THE EFFECT OF TIP GEOMETRY ON ACTIVE-TWIST ROTOR RESPONSE

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A parametric examination of the effect of tip geometry on active-twist rotor system response is conducted. Tip geometry parameters considered include sweep, taper, anhedral, nonlinear twist, and the associated radial initiation location for each of these variables. A detailed study of the individual effect of each parameter on active-twist response is presented, and an assessment offered of the effect of combining multiple tip shape parameters. Tip sweep is shown to have the greatest affect on active-twist response, significantly decreasing the response available. Tip taper and anhedral are shown to increase moderately the active-twist response, while nonlinear twist is shown to have a minimal effect. A candidate tip shape that provides active-twist response equivalent to or greater than a rectangular planform blade is presented.

INTRODUCTION

The study of active-twist rotor systems has indicated significant promise for the reduction of rotorcraft fixed-system vibratory loads, and the potential for noise reduction and performance improvement.[1-7] Other possible, yet unstudied, applications include active blade tracking control, stability augmentation, and rotor blade de-icing. The most thorough data set available to date is for the NASA/Army/MIT Active Twist Rotor (ATR), which has been tested in both hover and forward flight to demonstrate vibration and noise reduction using both open-loop and closed-loop control.[1-5] The other active-twist rotor systems that have utilized piezoelectric fiber composite actuators to achieve twist actuation have been tested only in hover.[6,7] While the results from ATR testing have been compelling, the intent of the program was to demonstrate the feasibility of active-twist control in a forward-flight environment. As such, the ATR used simplified design parameters, such as a rectangular blade planform and NACA-0012 airfoil, to reduce system complexity and ease fabrication processes. To successfully implement active-twist control in a fielded military or commercial helicopter, more modern blade design techniques and parameters must be considered. Such design parameters include advanced airfoils and blade tips incorporating sweep, taper, and droop. The Boeing/MIT Active Materials Rotor (AMR) incorporated both sweep and taper, however, open literature information regarding the rotor design is limited and the AMR has been tested only in hovering flight.[7]

Following the completion of the ATR program in 2003, the U. S. Army Research Laboratory Vehicle Technology Directorate initiated the Advanced Active Twist Rotor (AATR) program to study advanced blade design techniques.

Although no advanced blade hardware has yet been fabricated under this program, three analytical studies have been conducted to examine the effect of advanced design parameters on active-twist rotor response. The results of the first of these studies were published in early 2004.[8] This paper examined the impact of the blade aerodynamic design parameters on vibration, performance and active-twist control authority, and resulted in a recommended aerodynamic design for the AATR. A second study[9] expands upon the results of reference 8 by examining the effect of blade structural parameters on AATR active-twist control authority, response, and blade loads. The third and final (present) analytical study examines critical features identified by the first two studies – the active-twist blade tip aerodynamic and structural design.

ROTOR SYSTEM DESCRIPTION

The notional rotor system chosen for this study is the final design from the analytical study described in reference 8, in which the design for the Advanced Active Twist Rotor was selected based upon rotor performance and vibratory loads criteria. Because the design was considered for fabrication as a wind-tunnel model, the 9.37 ft diameter rotor is Mach and dynamically scaled for the Langley Transonic Dynamics Tunnel (TDT). Advanced rotorcraft airfoils[10,11] and the dynamic design from the original NASA/Army/MIT Active Twist Rotor are incorporated into a 4-bladed, articulated rotor system that includes -10° of built-in linear twist and a tip shape with 2.5:1 taper, 30° sweep, and 10° anhedral, each initiating at 0.95R. Figure 1 presents the blade planform and the distribution of the airfoils used, and figure 2 presents a detailed view of the tip shape and a side view indicating the 10° anhedral. Table 1 presents critical blade design parameters for the AATR. Table 2 presents the AATR blade frequencies and modal identity.
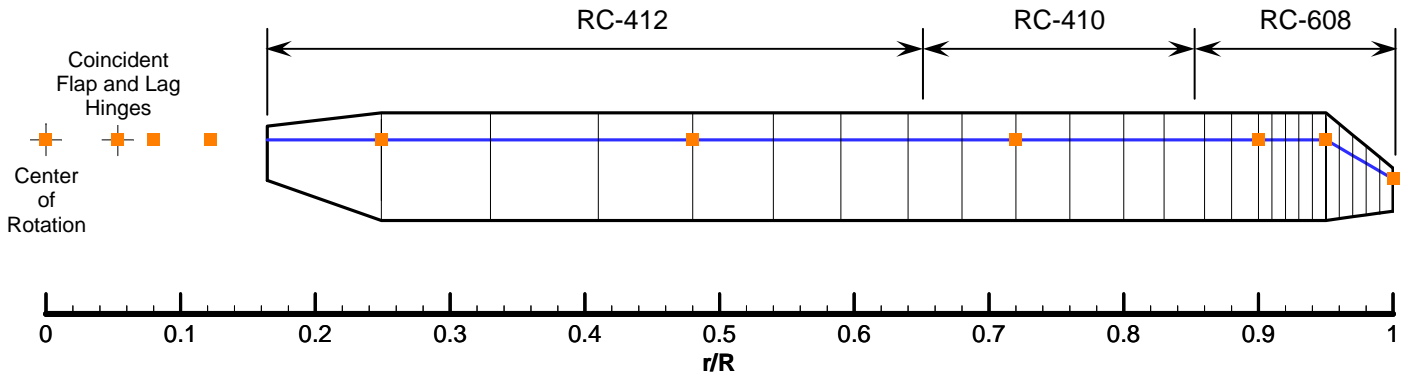
Figure 1. AATR baseline aerodynamic design planform and airfoil distribution. The blue line identifies the blade quarter-chord. The distribution of the aerodynamic panels (black chordwise lines) and the structural node points (orange squares) for the CAMRAD II model of the baseline AATR are included.
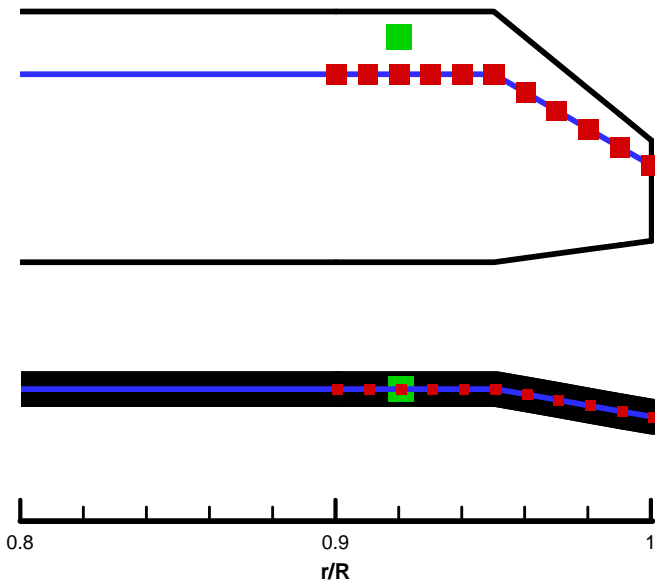

