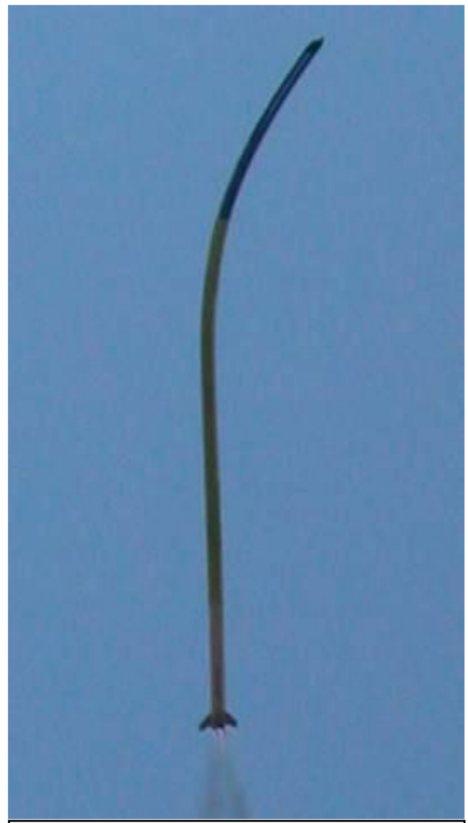
AVOIDING THE BENDS!

Why Super-Roc Models Buckle and How to Design for a Successful Flight

by Chris Flanigan (NAR 17540 L1)

INTRODUCTION

Super-Roc events are very challenging. They are well known for impressive flights of very tall models. But they're probably best known for spectacular buckling and crimping failures of models that are too long or too flexible.



G Super-Roc Alt Model at NARAM-49
Photo by Chris Taylor
http://www.naramlive.com/naramlive-2007

Super-Roc models also have peculiar aerodynamic stability issues. Super-Roc models need fins much larger than indicated using the classic Barrowman method. Why is that?

Traditionally, Super-Roc models have been designed by trial-and-error. First, you design a model that you hope will work, perhaps based on prior experience. If the model works successfully, you add another length of body tube and fly it again. Eventually, the model will buckle or perhaps go unstable during flight, indicating that you've exceeded some kind of design limit. This is a slow and expensive approach. It also doesn't provide any understanding regarding the behavior of the model.

This article provides insight into the unique characteristics of Super-Roc models. In addition, a new analysis approach is presented for designing high performance Super-Roc models that will fly successfully the first time.

OVERVIEW

Super-Roc models have two primary failure modes. The most common failure mode is where the vehicle crimps or buckles during ascent. This is often attributed to "my model must have hit a wind shear at high altitude." However, as this article will describe, the problem is caused by a combination of aerodynamics and vehicle flexibility, not wind shear.

The other failure mode for Super-Roc models is where the vehicle goes aerodynamically unstable, even though traditional Barrowman calculations [1] show that the model has sufficient stability margins. Prior research [2, 3] has focused on higher order aerodynamic terms (such as lift from body tubes) that the classic Barrowman method did not include. These higher order terms may contribute somewhat to the situation. However, the most significant issue for Super-Roc models is the combination of aerodynamics and vehicle flexibility.

RIGID VS FLEXIBLE AIRFRAMES

The Barrowman method assumes that a model rocket is a rigid structure as shown in Figure 1a. Aerodynamic forces on the nose cone, transitions, and fins are calculated assuming that all components of the vehicle are at the same angle of attack. For typical model rockets, this is a good assumption. The Barrowman method has been shown to be an excellent and reliable method for designing stable rockets.

However, long Super-Roc models are flexible. When a Super-Roc model rotates relative to the flow direction, the resulting aerodynamic forces will cause the vehicle to bend. As shown in Figure 1b, the vehicle components (nose cone, fins, etc.) are no longer be at the same angle of attack. Airframe bending generally increases the force on the nose cone and decreases the force on the fins. Therefore, the Barrowman method, as typically implemented for a rigid airframe, is not sufficient to determine if a flexible Super-Roc model is viable.

