A Variable Diameter Short Haul Civil Tiltrotor

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Abstract

The Short-Haul-Civil-tiltrotor (SHCT) component of the NASA Aviation System Capacity Program is an effort to develop the technologies needed for a potential 40-passenger civil tiltrotor. The variable diameter tiltrotor (VDTR) is a Sikorsky concept aimed at improving tiltrotor hover and cruise performance currently limited by disk loading that is much higher in hover than conventional helicopter, and much lower in cruise than turbo-prop systems. This paper describes the technical merits of using a VDTR on a SHCT aircraft. The focus will be the rotor design.

Nomenclature

p	Wing torsion mode
c	Wing chord mode
b	Wing up/down (beam) bending mode
Gimbal-1	Coupled rotor regressing flap/gimbal-1 mode
Gimbal+1	Coupled rotor progressing flap/gimbal+1 mode
1Fc	Collective flap mode
1Fp	Progressing flap mode
1Fr	Regressing flap mode
1Lp	Progressing lag mode
1Lr	Regressing lag mode

Introduction

Tiltrotor aircraft have the capability to vertically take off and land like a helicopter and have the high speed cruise performance approaching that of a conventional propeller airplane. The Short-Haul-Civil-Tiltrotor (SHCT) component of the NASA Aviation System Capacity Program is an effort to develop the technologies needed for a potential 40-passenger civil tiltrotor [1]. The variable diameter tiltrotor (VDTR) is a Sikorsky concept aimed at improving tiltrotors' hover and cruise performance.

With a VDTR, the rotor blades can be fully extended during hover, and then retracted to about 70% of their full length during cruise flight. Figures 1 and 2 illustrate this concept.

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Benefits of a VDTR

There are numerous advantages of a larger diameter rotor in hover. The lower disk loading reduces the magnitude of rotor downwash, improves the autorotation index, and enhances load-carrying capability.

The benefits of having a reduced rotor diameter for cruise are also significant. Our analysis indicates that a smaller rotor diameter reduces the potential for proprotor-whirl flutter, and lessens the wing stiffness and weight requirements. Smaller propellers ameliorate the sensitivity to head-on longitudinal gusts and roll/yaw coupling [2]. This reduces the size requirement of horizontal and vertical fins, and significantly improves passenger comfort.

A VDTR, unlike conventional tiltrotors, does not require a rotor speed reduction for efficient cruise flight. The necessary tip speed reduction is obtained instead by reducing the rotor diameter. This allows operation at 100% rpm that optimizes engine performance. Additional discussion of the performance gains associated with a VDTR can be found in Refs. [1-5].

For a SHCT that has to operate in urban helipads, the rotor outwash velocity becomes an important issue. Figure 3 compares the rotor outwash velocity at 50 ft away from the rotor shaft and 3 ft above the ground, for a SHCT VDTR at 50,000 lb gross weight, and a single-rotor helicopter with 25,000 lb gross weight and 56 ft diameter, and a single-rotor helicopter with 50,000 lb gross weight and 70 ft diameter. The diameters for the helicopter rotors are chosen to represent typical single-rotor helicopters of that gross weight. For a tiltrotor, the outwash velocities at the front and back of the aircraft are larger than at the sides. The larger hover diameter of the VDTR helps keep the outwash velocities reasonable as compared to conventional single-rotor helicopters. This attribute is especially beneficial for a civil tiltrotor that will be loading and unloading passengers and cargo with the rotor turning.

The flight simulation study of Ref. 3 shows that a conventional tiltrotor aircraft and a VDTR aircraft both exhibit Level One handling qualities during normal maneuvers with both engines operating. However, the VDTR has a greater power margin and performance in helicopter mode resulting from a lower disk loading and requires 20 to 25% less power at similar thrust levels. This is an advantage during one-engine and all-engine inoperative procedures. Reference 3 quantifies that a VDTR can enhance safety near the terminal area.

Figure 4 shows that the autorotation index for the VDTR SHCT is better than conventional tiltrotors and is almost as good as single-rotor helicopters. This index is defined as (rotor inertia)Ω^2/[(gross weight/no. of rotors)(disk loading)] and a value of approximately 20 or higher is needed for safe autorotations.