Figure 2. AATR baseline aerodynamic design – tip planform and anhedral. The blue line identifies the blade elastic axis, the red squares identify the chordwise c.g. distribution, and the green square the location of a static balance mass required to balance the mass of the swept tip about the blade quarter-chord.
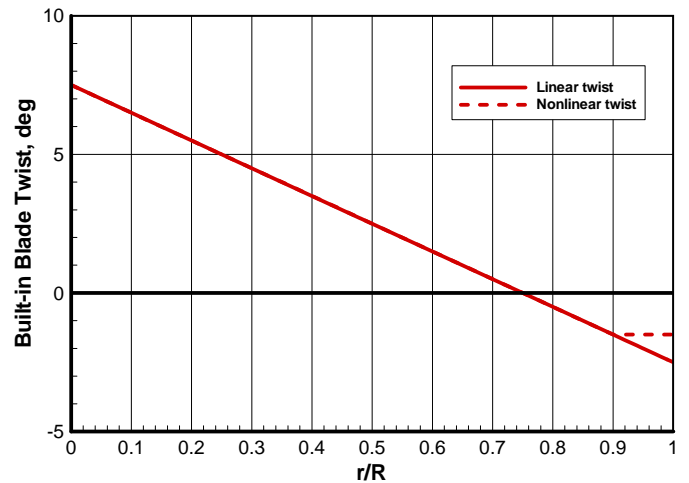

Figure 3. Blade twist definition. Linear blade twist is -10°. For nonlinear twist, the twist at the nonlinear twist initiation point is extended to the tip.

Table 1. AATR System Parameters

Rotor radius, R	4.685 ft
Root chord, c_r	0.3711 ft
Tip chord, c_t	0.1484 ft
Tip taper ratio, c_r / c_t	2.5:1
Tip taper radial initiation	0.95R
Tip sweep	30°
Tip sweep radial initiation	0.95R
Tip anhedral	10°
Tip anhedral radial initiation	0.95R
Solidity, σ	0.101
Lock number, γ	9.0
Twist, linear	-10°
Hover tip Mach number, M_T	0.628

Table 2. AATR Blade Frequencies

Mode	Frequency, per rev
Rigid lag	0.30
Rigid flap	1.04
1st elastic flap	2.48
2nd elastic flap	4.19
1st elastic lag	4.67
1st elastic torsion	6.50
3rd elastic flap	7.52

For the current parametric study the basic structural, dynamic, and aerodynamic design of the AATR is utilized, with the tip region considered to be outboard of 0.90R. The tip geometry variables chosen for examination include sweep, taper, anhedral, nonlinear twist distribution, and the associated radial-initiation location for each of these variables. The nonlinear twist distribution is generated by assuming the basic -10° linear twist distribution, however, constant twist is extended outboard of the nonlinear twist initiation location, as presented in figure 3. To provide consistent active-twist actuation for each blade design, piezoelectric actuators are assumed to span from 0.25R to 0.90R and produce an active-twist control moment of 6 in-lb, a level of actuation comparable to the original ATR. Similarly, all active-twist responses are observed at 0.90R to avoid any distortion that the tip geometry may have on observations made at the tip.