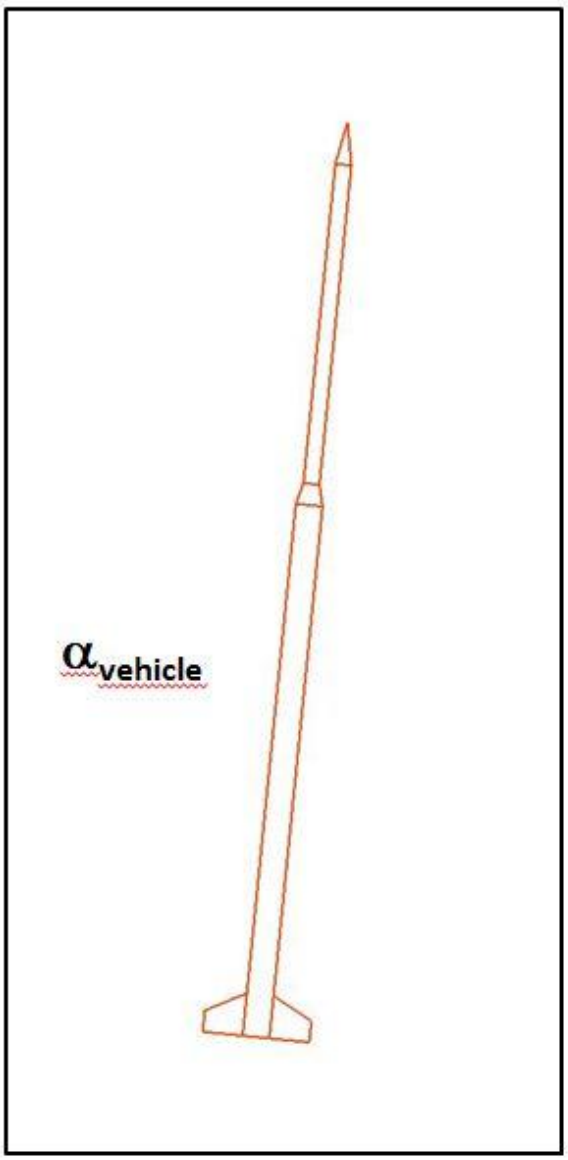


Figure 1a. The Barrowman method assumes that the airframe is rigid.

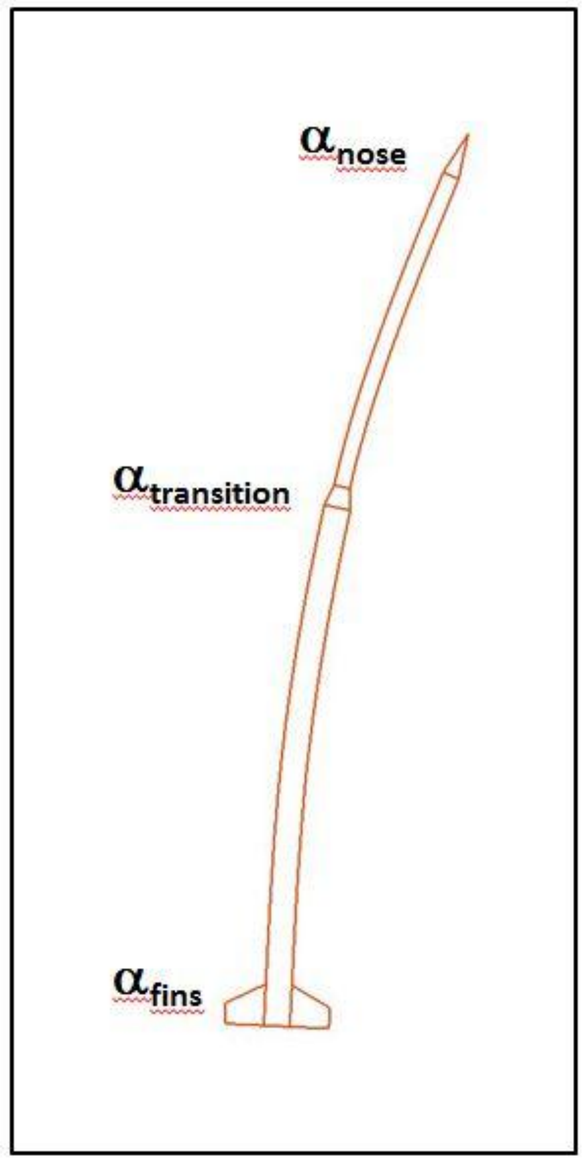


Figure 1b. Flexible body effects increase the force on the nose and decrease the force on the fins.

AEROELASTICITY IS THE KEY

Aeroelasticity is the term used to describe situations where elastic deformation of the airframe interacts with aerodynamic forces. As an example, if you rotate the aileron on the wing of a jet airliner, this will produce lift on the aileron. The lift on the aileron will cause the wing to bend and twist, which will affect the lift and torque distribution along the wing.

Aeroelasticity is very important in the aerospace industry. For military airplanes and commercial jet airliners, aeroelastic analysis is performed to verify that the wing and tail will not experience flutter or divergence within the vehicle's flight envelope. For rockets and launch vehicles, aeroelastic analysis is performed to assess interaction between structural flexibility and the guidance system.

Aeroelasticity is also important for low- and high-power model rockets. Boost Glider wings can flutter and shred when flown too fast. For high power rockets, fins can flutter at high speeds if the fins are too flexible. A fascinating example of HPR fin flutter is available at http://www.videorocketry.com/XPRS_2004/video/USS_Bakula.wmv.

