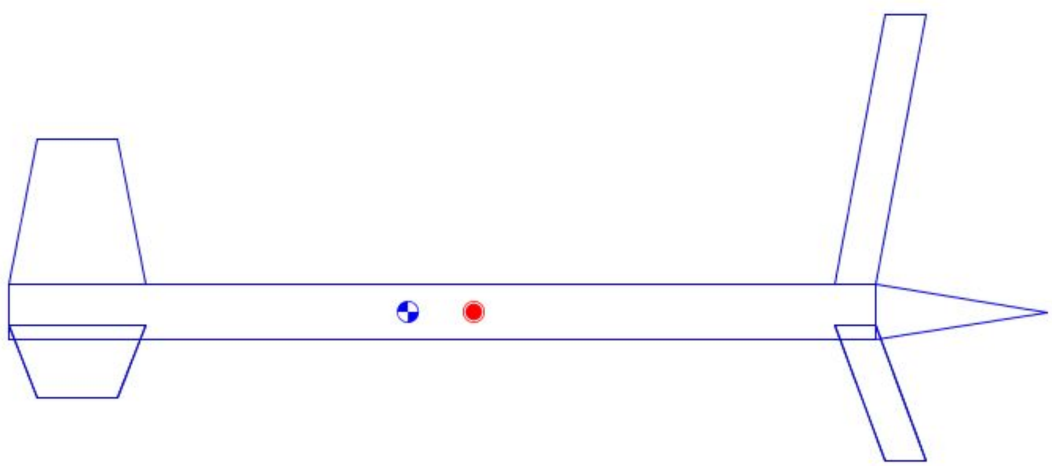


Figure 4 Small rotor, tail first case. This case also shows tail first stability.

So, for the small rotor, the same factor shows rather strong tail first stability in both cases, which does not match the test results. Thus, the equivalent fin method does not seem to work in Open Rocket. Since it only takes one failure to disprove a theory, we did not do any other cases, such as different fin sizes.

Now, as mentioned, Barrowman methods are low angle of attack, but the best determinant of stability might be the sideways drop, so what about CLA? Figures 5 and 6 show the two rotors with CLA, as drawn in a CAD program. In this case, it was easier to just scale the rotor blade chord, in the two cases (aspect ratio does not matter in a CLA type method). A scale of 50% is shown. It is not quite perfectly matching the 12” rotor test CM, but is pretty close. In this drawing, the drop test CM location is shown by the circle, while the nearby lines are the CAD generated CLA.

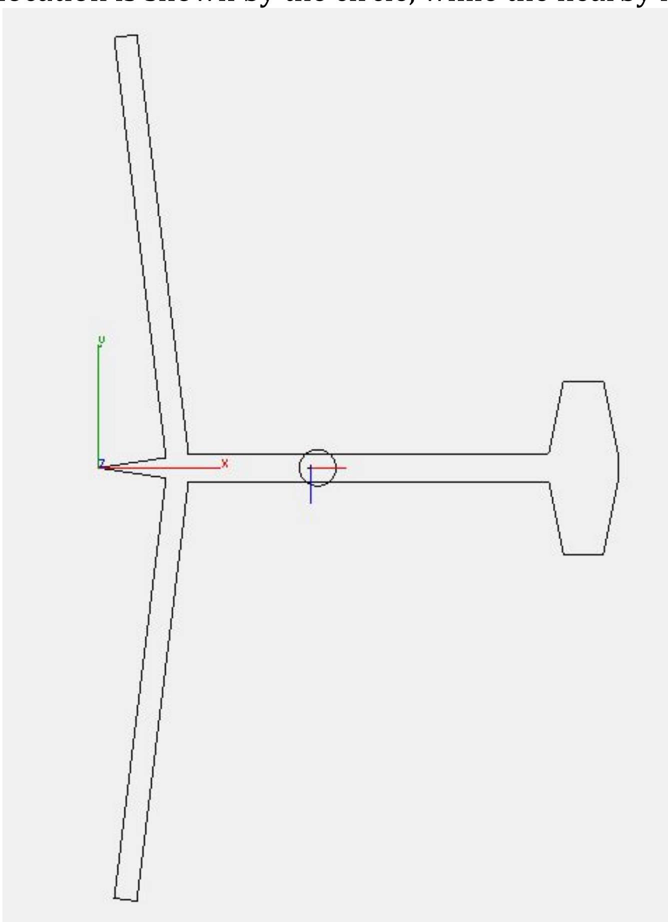


Figure 5 Center of Lateral Area drawing for large rotor, with chord scaled to 50%. CLA is close to drop test CM