ANALYTICAL MODEL

The second-generation version of the Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics[12] (CAMRAD II), a comprehensive aeromechanical analysis for rotorcraft, was chosen to perform the current study. The CAMRAD II rotor model was developed specifically to simplify the inputs necessary to vary the tip geometry parameters. Therefore, increased resolution of both structural and aerodynamic input parameters are utilized in the tip region of the model (see figure 1). Structural element (beam) nodes are included whenever a change in the orientation of the blade tip occurs – at the sweep and anhedral initiation locations, for example. The model employs 25 aerodynamic panels.

For this study, the basic blade stiffness, mass, and torsional inertia distributions are held constant for each of the tip geometries studied, regardless of shape or total area. All blade stiffness properties are assumed uniform between 0.25R and 1.0R. Mass and torsional inertia are uniform between 0.25R and 0.95R, but are reduced by 50% outboard of 0.95R to

account somewhat for reduced volume due to taper and to reduce the aft weight of a swept tip. To avoid rotor instability, a leading-edge balance mass is modeled for cases in which tip sweep is included. The leading-edge balance mass is sized to achieve static balance of the blade tip about the quarter-chord, is placed 0.03R inboard of the blade sweep initiation point and 15% of the chord (0.15c) forward of the quarter-chord, and is assumed to be a point mass that has no inertia.

The active-twist actuation moment is assumed to be generated by the piezoelectric fiber composite class of actuators, such as the Active Fiber Composite[13] (AFC) and the Macro-Fiber Composite[14] (MFC). The effect of the actuators is modeled in the analysis by imposing equal and opposite external torsional moments to the blade model at 0.25R and 0.90R. Other structural coupling effects (e.g., extension-twist coupling) introduced by the actuators are typically minimal, and are neglected in the analysis.

RESULTS

Effect of Inflow Model, Thrust, and Flight Condition

Previous analytical efforts on an active-twist rotor blade with a rectangular planform and a symmetric airfoil suggested that blade thrust and the type of analytical inflow model had minimal effect on active-twist response.[15] The baseline AATR model of this study, however, has been determined to be sensitive to both the inflow model and rotor thrust variation, as presented in figures 4 and 5.

Inflow Model Sensitivity. Figure 4 presents the active-twist frequency response results for hovering flight at 8° collective pitch. As presented, three different inflow models were used – uniform inflow, prescribed wake, and free wake. The results clearly show that a nonuniform wake model, represented by the prescribed and free wakes, reduces the active-twist
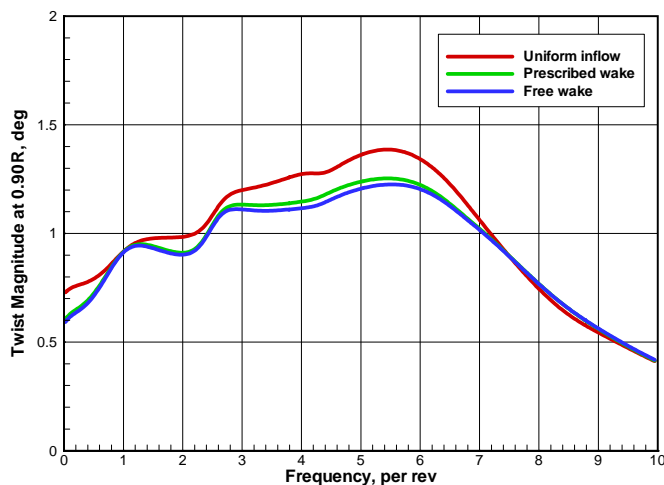
Figure 4. Wake effect on active-twist rotor response. AATR baseline design with 30° sweep, 2.5:1 taper, and 10° anhedral initiating at 0.95R. Hovering flight at 8° collective pitch.
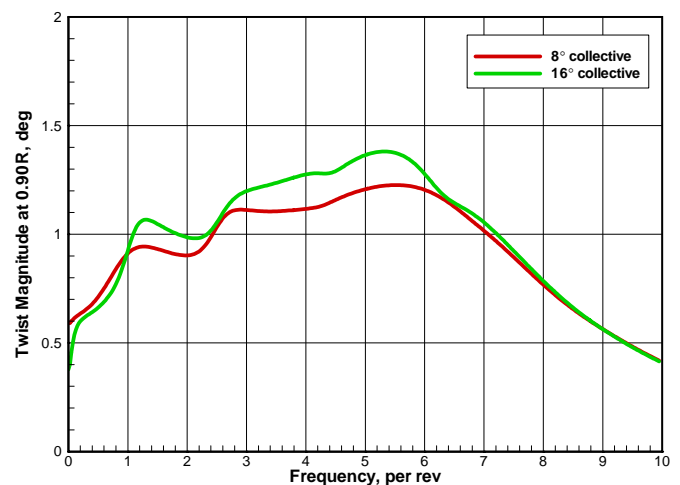
Figure 5. Effect of collective pitch variation on AATR response. Hovering flight using free wake inflow model.

response of the rotor system throughout much of the frequency range. In particular, active-twist reductions of nearly 0.2° are evident across much of the 3P through 5P frequency range associated with the vibration control of 4-bladed rotor systems. Based upon the results of the inflow model sensitivity study, a free wake inflow model was chosen for use during the current study. All wake input parameters were held constant for each of the configurations examined.