AEROELASTIC ANALYSIS OF SUPER-ROC MODELS

Aeroelastic analysis of a Super-Roc model is straightforward, with the help of a computer program. The procedure described in this article is based on calculating "modes" of the Super-Roc vehicle including stiffness, mass, and aerodynamic effects.

To understand what a "mode" is, get your trusty 1/8" launch rod. Hold it in the middle, and shake it laterally. The resulting bending shape represents the first bending mode of the unrestrained launch rod. You can easily find the excitation frequency that produces the maximum response. This is the natural frequency of the first lateral bending mode. If you insert one end of the launch rod into a launch stand, you'll see a different set of modes due to the constraint applied by the launch stand to the rod. In this condition, it's pretty easy to see the 1st bending mode, perhaps the 2nd bending mode, and maybe even the 3rd bending mode of the constrained launch rod.

A Super-Roc model at zero airspeed has three primary modes of interest, as shown in Figure 2:

1) lateral translation mode, where the entire rocket moves from side to side
2) rotation mode, where the entire rocket rotates about the center of gravity (CG)
3) first lateral bending mode

At zero airspeed, the first two modes are "rigid body" modes, and the third mode is the first elastic mode.

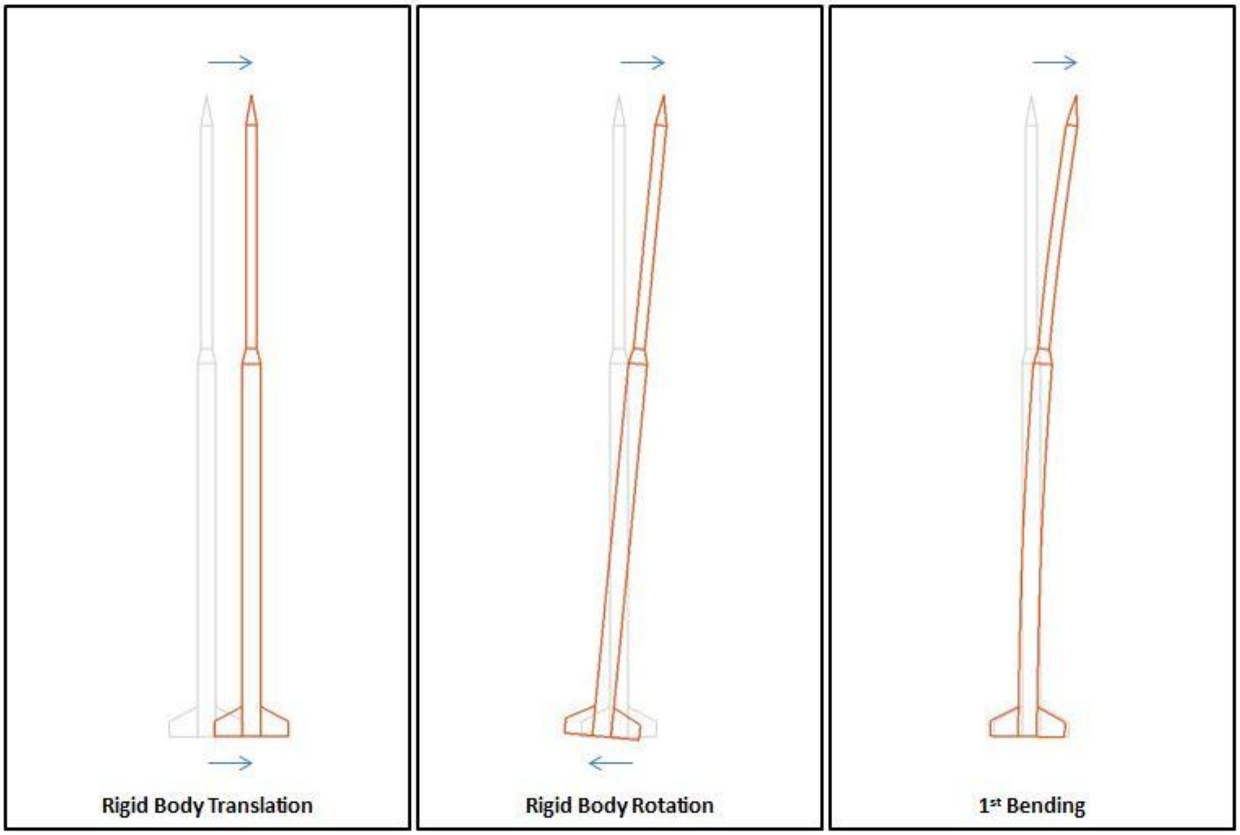


Figure 2. The first three modes are important for Super-Roc models.