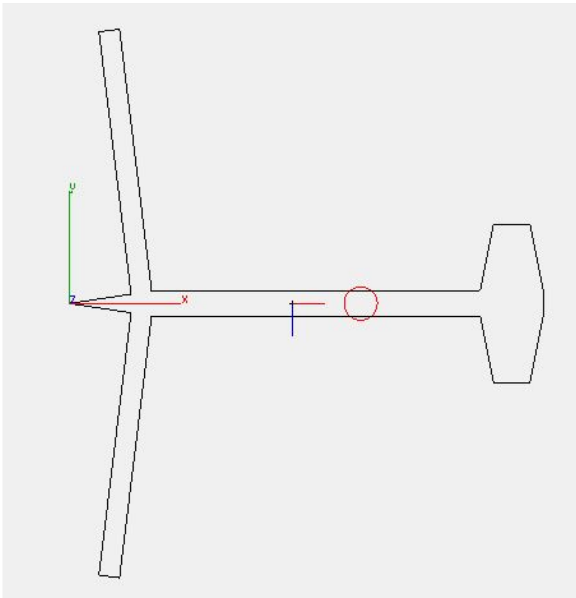


Figure 6 CLA for small rotor, with the same scale factor as above. CLA is well ahead of CM indicating tail first stability

Again, only one case was tested, but again, it failed. Thus, it does not appear that a simple “equivalent fin” method will work for HD type models. It does appear that the rotor has SOME equivalent fin type effects, since the CP from the tests is much closer to the rotor than just what you would expect from the rocket fins.

The other surprise result from the testing was the very large range of CM positions that resulted in bistable behavior. Is there a way to explain this? As mentioned above, normal helicopter theory (and similar windmill theory) say that a spinning rotor that tilts will produce a moment that attempts to tilt the rotor back to level . This moment does not depend on CM location (aside from the CM being on the rotor axis). The textbooks have very complicated methods of estimating this moment, since it depends very much on blade flexibility (including the hub flapping hinges or flexures that are common on full scale helicopters). As mentioned in Reference 12, in the context of windmills in yaw, the blade stall behavior may result in a large increase in this stability as well. (all normal NAR type HD models with untwisted blades certainly have fully stalled root airfoils). The stall behavior has some lag and hysteresis which is not critical in airplanes, but is very significant in spinning rotors. So, while we do not have an easy way to estimate it, we know this stability mechanism exists and probably applies to HD type rotors.

It appears that this effect is at least a partial explanation for the bistable behavior. To understand this, we need to look at typical stability effects. While different branches of engineering use different terms, and different axis conventions (and thus signs for forces), we will explain this using normal aircraft pitch stability type axes and terms. In the case of an HD rotor the behavior in pitch and roll should be identical. (the yaw axis is defined as the rotor spin axis in this case)

There are two requirements for static stability. At the desired angle of attack, the moment about that axis must be zero, so if the model is at zero angle of attack there should be no moments trying to rotate it away from zero. The other requirement is that for a small perturbation of angle of attack, the model should make a moment that tends to return the model to zero. Thus at positive angle of attack, a negative moment is produced. (there are many more requirements for dynamic stability that are beyond the scope of this discussion).

So, if we plot pitching moment (in arbitrary units) vs angle of attack we get the following in Figure 7:

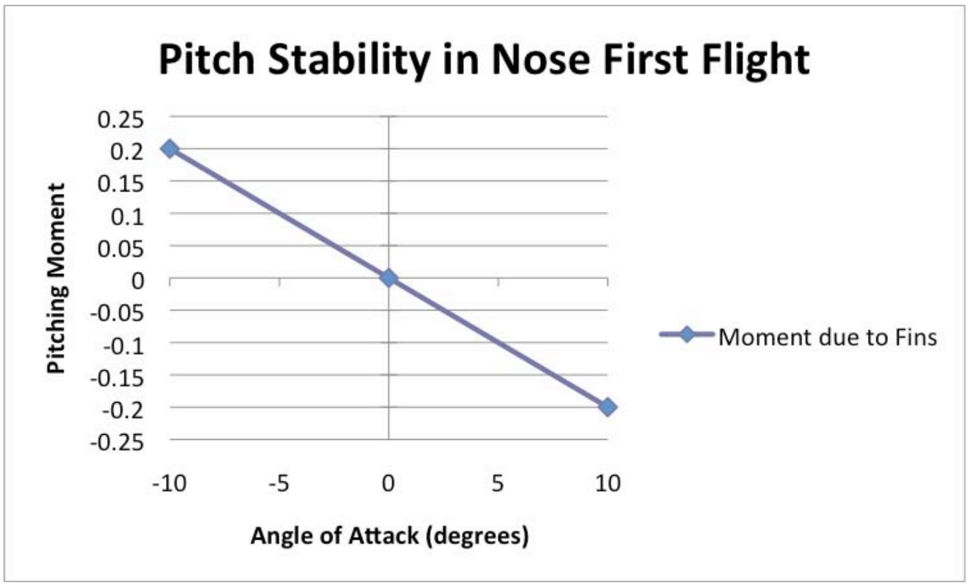


Figure 7 Moment vs Angle of Attack for a conventional, stable rocket

This, for example, is exactly what you will get from the fins on a normal, stable rocket.

Now, if you try to fly that rocket backwards (i.e. tail first), the fins are destabilizing. Again, the moment is zero with the tail pointing directly into the relative wind (180 deg angle of attack in this case), but once the rocket is perturbed, the lift on the fins now tries to move the rocket AWAY from zero. Thus, the moment increases as the angle of attack goes away from 180 deg. This is shown in Figure 8.

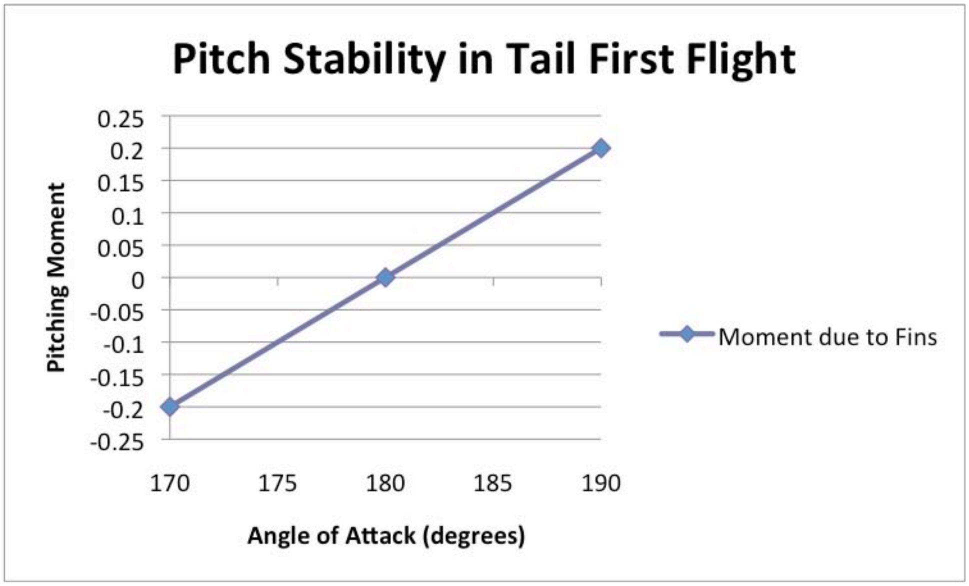


Figure 8 Moment vs Angle of Attack for a normal stable rocket in tail first flight. The positive slope of the curve implies that the rocket is not stable in this orientation.

However, as we mentioned the rotor itself has a stabilizing effect when it is moving sideways due to a tilt. That tilt is an angle of attack change for the body axis, so we can plot the moment of the rotor on the same plots as above. The other thing is that the total moment on the rocket is just the sum of the individual effects, so we also plot the total moment. The results are shown in Figures 9 and 10.