Description of the SHCT VDTR Rotor

Table 1 shows the properties of a Sikorsky SHCT VDTR design. The VDTR selected for this SHCT study is a 4-bladed gimbaled rotor design. The four major components are the blade, the torque tube, the jackscrew and the tension strap (Fig. 5). The blade is the main lifting section. It slides in and out on the torque tube to effect radius changes. When the electric motor rotates the jackscrew, the jackscrew exerts a corkscrew action on the nut sitting inside the torque tube, which then extends or retracts the blade. The tension straps are responsible for holding the blade against the centrifugal force. The tension straps connect the blade tip to the nut on the jackscrew. During flight, the main portion of the blade is in compression, rather than extension, which is typical for conventional rotors.

A Froude-scale and a Mach-scale model of this VDTR design have been built and successfully tested at the UTRC wind tunnel, at the Sikorsky hover stand, and on the BART stand at NASA Langley. The flight envelope tested includes hover, transition flight, and airplane cruise mode [5-8]. The retraction mechanism has been tested on the Froude-scale rotor over a wide range of conditions.

Table 1:

Gross Weight	50,000 lbs
Cruise Speed	350 knots
Range	600 nm
Rotor Diameter	35.5 – 53 ft
Number of Blades	4
Hover Disk Loading	11.33 lb/ft^2
Hover Rotor speed	216 rpm
Cruise Rotor speed	216 rpm
Hover Tip Speed	600 ft/sec
Cruise Tip Speed	402 ft/sec

Aeroelastic Analysis of VDTR

In recent years, Sikorsky Aircraft has performed analytical studies and wind tunnel tests [6-8] to validate the variable diameter tiltrotor concept. The Sikorsky version of the University of Maryland Advanced Rotorcraft Code (UMARC/S) was modified to analyze a VDTR [8-11]. Having a validated and trustworthy code is an indispensable tool for designing future tiltrotors.

The analysis of a variable diameter tiltrotor is more complex than that of a basic tiltrotor system. A VDTR design can have many redundant load paths, as well as a telescoping blade that operates in compression rather than in tension. Due to the redundant load paths and nonlinear structural couplings, a finite element rotor analysis was modified to model a VDTR and was used for the predictions described in this paper. The tiltrotor blade is modeled as an elastic beam undergoing flap bending, lead-lag bending, elastic twist, and axial extension. This Euler-Bernoulli beam is allowed small strains, and moderate deflections. Due to the moderate deflection assumption, the equations contain nonlinear structural, inertial and aerodynamic terms. The blade, torque tube, and strap are each discretized into a number of beam elements. Boundary conditions or springs are used to connect the segments. The wing is also modeled as elastic beam elements. The rotor and wing are analyzed as a complete system. The finite element modeling is shown in Fig. 6. The aerodynamic modeling includes quasi-steady strip theory for the wing and a free wake model, and the Leishman and Beddoes unsteady aerodynamic model for capturing the unsteady shed wake effects, trailing edge separation, and dynamic stall on the rotor [11].

Figure 7 shows the SHCT VDTR blade nonrotating frequencies as a function of blade retraction ratio. As the blades retract, the system becomes stiffer and the frequencies rise. The rotating blade data and predictions are shown for the 100% diameter hover condition. The data were obtained from model tests conducted at the Sikorsky hover stand.

Figure 8 shows a comparison of measured and predicted rotor damping in hover for the 4-bladed Froude-scale model VDTR. The blade data were only available from strain gauges on blade number 1, 2 and 3. The result shows the rotor is stable at all thrust conditions that were tested. The SHCT VDTR is a stiff-inplane design; therefore, it precludes any possibility for ground or air resonance.

The ability of the code to predict forward flight stability was evaluated by comparing predictions with two other analyses [12], [13]. Figure 9 shows the predictions from all three analyses for the XV-15. The trends from all three calculations agree with one another.