Typical aeroelastic results for a Super-Roc model are shown in Figure 3. As the velocity increases, aerodynamic forces build on the nose cone, transitions, and fins. These terms are calculated using the Barrowman equations but extended to use the local angle of attack of each component. (For additional details on these calculations, see [4].) The lateral translation mode starts at 0 Hz and remains there. The frequency of the rotation mode starts at zero and increases linearly with velocity. Note that, at low speeds, this is the same value as calculated by Rocksim for the pitch rotation frequency. At higher velocities, the aerodynamic terms become significant and begin to couple the vehicle rotation and bending modes. In general, this causes the bending mode frequency to increase with velocity. However, at a sufficiently high velocity, the aerodynamic terms cause the rotation mode frequency to begin decreasing and eventually drop to zero. This is the velocity at which the airframe will buckle or go unstable.

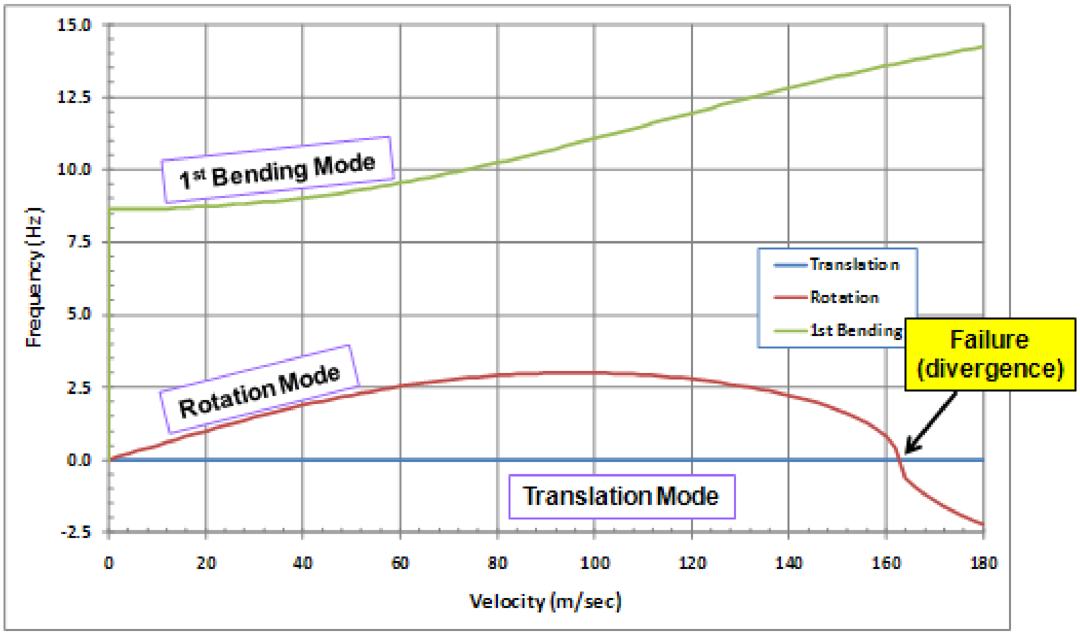


Figure 3. Super-Roc airframe failure occurs at the velocity where the frequency of the rotation mode drops to zero.

ANALYSIS USING FLEXROC

FlexRoc is a computer program for performing aeroelastic analysis of Super-Rocs and other model rockets. FlexRoc can be freely downloaded from the "Files" area of the ContestRoc Yahoo group.

FlexRoc is somewhat like Rocksim and OpenRocket in that you define the components of the model rocket (nose cone, body tubes, fins, etc.). You also need to define the velocity range of interest and a reference altitude. Additional information on the input file for FlexRoc is provided in the User's Guide (also freely available on ContestRoc).

Internally, FlexRoc performs an aeroelastic analysis using the finite element method [5, 6]. At each analysis velocity, the first four modal frequencies are calculated using the vehicle stiffness, vehicle mass, and aerodynamic matrices. The modal frequency results are written to an output file which can be inspected and plotted by the user.

ASSUMPTION AND LIMITATIONS

FlexRoc makes several assumptions regarding the model and analysis methods. Major assumptions include:

- The model is assumed to be well constructed (geometrically straight, no large gaps or loose couplers, etc.)
- Fins are assumed to be fully effective. The buildup of boundary layer thickness along a long vehicle is not considered.
- The fins are assumed to be rigid. The effects of flexible fins and any flexibility at the fin/tube joint are neglected. Fin flutter is not considered.
- Aerodynamic terms are calculated using low subsonic aerodynamics. Compressibility and supersonic effects are not included.

An important issue is what margin to apply to the results. For example, the Barrowman method suggests a stability margin of one caliber. What is a suitable margin for FlexRoc results? In the aerospace industry, it is typical to apply a 15% velocity margin for flutter and divergence analysis. This has been shown to be generally suitable for mission-critical aerospace systems. For a competition Super-Roc model, a velocity margin of 10% (or perhaps as low as 5%) might be suitable. More experience is needed here.

PREDICT SUCCESS – AND FAILURE!