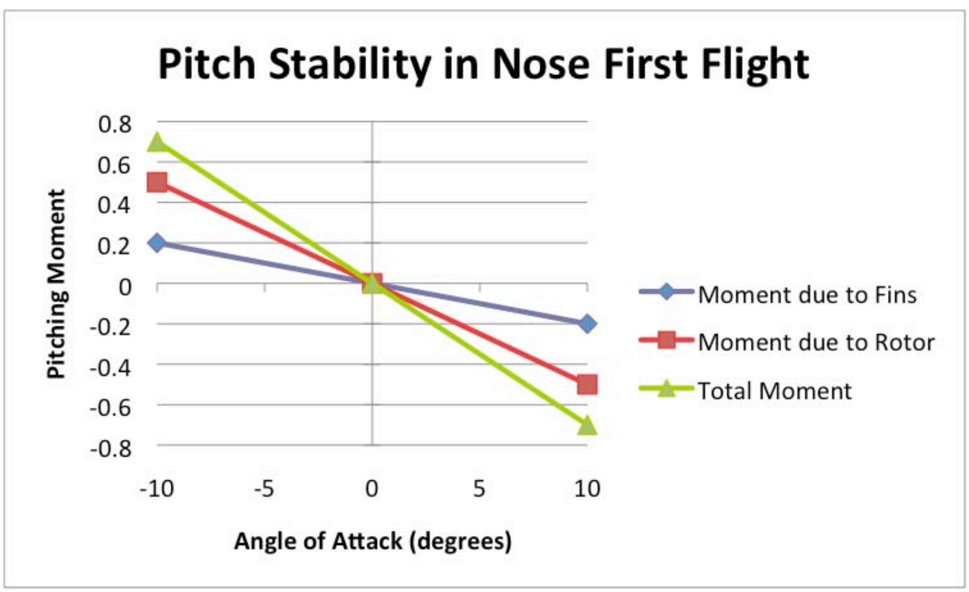


Figure 9 The same rocket as before, but now with a rotor stability term added. In this case the fins and rotor are both stable, resulting in strong overall stability

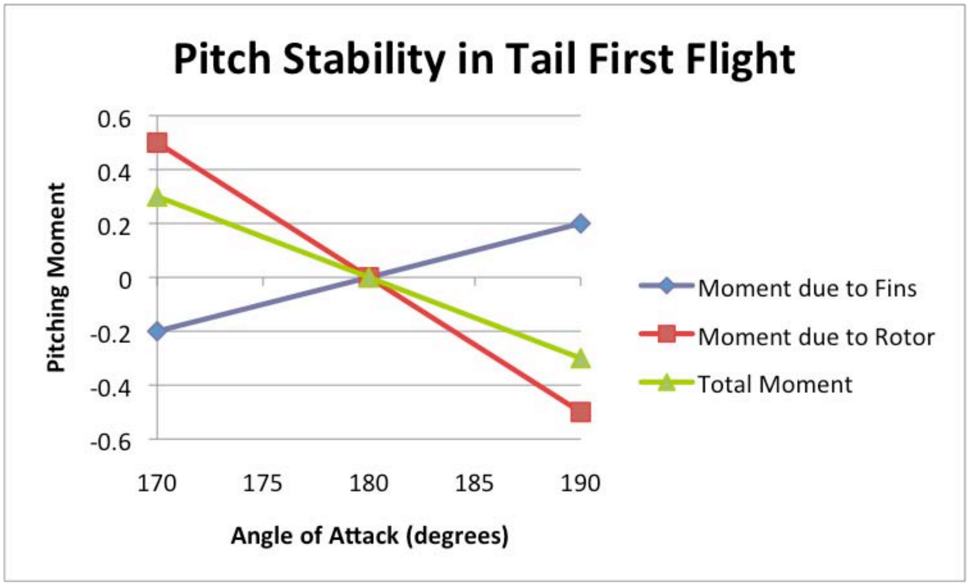


Figure 10 The same rocket as above, but now in tail first flight. The fins result in instability, but the greater stablity of the rotor results in net overall stability.

Note that if the instability of the model due to fins is smaller than the stability added by the rotor, as shown here, the result is that the model has overall stability in EITHER direction.

As we move the CM on the model, we change the stability due to the fins. Moving the CM forwards increases the stability in nose first mode, and also increases the instability in the tail first mode. At some point, the CM is so far forward that the fin instability slope is greater than the rotor stability slope and the net result is overall instability. At this point, a model which is dropped tail first will flip around into nose first descent. A similar thing happens as the fins get smaller or the CM moves aft.

This totally matches the observed results. So, while we cannot (easily) predict this, we can certainly make use of the conclusion to help understand HD models. In order to make a model that will descend in a preferred orientation regardless of initial attitude, we need to have very strong stability in that mode.