Figure 10 presents the UMARC/S predicted root locus for an initial unoptimized SHCT VDTR as a function of flight speed. The maximum diameter and tip speed are 53 ft and 600 ft/sec, respectively, as documented in Table 1. The baseline rotor parameters were arbitrarily selected as:

Gimbal stiffness	19,800 in-lb/deg
Gimbal damping	5% critical
Delta-3 angle	38 degrees (flap up-nose up)
Pylon length	.23R

For the initial baseline rotor design, the wing beam bending mode became unstable at around 300 kt. A parametric study was then carried out to vary the design variables to help understand the SHCT VDTR. The parameters examined included wing stiffness, blade stiffness, gimbal stiffness, gimbal damping, delta-3 angle, nacelle pylon length, rotor speed, and rotor diameter.

One of the design parameters that has the strongest influence is the blade δ_3 angle. Figures 11 shows the root locus of SHCT wing and blade modes as a function of blade δ_3 angle at 300 kt. The δ_3 angle can improve flight handling qualities, but very large δ_3 angles degrade aeroelastic stability. Figure 11 shows the optimum δ_3 for this particular rotor is between +15 and -15 degrees (in Figure 11, positive δ_3 is flap-up nose-up). This observation is in agreement with the δ_3 results presented by Ref. 12 for a conventional tiltrotor rotor.

Additional results of the parametric study reveal that increasing the rotor speed has a stabilizing effect on wing torsion and wing bending modes. The Gimbal+1 mode becomes more stable at higher rotor speeds due to the increased aerodynamic damping resulting from flap coupling. At 350 kt, the Gimbal+1 mode is unstable at a tip speed of 600 ft/sec (216 rpm), but becomes stable at 720 ft/sec (256 rpm).

As expected, blade dynamics are not influenced by arbitrary changes in wing stiffnesses. Increasing the wing beam stiffness increases the beam frequency and reduces the stability slightly. The wing chord mode becomes slightly more stable with increasing wing beam stiffness. Increasing the wing chord stiffness only increases the wing chord frequency and has a minimal effect on wing beam and torsion frequencies. The rotor 1Fp mode damping increases, but this mode is already very stable. Increasing wing torsion stiffness does not change the wing torsion mode damping. However, increasing the wing torsional stiffness improves the SHCT beamwise stability slightly. The effect on chordwise stability is negligible.

The effects of pylon length are similar to the effects of wing torsional stiffness. A shorter pylon is beneficial for all three wing modes. In 1957 Bell solved the Bell XV-3 instability by shortening the mast by two feet and stiffening the wing by adding a strut. This corroborates with our prediction for SHCT that a shorter pylon is better for aeroelastic stability.

Increasing gimbal stiffness (by adding a spring or an elastomeric ring inside the hub) increases rotor flap frequencies, and wing torsion frequency, significantly. The effect on gimbal modes, however, is less obvious. The cyclic flap modes (1Fp and 1Fr) changed because their motions are dependent on gimbal tilting motion. Collective and differential flap modes (1Fc and 1Fd) do not change at all because the gimbal motion can only influence cyclic modes.

Stiffening the gimbal improves wing beam, chord and torsion mode stability.

One of the key advantages of a VDTR is its ability to change rotor diameter during flight. Figure 12 shows the effect of rotor diameter on aeromechanical stability at 300 kt for the baseline VDTR design. It shows a smaller diameter (67.5 %) is better for cruise than a large diameter (88.5 %), although the aircraft remains unstable at this flight speed.

Using the SHCT as an example, the parametric study conducted for this paper shows the follow variations tend to improve tiltrotor stability:

smaller diameter
reduced δ_3 angle
higher tip speed
stiffer gimbal spring
decreased pylon length

Based on the results of the parametric study, a revised SHCT VDTR design was developed. The stability characteristics for the revised SHCT design are shown in Figure 13. Figure 14 shows the wing beam mode flutter airspeed has increased from 280 kt to 430 kt. By optimizing the design parameters, it is possible to increase the flutter speed.