Thrust Sensitivity. Figure 5 presents the active-twist frequency response for hovering flight at 8° and 16° collective pitch settings, representing two different rotor thrusts. As presented, a clear effect on active-twist response is noted, so a minimum of two collective pitch settings (8° and 16°) were chosen for examination throughout the current study.

Flight Condition Sensitivity. Additional analyses have been executed at a range of forward flight conditions to identify any effect upon active-twist response. Typically, little difference was observed between hovering flight frequency response results and those obtained in forward flight. At high flight speeds, some increase in active-twist response was evident, therefore, the hovering flight conditions have been chosen as providing representative, yet conservative, estimates of active-twist frequency response, and are utilized throughout this paper.

Effect of Individual Parameters

The effects of tip sweep, taper, anhedral, nonlinear twist and the associated radial-initiation locations of each parameter were first studied independently. The results for each parameter are presented below in order of their impact, from greatest to least, on active-twist response.
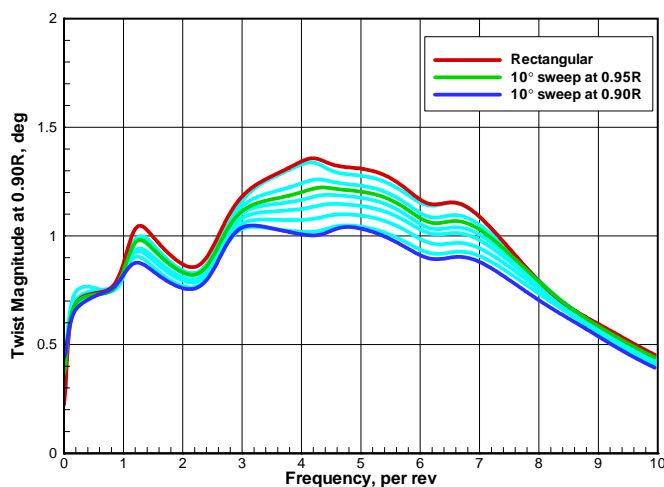
Sweep. Figures 6 through 10 present the effect of blade tip sweep on active-twist frequency response. As shown, sweep
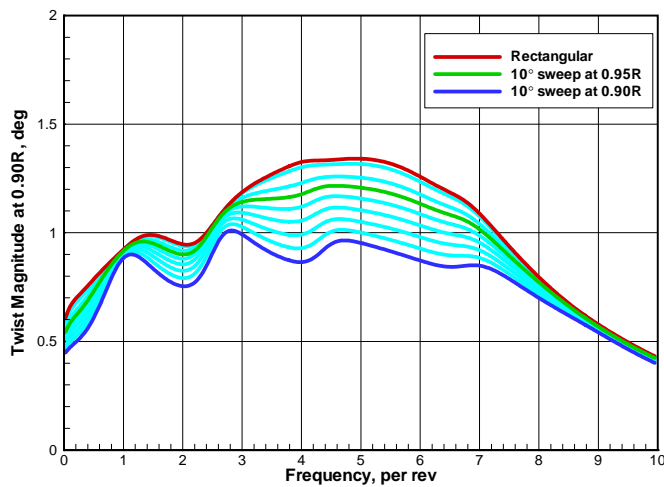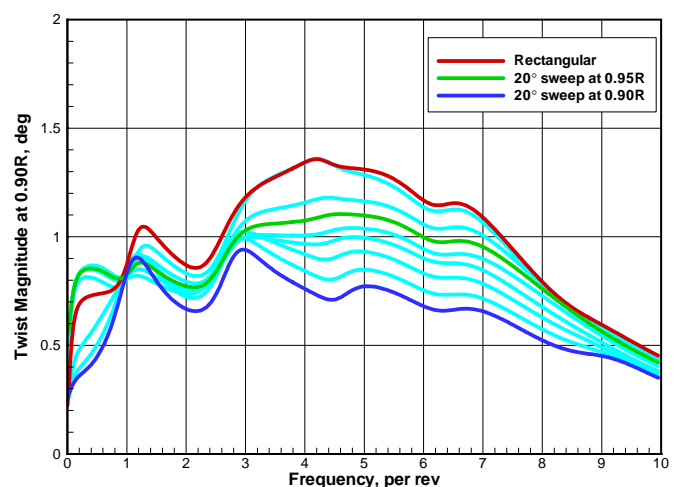