Several Super-Roc models have been analyzed using FlexRoc. So far, on a limited number of samples, FlexRoc has a perfect batting average! It has predicted success for Super-Roc models that have flown successfully, and it has predicted failure for Super-Roc models that have failed.

As an example, FlexRoc was used to analyze the Estes Mean Machine. Results for a "stock" model (no custom modifications) are shown in Figure 4. FlexRoc predicts that the Mean Machine should be good for velocities approaching 150 m/sec. The maximum vehicle velocity (calculated using Rocksim) is 52 m/sec using a D12 and 68 m/sec using an E9. Therefore, the Mean Machine should be fine for these conditions. Some people have flow uprated models of the Mean Machine using larger motors. Care should be used for any model/motor combination where the maximum velocity will approach or exceed 150 m/sec.

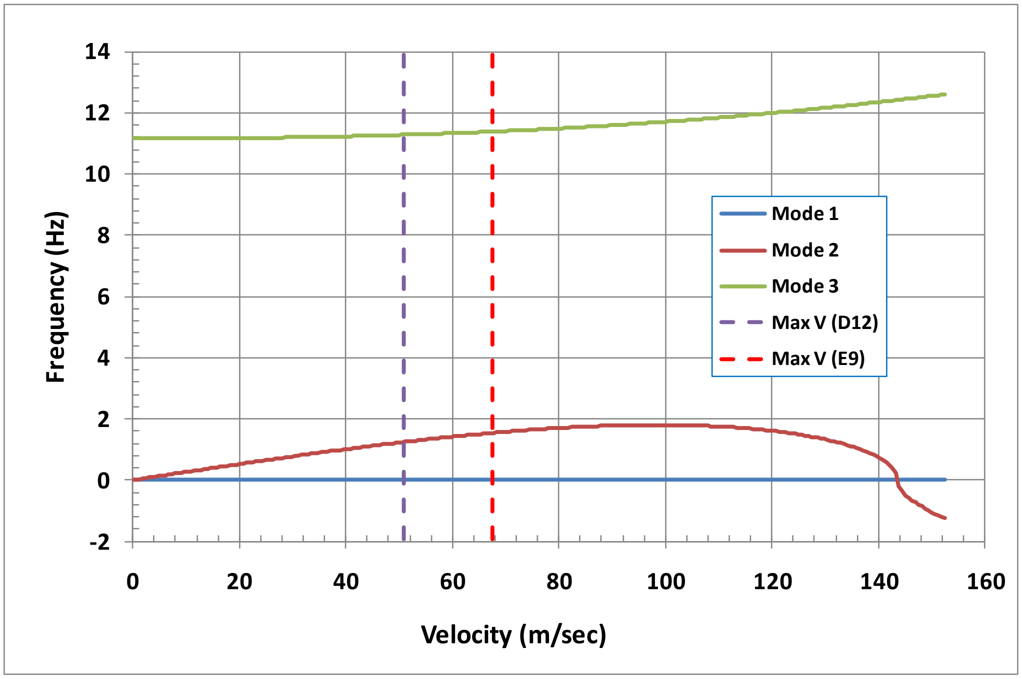


Figure 4. The Estes Mean Machine has large safety margins
when flown using D12 or E9 motors.

Two important examples come from G Super-Roc Altitude models flown by the Southern Neutron team at NARAM-49. Their first model was a maximum length (450 cm) model using BT-60 body tubes and two Apogee F10 motors. As shown in Figure 5, FlexRoc predicts that the model should have failed at approximately 62 m/sec, well below the maximum velocity of 83 m/sec predicted by Rocksim. As documented in their R&D report [7], the Southern Neutron team reported that their first model failed toward the end of the motor burn. Their second model also used BT-60 body tubes but was augmented with long internal lengths of coupler stock. Propulsion was two E6 motors and one F10 motor. As shown in Figure 6, FlexRoc predicts that model #2 should have worked successfully. The vehicle, shown in Figure 7, flew successfully and took first place in G SRA, Team Division. FlexRoc correctly predicted failure for their model that buckled and success for their model that flew well.

Another example was one of the author's F Super-Roc models flown at NARAM-52, shown in Figure 8. FlexRoc wasn't available at that time, so the model was designed using an earlier, more conservative method. The FlexRoc results, shown in Figure 9, indicate that the model should fly successfully, which it did. However, FlexRoc also indicated that the model was overdesigned, with a velocity margin of nearly 38%. This is probably too large a margin for a seriously competitive design, which helps explain why the model finished in 8th place in C Division at NARAM-52.