Conclusions

A variable diameter rotor design has been investigated as a potential option for a Short Haul Civil Tiltrotor. The ability to change diameter in flight provides benefits in hover and forward flight. The analysis shows reduced delta-3 angle, stiffer gimbal stiffness and smaller rotor diameter in airplane-mode reduce the potential for proprotor-whirl flutter. Based on a parametric study for the rotor and wing design parameters, the flutter airspeed was increased by 54% for this hypothetical civil tiltrotor design.

Acknowledgments

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Figure 1: A rendering of a variable diameter civil tiltrotor aircraft.

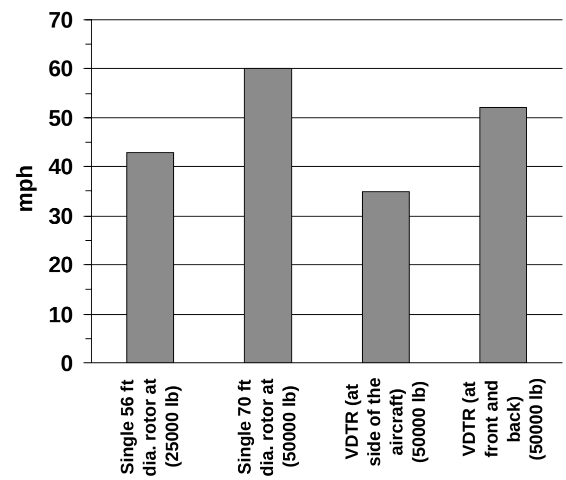

Figure 3: Rotor outwash velocity for a VDTR SHCT and two single-rotor helicopters.

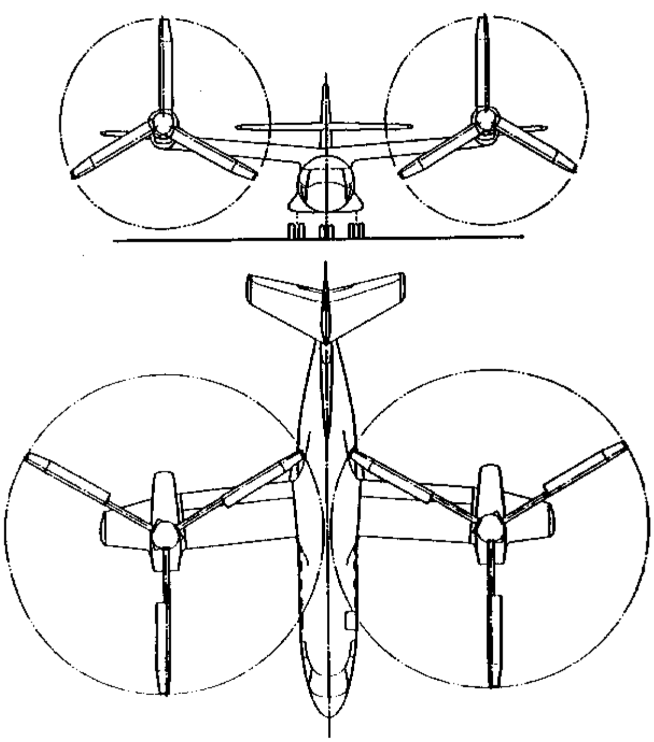

Figure 2: The variable diameter tiltrotor concept.