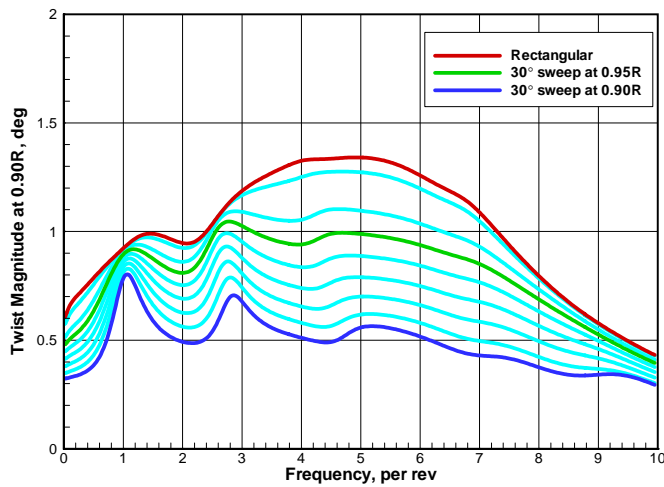(a) 8° collective pitch.
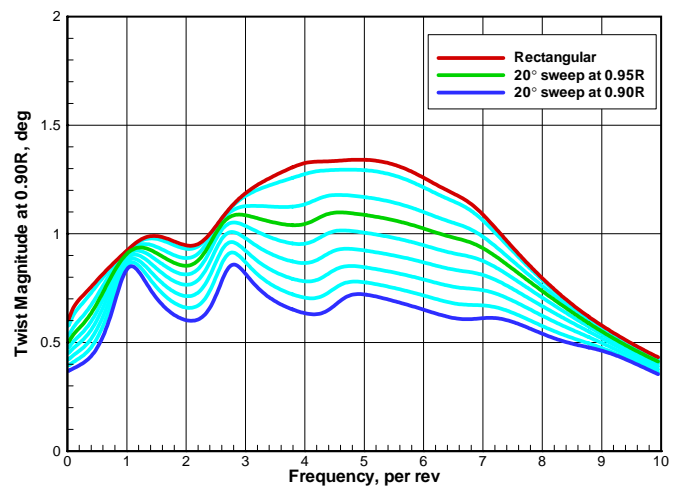
(b) 16° collective pitch.

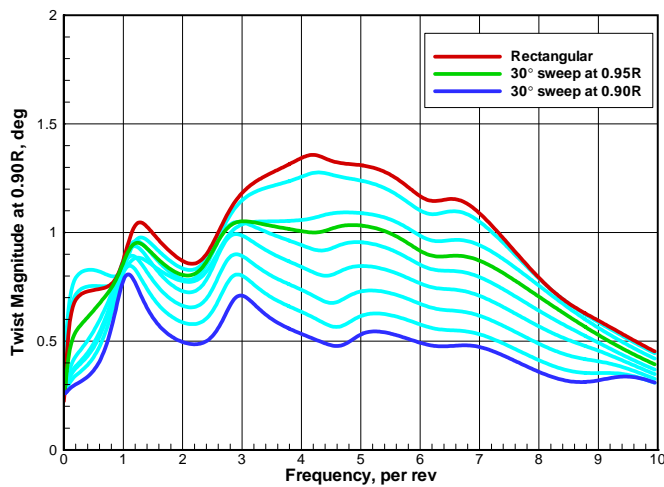Figure 6. Active-twist frequency response for 10° sweep at various radial initiation points.

(a) 8° collective pitch.

(b) 16° collective pitch.

Figure 7. Active-twist frequency response for 20° sweep at various radial initiation points.

(a) 8° collective pitch.

(b) 16° collective pitch.

Figure 8. Active-twist frequency response for 30° sweep at various radial initiation points.

can produce a very significant (~60%) reduction in the magnitude of the response. The shape of the response is also observed to be affected significantly. In figures 6 through 8, three tip sweep angles of 10°, 20°, and 30°, respectively, are emphasized – the rectangular tip in red, the tip with sweep initiating at 0.95R in green, and the tip with sweep initiating at 0.90R in blue. The cyan lines represent intermediate configurations in which tip sweep initiates at 0.98R, 0.96R, 0.94R, 0.93R, 0.92R, and 0.91R. As presented, the active-twist response transitions smoothly and significantly as the radial sweep initiation point is moved inboard. Tip sweep is observed to introduce flap-torsion coupling as evidenced by the clear response peaks that emerge near 1P and 3P with increasing sweep and inboard sweep initiation.

Figures 9 and 10 present the effect of blade sweep for tip sweep initiation at 0.95R and 0.90R, respectively. The figures show that both sweep angle and radial sweep initiation point are significant drivers for the magnitude of the active-twist

response. Collective pitch variation is observed to affect the overall magnitude of the response very little.

Figures 6 through 10 present clear evidence that tip sweep and radial initiation point are important considerations in active-twist rotor design. It is therefore necessary to develop a physical understanding of the phenomena associated with the change in response. To more fully investigate these phenomena, a series of analytical models were generated that provide different combinations of aerodynamic and structural characteristics. It is important to note that these models have characteristics that can be investigated easily with a comprehensive analysis, but would be impossible to fabricate physically. The tip parameters of the analytical models are presented in figure 11. The first model, presented in the upper part of figure 11, combines 30° of aerodynamic sweep initiating at 0.95R with a blade that has no structural sweep (i.e., both the c.g. axis and the elastic axis are unswept). This model is exercised both with and without the leading-edge balance mass. The second model, presented in the lower half of figure 11, combines 30° of structural sweep initiating at 0.95R with unswept aerodynamic properties.