Note, both authors have observed HD models in flight that will tumble or will rotate normally for a short period, then flip, rotate normally in the new orientation, and then flip again. Our drop tests were not from high enough altitude to show this behavior, but we have never observed it in any of our own models in flight. We have also never had a close up look at models that did tumble. However, we suspect that behavior may just be due to poor construction, such as blades that are not at the same pitch angle or are able to flop around to different pitch angles while in flight.

Conclusions

So far, we have not been able to create any sort of simple numerical model of the stability. There is a large range of CM locations for a given configuration where it can descent stably either nose first or tail first if it is originally dropped in that attitude. If the model is dropped sideways, the more forward CM locations will result in a rotation to nose first descent, while more aft CM gives a tail first descent. In the middle, the rocket may descend sideways, which means that it has at least 3 different equilibrium attitudes! Thus, it is currently hard to say just what is "adequate" stability, much less being able to isolate a single "center of pressure" for a given configuration. Ideally, an HD model will stabilize in the desired orientation regardless of initial attitude, but the existence of an "either way up" rotor stability effect means that there must be VERY strong stability in the desired orientation to get a model to "flip" out of the undesired orientation.

Fin size is very significant, just as it is in normal rockets. Larger fins make the model more likely to descend nose first. A heavy rotor will move the CM forward and also make the model more likely to descend nose first.

Cone angle of the rotor has a minimal effect and does not work like wing dihedral on a fixed wing airplane. Much of the effect can probably be explained by the fact that it offsets the rotor blade area axially on the rocket. This area really needs some more testing. Going from 7 deg to 11 deg cone angle gave a noticeable change of stability in the sideways drop tests. The rotor blade area centroid would move about .5", resulting in an even smaller shift of the overall vehicle "CP". But this shift was small compared to the large range of CM that could be stable either nose or tail first.

The mechanism for stability vs cone angle may have some effects in it that change the sign of the moment when the blades are below the CM so its totally unclear what the effect of cone angle is on a rocket that descends nose first. It may be that cone angle with the blades pointing away from the tail might also increase stability in a nose down descent! One of the authors has flown rubber band powered toy helicopters with bottom mounted rotors where the blade tips were angled down, and they worked just fine!

Blade pitch had no noticeable effect on stability. The flatter pitch took longer to spin up after drop, but descended noticeably slower.

Suggestions for future work

It would be good to adequately explore the “bistable” region. In the tests we did, we had models that were stable both nose up and nose down, for a wide range of CM positions. In particular, identify the CM locations at the boundaries of where a model dropped sideways will pitch nose downward vs nose upward, and also where a model dropped nose upward will rotate to nose downward, and also the inverse. The problem is that this testing will result in a lot of broken rotors on the test models.

This data, if obtained for a half dozen configurations, might then allow the development of some sort of empirical stability model that would, hopefully, allow easy prediction of the stability of a new design.

In addition, similar tests should be done for models with varying cone angles on the rotors. While, at the moment, the only cone angle effect that we can explain is just that cone angle moves the blade area centroid axially, the little bit of data we have seems to imply that the effect may be greater than this could explain.

Design Recommendations

If you want the model to descend tail first, then it is important to have the fins as small as possible (while retaining good boost stability). Note that Barrowman type stability predictions (as used in most rocket simulation software) may not properly predict the stability of a rocket body with folded, external blades. Also many HD models have a lot of rotor hinge hardware at the nose, and this can also be destabilizing on boost. Some caution and experimentation is needed here. Test flying before a contest ALWAYS helps!

If you want it to descend tail first, then it is also important to have a rotor that has a low blade loading (i.e. rotor weight/blade area). This helps keep the CM close to the tail, a requirement for a tail down descent.

On the other hand, there is no reason why models that descend nose first cannot work just as well as tail first models. The blade airfoils and twist (if any) need to be set up appropriately. Just use large, lightweight fins on the model.

Common likely problems that cause models to descend in the 'wrong' nose-first orientation include making the rotor unit near the nose too heavy and making the fins bigger for increased stability during ascent.