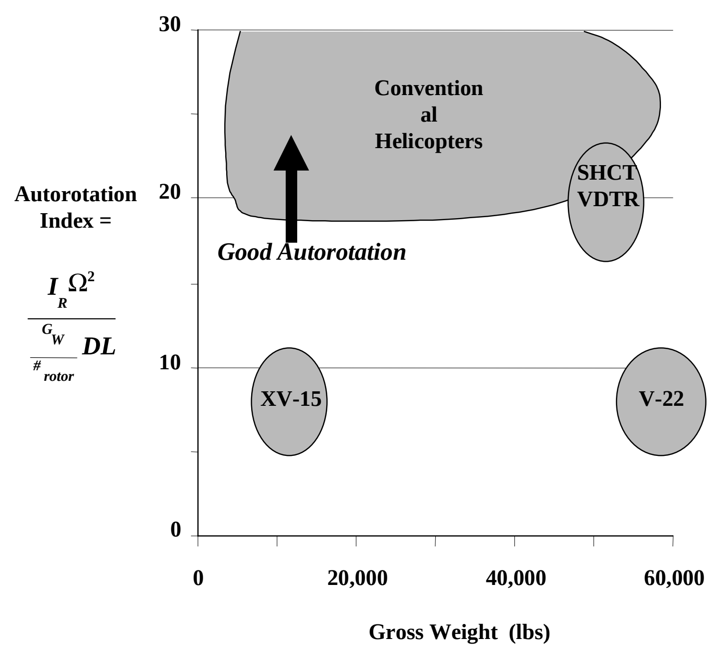

Figure 4: Autorotation index for the VDTR SHCT and a single-rotor helicopter.

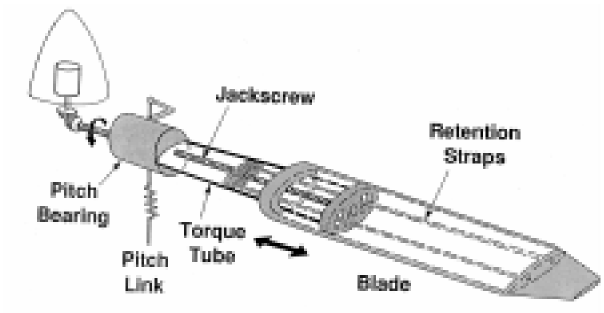

Figure 5: An example of the variable diameter tiltrotor blade.

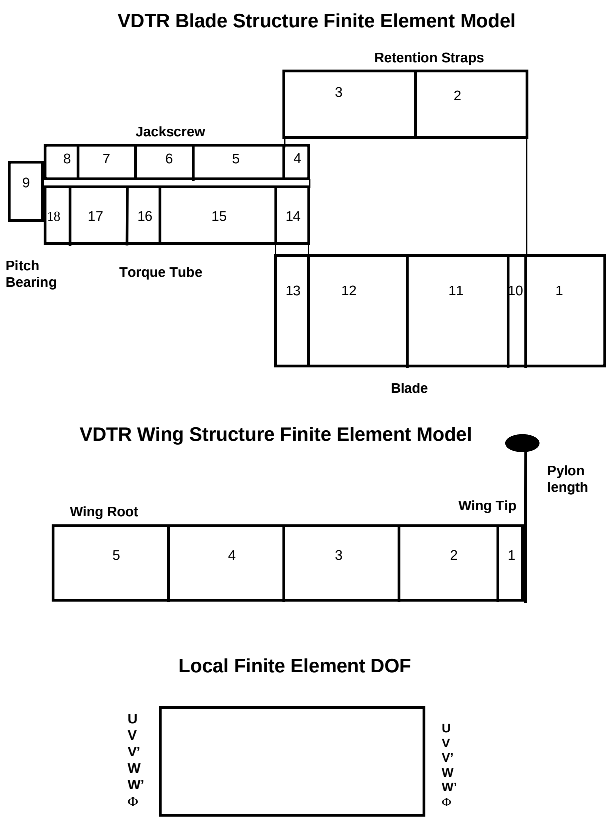

Figure 6: The analytical finite element modeling used for designing the VDTR blade and wing.