Hovering flight analysis at 8° collective pitch was executed on the models of figure 11, the results of which are presented in figure 12. Figure 12 illustrates that removing the structural sweep while keeping the aerodynamic sweep and static balance mass (dark blue line) results in further degradation of the active-twist response over that observed for the conventionally swept blade model (green line). Removing the structural sweep and the static balance mass (orange line) improves the response to coincide approximately with that of the conventionally swept blade model, and demonstrates that the leading-edge balance mass is effective in minimizing the impact of structural sweep on active-twist response. This also serves to illustrate that the first elastic torsion frequency, within limits, is not a significant driver in the response. This is demonstrated by the difference in the torsion frequency of the two configurations – 6.53P for the conventionally swept blade model (green line) vs. 6.95P for the blade with no structural sweep or leading-edge mass (orange line). Removing the aerodynamic sweep and restoring the structural sweep (light blue line) is observed to re-establish the response to that of the rectangular tip. Thus, the primary reason for the significant degradation in active-twist response for swept configurations may be attributed primarily to the aerodynamic loads on the tip, not the inertial loads or structural configuration. Additionally, the leading-edge static balance mass is a source of reduced response, however, not to an extent as great as the aerodynamic loads.

Taper. Figures 13 and 14 present the effect of taper on active-twist frequency response. Increasing taper or the inboard extent of the taper is shown to generally increase active-twist response, particularly in the range of 4P to 7P for this rotor design. Increasing collective pitch is observed to have minimal effect on active-twist response magnitude.
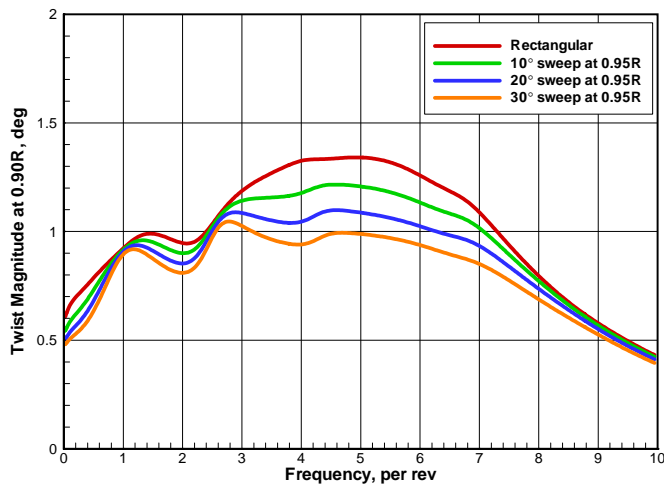
(a) 8° collective pitch.
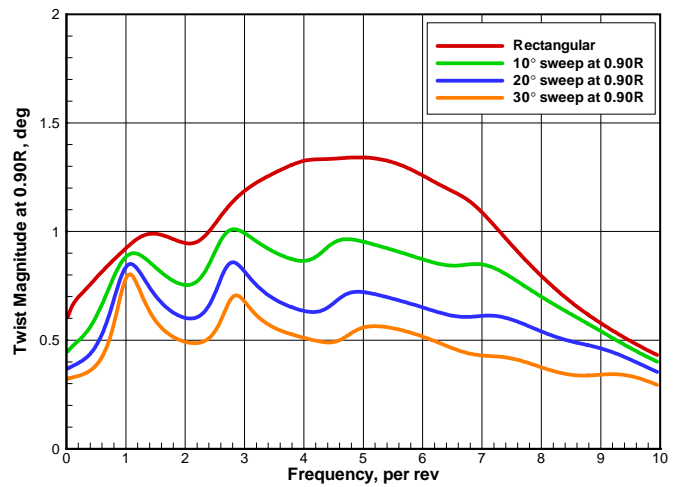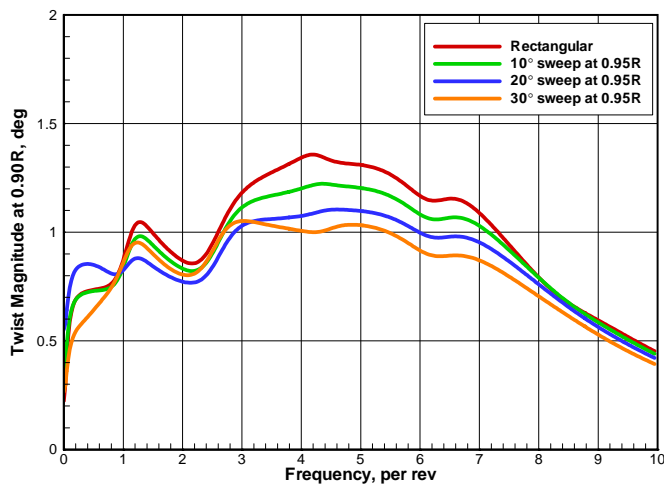
(b) 16° collective pitch.