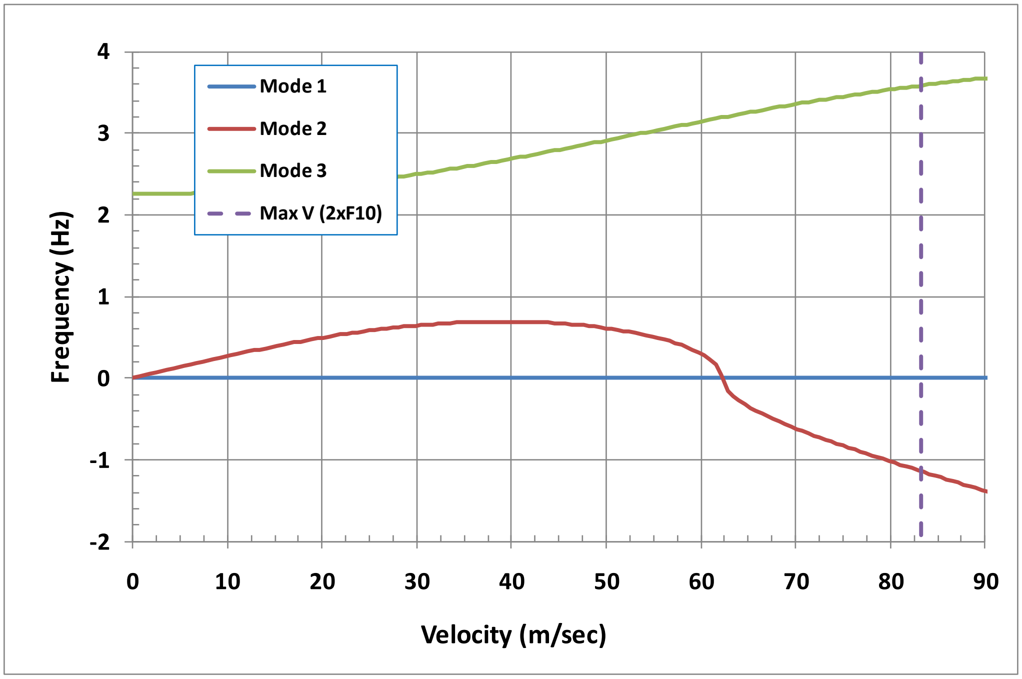


Figure 5. The first Southern Neutron G SRA model was predicted to fail at a velocity below the maximum expected velocity.

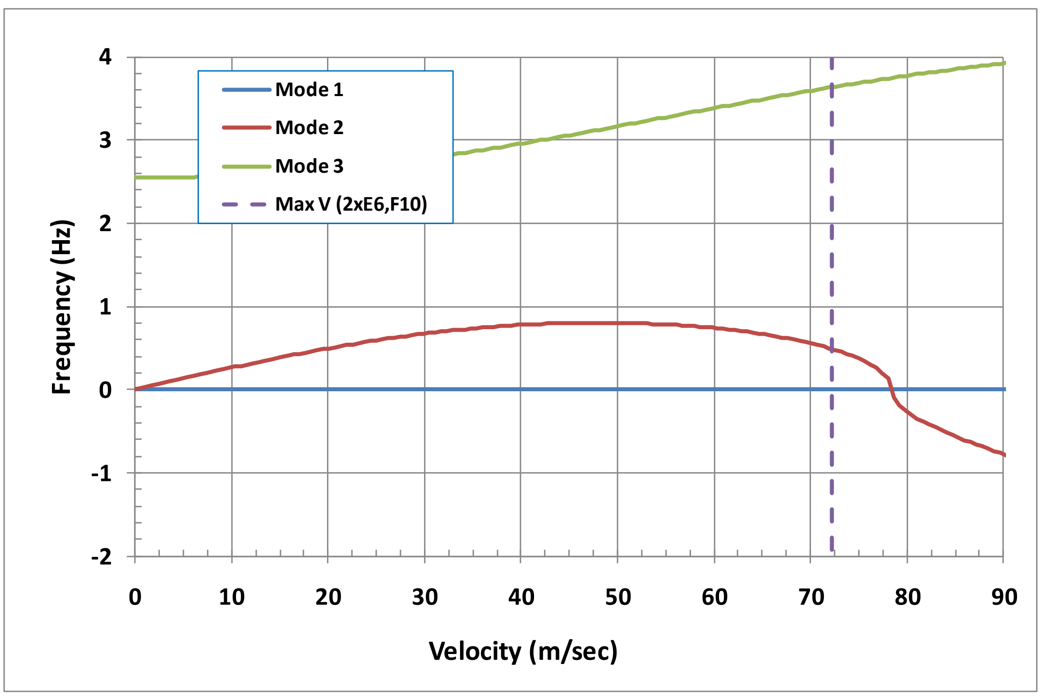


Figure 6. The second Southern Neutron G SRA model was predicted to work successfully, which it did.

Figure 7. The second G SRA model by the Southern Neutron Team flew successfully and took 1st place in Team Division at NARAM-49.