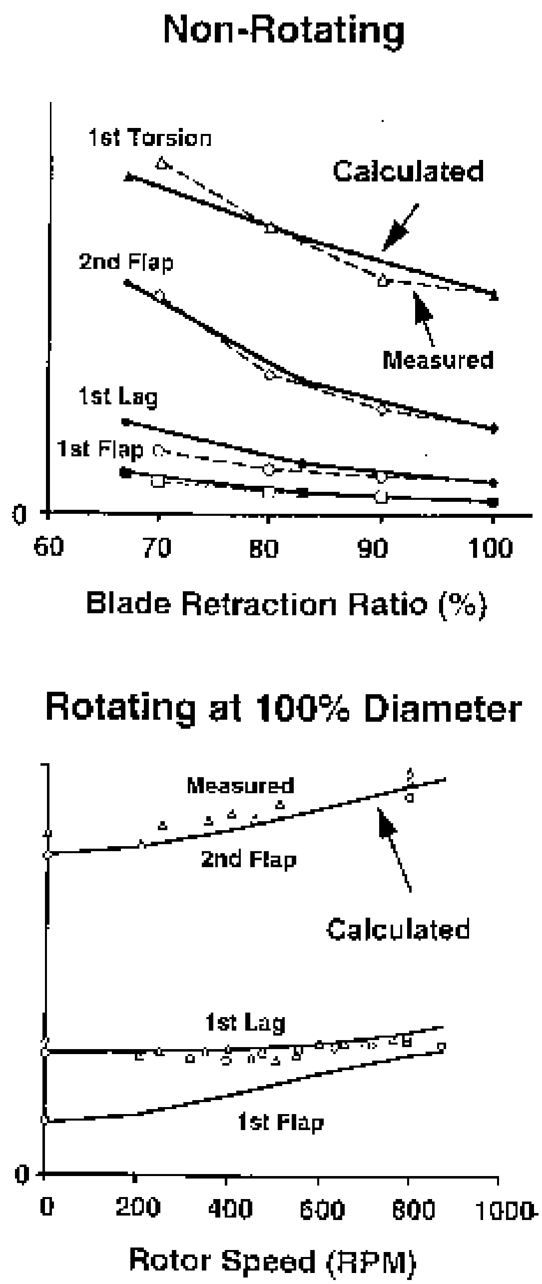

Figure 7: Predicted and measured nonrotating model VDTR blade frequencies as a function of retraction ratio and the rotating frequencies as a function of RPM.

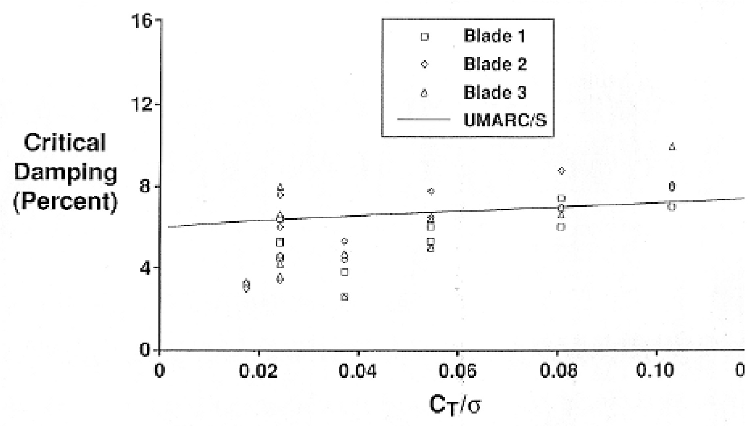

Figure 8: Correlation of lag mode stability for the 4-bladed Froude-Scale VDTR in a hover test at 83% retraction ratio.

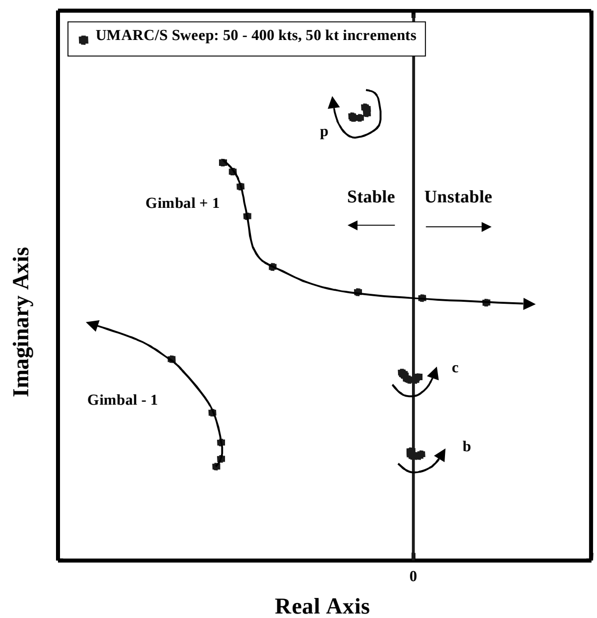

Figure 10: Effect of forward velocity on rotor and wing stability for the baseline rotor design