References

1) NASA TN D-318, “A wind-tunnel investigation of three propellers through an angle of attack range from 0 to 85 degrees”, Yaggy and Gogallo, NASA Ames, 1960

2) NACA Technical Note 3228, “Aerodynamic investigation of a four blade propeller operating through an angle of attack range from 0 to 180 deg”, McLemore and Cannon, NACA Langley, 1954

3) NACA Technical Memorandum 562, “Experimental Investigation of Aircraft Propellers exposed to oblique air currents”, Flachsbart and Krober, 1930 (translation of a German report)

4) NASA Technical Note D-1766, “Wind Tunnel Tests of Two VTOL Propellers in Descent”, Yaggy and Mort, NASA Ames, 1963

5) NACA Report 819, “Formulas for Propellers in Yaw and Charts of the Side-Force Derivative”, Ribner, NACA Langley, 1943

6) NACA Report 820, “Propellers in Yaw”, Ribner, NACA Langley, 1943

7) http://en.wikipedia.org/wiki/Betz'_law, downloaded July 21, 2011. This is a good concise explaination, that we have verified against other references.

8) Optimum Shroud Line Length for 50 cm Parachutes. Ryan Coleman. NARAM 41. August 1999. Pittsburgh, Pennsylvania. http://ryancoleman.name/rd41.html

9) Aerodynamics of the Helicopter, Gessow and Meyers, College Park Press, 1999 reprint.

10) Helicopter Performance, Stability and Control, Prouty, Kreiger Publishing, 1995

11) Rotary Wing Aerodynamics, Stepniewski, Dover Publications, 1984

12) Yaw Dynamics of Horizontal Axis Wind Turbines, Hansen, NREL/TP-442-4822, 1992 http://www.google.com/url?sa=t&source=web&cd=1&ved=0CBoQFjAA&url=http%3A%2F%2Fwww.nrel.gov%2Fdocs%2Flegosti%2Fold%2F4822.pdf&ei=HjosTvyLGvHKiALGuIywAg&usg=AFQjCNFMSoq8ZavYnQ3al3gOh-U8QDKaag

Table 7. Complete table of all tests

Test #	CM from rear	blade pitch	cone angle	small rotor	fin type	dropped[1]	result
1	7	7	7		m	tail	tail first coning
2	7	7	7		m	nose	nose first
3	6.5	7	7		m	tail	tail first
4	7.25	7	7		m	tail	tail first
5	7.5	7	7		m	tail	tail first
6	8	7	7		m	tail	tail first
7	8	7	7		m	nose	nose first
8	8.25	7	7		m	tail	tail first
9	8.25	7	7		m	nose	nose first coning
10	8.25	7	7		m	side	nose first
11	8.25	7	7		s	side	tail first
12	8.25	7	7		l	side	nose first
13	8.25	4	7		m	side	nose first
14	8.25	4	7		m	tail	tail first
15	8.25	4	7		m	nose	nose first
16	8.25	7	3		m	side	nose first
17	8.25	7	3		m	tail	tail first
18	8.25	7	3		m	nose	nose first
19	8.25	7	11		m	side	tail first
20	8.25	7	11		l	side	sideways
21	8	7	7	S	m	side	nose first-marginal
22	8	7	7	S	m	tail	nose first
23	7.5	7	7	S	m	tail	nose first
24	6.25	7	7	S	m	tail	side tending nose first
25	5.5	7	7	S	m	tail	marginal but tail
26	5.5	7	7	S	m	nose	nose first
27	5.5	7	7	S	m	side	side towards nose first
28	5.5	7	7	S	s	tail	tail first
29	5.5	7	7	S	s	side	tail first
30	6	7	7		s	nose	coning trying to flip

[1]**(tail means tail first, nose means nose first, side means sideways)**

Table 8. Fin sizes.

Fin sizes	small	medium	large
root c	1.5	1.9	2.3
tip c	0.9	1.1	1.3
span	1.55	2	2.3

Budget:

The models were built from $45.20 in parts from Aerospace Specialty Products and other vendors.

Expenses			
item	quantity	$ each	total
T-20 tube 30"	2	1.75	3.5
TT-20 tube 30"	1	2.5	2.5
T-20 balsa bulkheads	5	2.25	11.25
TT nose cones	5	2.99	14.95
3/32x4 x 36 balsa	2	3.5	7
lite ply	1	3	3
misc supplies tape, glue	1	3	3
			45.2

Fishing Pole, RC equipment, Genentech Hall, camera, tow release mechanism, laser cutter (owned or used at no cost)

Previous R&D reports entered by authors:

Both authors have entered R&D reports before, but never on this topic. One author did drop tests before where some initial reel and release technology was developed, which was improved upon in this report.