Figure 9. Active-twist frequency response for varying sweep angles initiating at 0.95R.
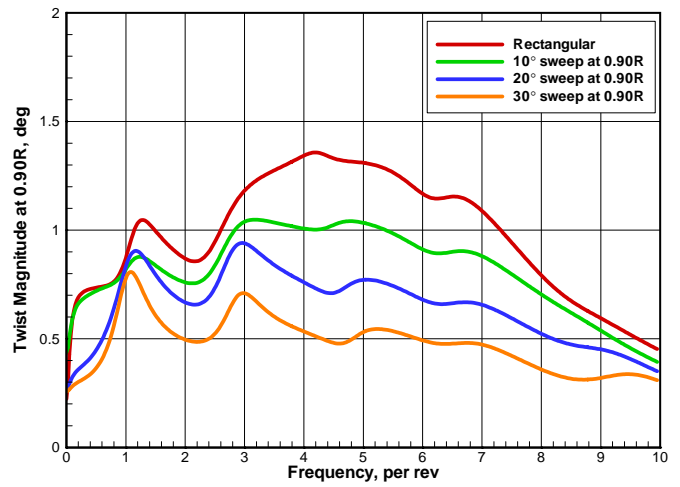

(a) 8° collective pitch.

(b) 16° collective pitch.

Figure 10. Active-twist frequency response for varying sweep angles initiating at 0.90R.

Unlike the swept tip configurations, there are no differences in the blade structural models between the rectangular planform and the tapered tip configurations. It can thus be inferred that the change in response exhibited due to the use of tip taper is due purely to changes in the aerodynamic loads.

Anhedral. Figures 15 and 16 present the effect of anhedral on active-twist frequency response. As with blade taper, anhedral is shown to provide some increase in active-twist response, however, to a somewhat lesser degree than taper. An analysis similar to that performed for tip sweep was conducted to determine whether inertial or aerodynamic loads are the primary contributor to increased response due to anhedral. The results of this analysis are presented in figure 17, indicating that the aerodynamic loads of the anhedral tip provide the bulk of the additional response.

Nonlinear Twist. Nonlinear twist was determined to have virtually no effect on active-twist frequency response at 8° collective pitch. At 16° collective pitch, a small improvement in response is noted from 2P through 5P, as presented in figure 18.

Effect of Multiple Parameters

Analytical studies have been conducted utilizing combinations of the tip geometry parameters examined above. Table 3 lists the values of the parameters studied, which were combined in groups up to and including the use of all variables, to provide a thorough assessment of the effect on active-twist response. Through this process literally hundreds of configurations were examined in addition to those configurations already presented. The shear volume of results makes an accurate synopsis of the results in a conference
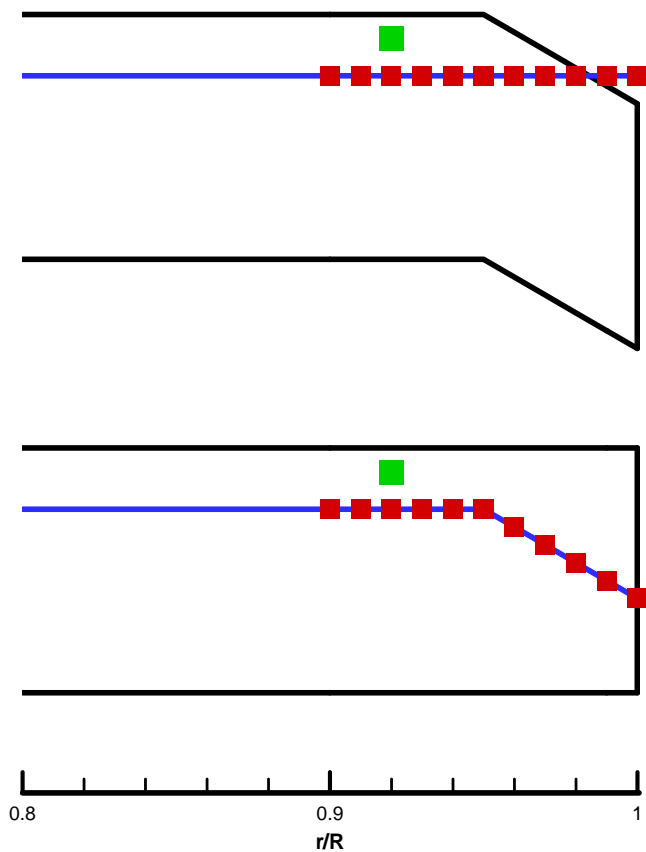
Figure 11. Blade configurations to examine active-twist response characteristics due to blade sweep. The upper configuration has aerodynamic sweep, but no structural sweep. The lower configuration has structural sweep, but no aerodynamic sweep.

paper difficult at best. However, an attempt has been made to identify a small subset of the most interesting results for presentation herein.