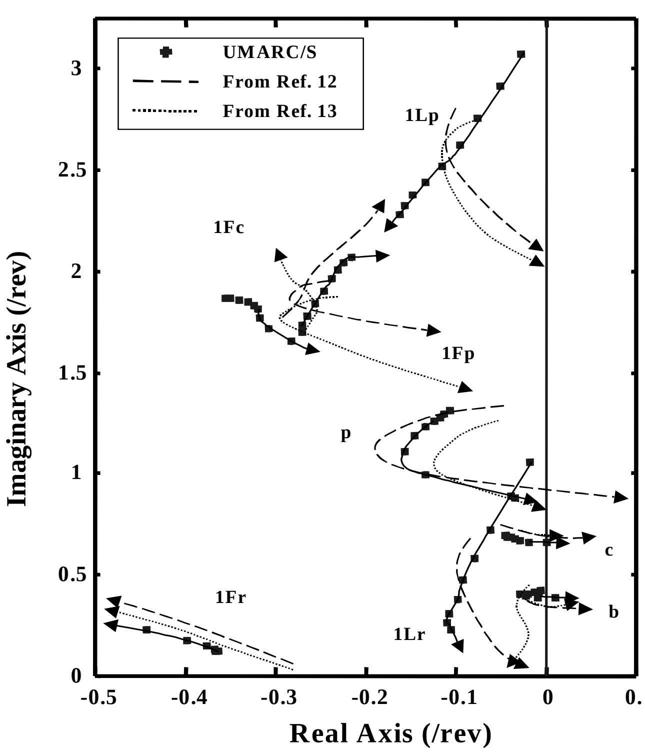

Figure 9: Correlation of predicted XV-15 blade and wing modes

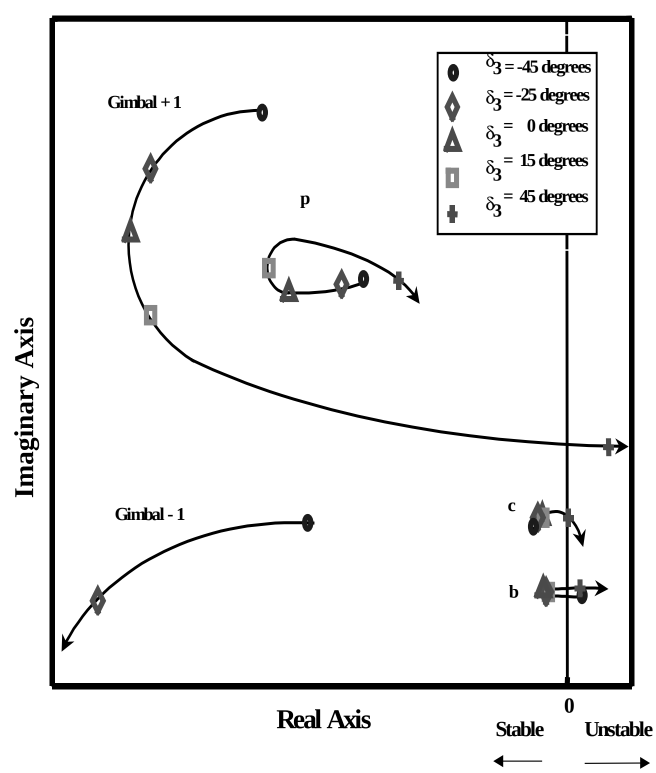

Figure 11: Effect of delta-3 on rotor and wing stability.