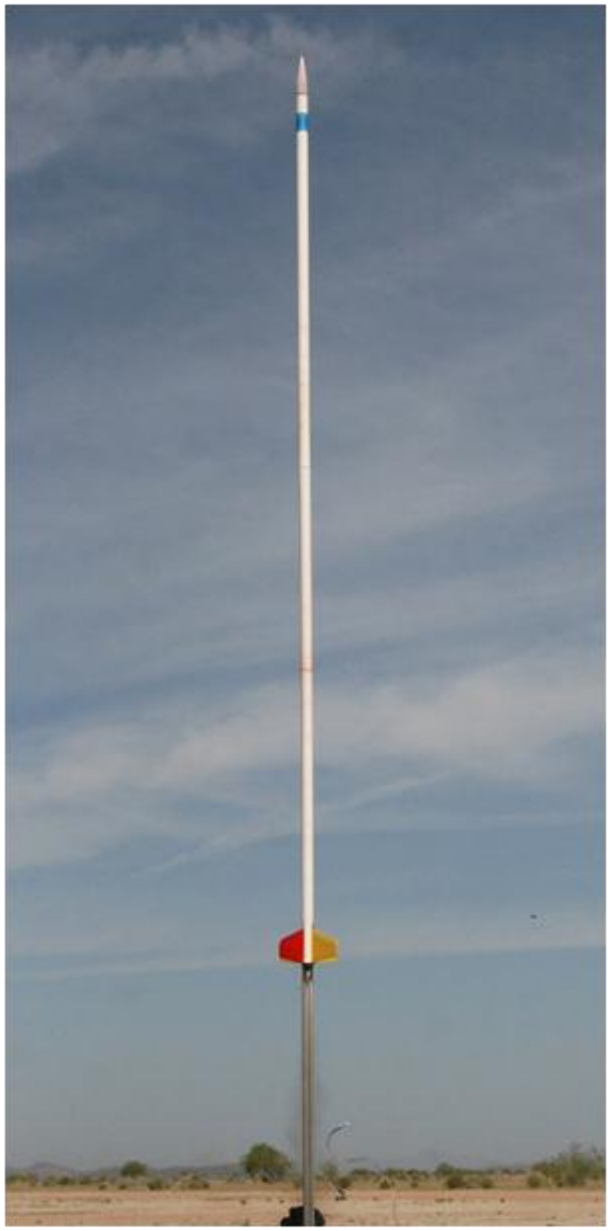


Figure 8. Chris Flanigan's "windy weather" F SRA model used T-52H tubing and finished in 8th place at NARAM-52.