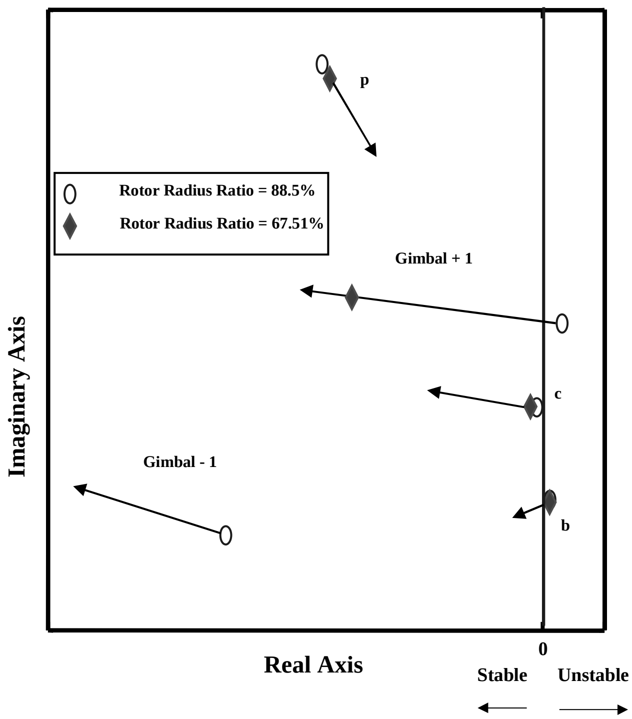

Figure 12: Effect of rotor radius on rotor and wing stability.

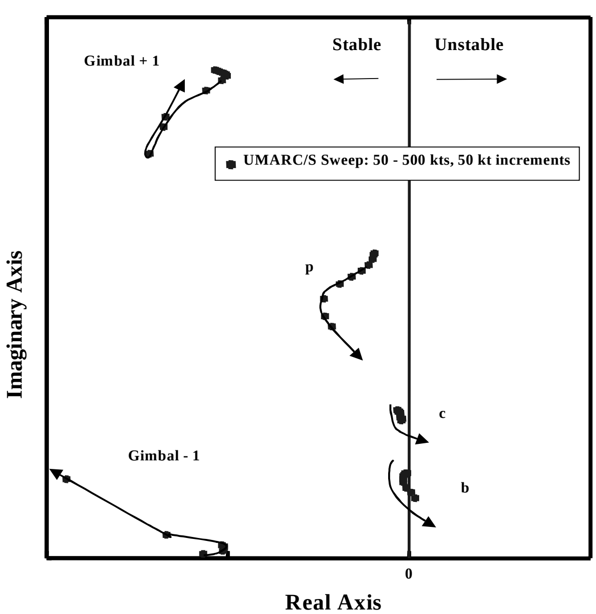

Figure 13: Effect of forward velocity on rotor and wing stability for the revised rotor design.

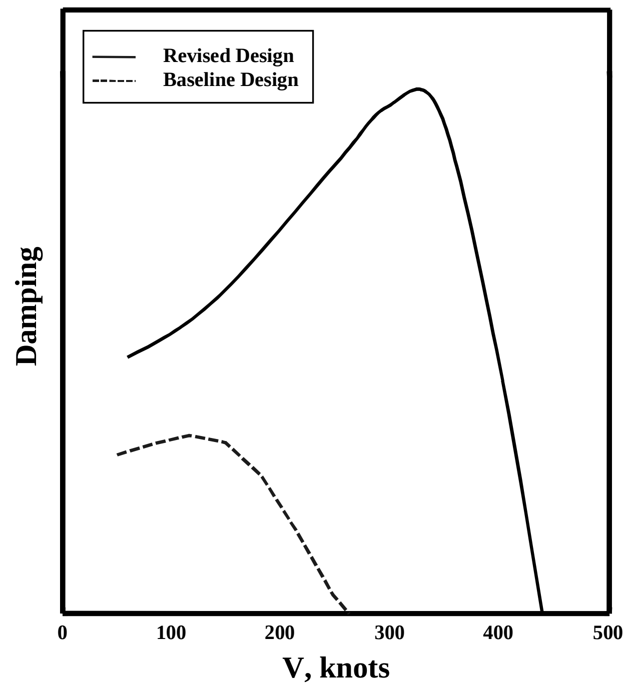

Figure 14: Stability of wing beam mode for baseline and revised SHCT VDTR deigns.