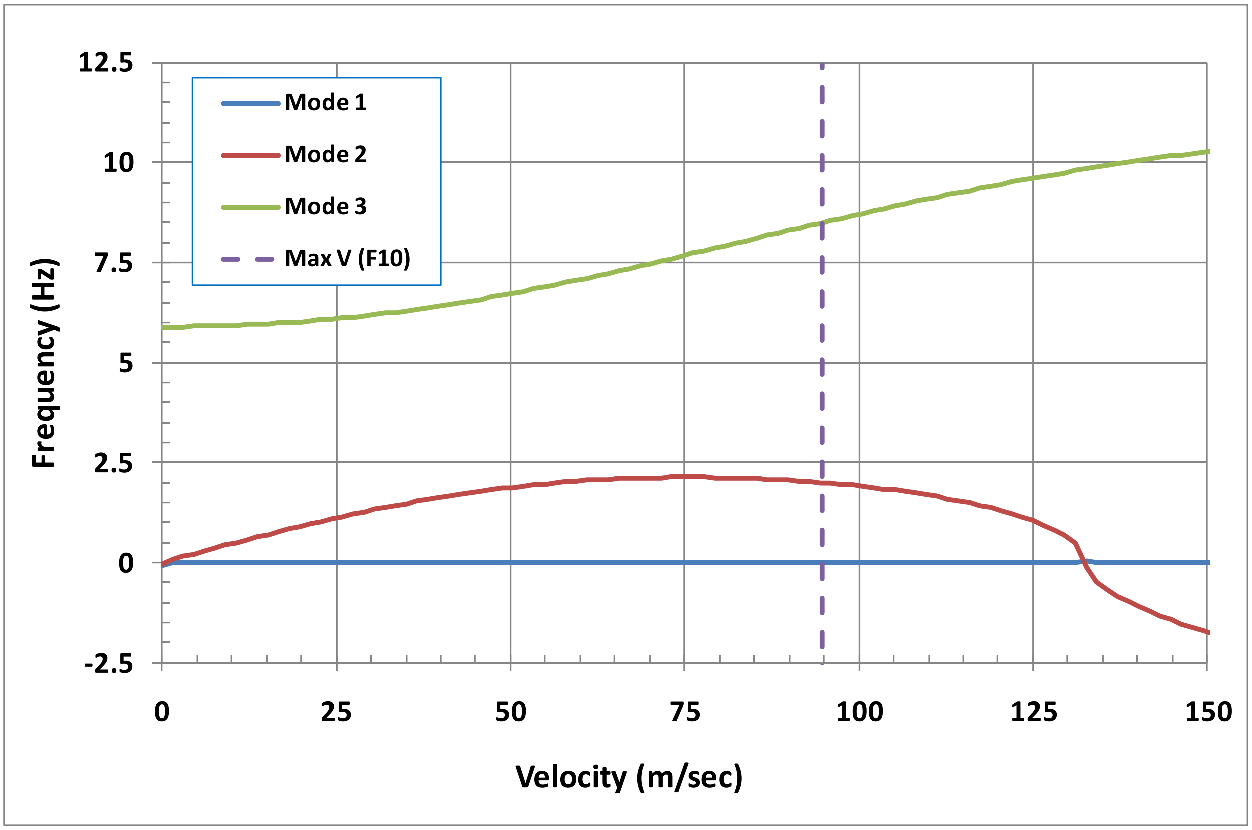


Figure 9. FlexRoc showed that Chris Flanigan's "windy weather" F SRA model was overdesigned for a competition model.

A final example is the author's A Super-Roc Duration model flown at NARAM-54. This model, shown in Figure 10, consisted of a large diameter (40 mm) base section and a long upper section of BT-4 and BT-3 body tubes. When assembled, the model felt flimsy. However, FlexRoc predicted successful behavior. The model was flown for the first time at NARAM-54, and the model had two successful flights with no buckling or stability issues.

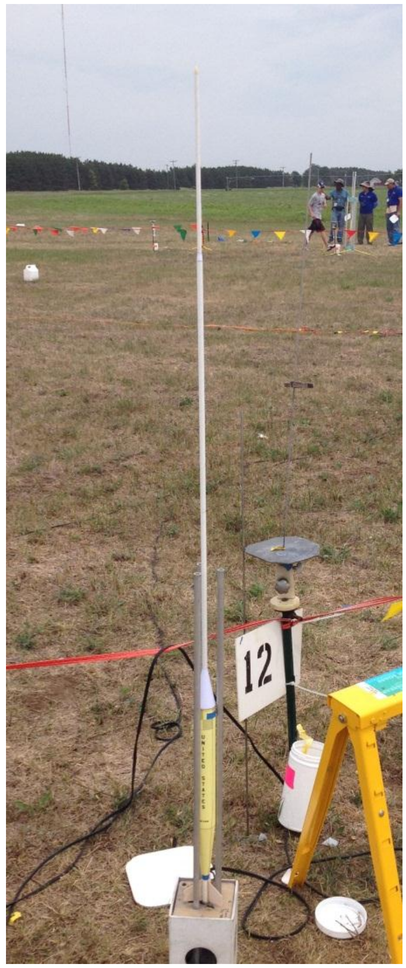


Figure 10. FlexRoc was used to design the author's A Super-Roc Duration model that flew successfully at NARAM-54 on its first flight.

SUMMARY

The Barrowman method is an excellent method for predicting aerodynamic stability for rigid models. For long Super-Roc models, flexible body effects must be included. The FlexRoc program performs an aeroelastic analysis to predict the velocity at which a Super-Roc model will fail or go unstable. So far, FlexRoc has provided accurate results. It has predicted failure for models that buckled in flight, and it has predicted success for models that have flown successfully. FlexRoc can be a valuable tool for designing high performance Super-Roc models that will work the first time.

If any question, feel free to contact the author at ccflanigan@alum.mit.edu.

REFERENCES

1. Barrowman, J., Barrowman, J., “The Theoretical Prediction of the Center of Pressure,” NARAM-8 R&D report, 1966.

2. Galejs, R., “Wind Instability - What Barrowman Left Out,” http://projetosulfos.if.sc.usp.br/artigos/sentinel39-galejs.pdf.

3. LaBudde, Edward, “Extending the Barrowman Method for Large Angles of Attack,” NARCON R&D report, March 1999.

4. Flanigan, C., “Modal Aeroelastic Analysis of Super-Roc Vehicles,” NARAM-53 R&D report, July, 2011.

5. Robert D. Cook, David S. Malkus, Michael E. Plesha, and Robert J. Witt, Concepts and Applications of Finite Element Analysis, 4th Edition, Wiley (2001), ISBN-10: 0471356050.

6. Craig, R.R., Kurdila, A.J., Fundamentals of Structural Dynamics, Wiley (2006), ISBN 13: 978-0471430445.

7. G. Gassaway, E. LaCroix, T. Willard, and R. Woebkenberg, “Development of a High-Scoring G Super-Roc by Use of Optimized Engine Choice, Conventional Design, and Conventional Construction Methods,” NARAM-49 R&D report, August, 2007.