In general, the results of the multi-parameter study are similar to those obtained during the single parameter study, which considered sweep, taper, anhedral, nonlinear twist, and their associated radial initiation locations. That is, if a set of parameters such as taper and its initiation location were determined to increase response in the single parameter study, then response was generally observed to increase when taper was incorporated with another parameter, such as sweep. As an example, this particular parameter set is presented in figures 19 and 20 where taper is combined with 20° of sweep at 0.95R and 0.90R. As shown, the increase in response due to taper is greater when combined with sweep than when utilized as an individual parameter. For example, when comparing the results of figure 19 with those in figure 13, in which taper alone was utilized, a marked increase in the response is noted with increasing taper ratio. Such increases in effectiveness when combining parameters were generally noted throughout the multiple parameter study. This effect
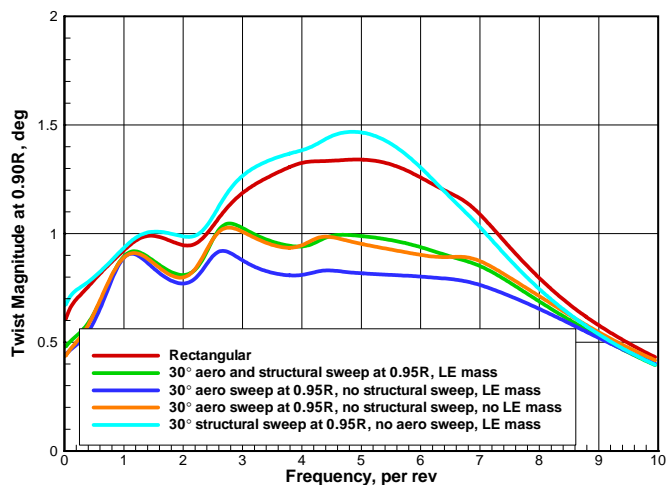

Figure 12. Results of blade sweep investigation showing that aerodynamic loading on the swept tip is chiefly responsible for the reduction in active-twist response. Results are for hovering flight at 8° collective pitch.

can be used to an advantage when designing advanced active-twist rotor systems, particularly those for which tip sweep is desirable.

Figure 20 provides an example of a potential difficulty with advanced active-twist rotor design. As discussed earlier, tip sweep tends to exacerbate flap-torsion coupling. When coupled with taper, this flap-torsion coupling becomes more pronounced, particularly at high collective pitch settings (see figure 20b). Such parameter combinations result in a highly variable active-twist response, particularly through the 4P to 6P frequency range.

The tip shapes that were determined to provide the best overall active-twist frequency response are somewhat untraditional. These tip shapes combine moderate tip sweep angles and large anhedral confined to the outer five percent of the blade tip, and high taper ratios initiating more inboard. Figure 21 presents an example of one such geometry. Nonlinear twist does not seem to affect these configurations significantly, and could be selected depending upon other rotor system design goals. Figure 22 presents the active-twist frequency response comparison of the tip shape in figure 21 with a rectangular blade planform. As presented, the advanced tip shape generally maintains a level of response that is equivalent to or greater than the rectangular blade response.

**Active-Twist Rotor Design Implications**

The results presented herein illustrate the complexity involved in proper active-twist rotor design. Due to the interdisciplinary nature of rotor design and, in this case, active rotor design, it is difficult to envision successful rotor systems unless they have been designed to incorporate active-twist from the early stages of the design phase. Based upon the
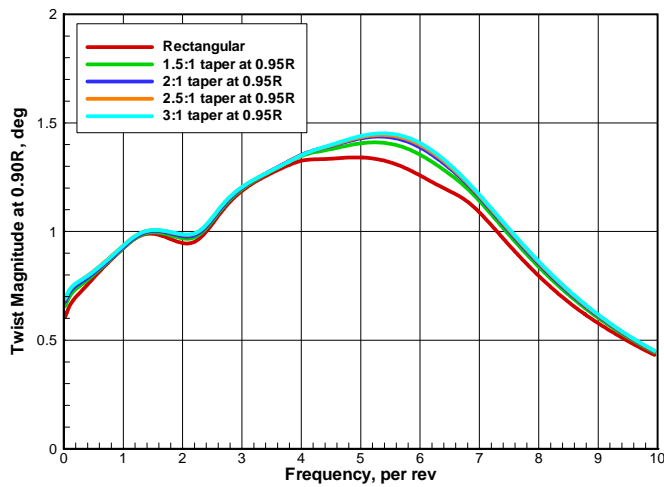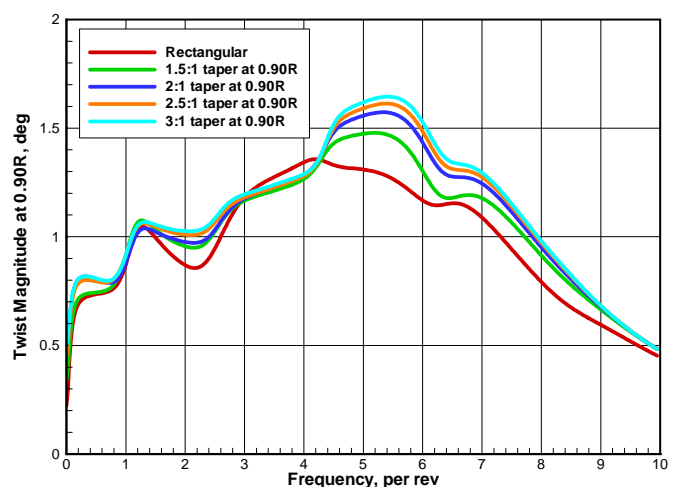
(a) 8° collective pitch.
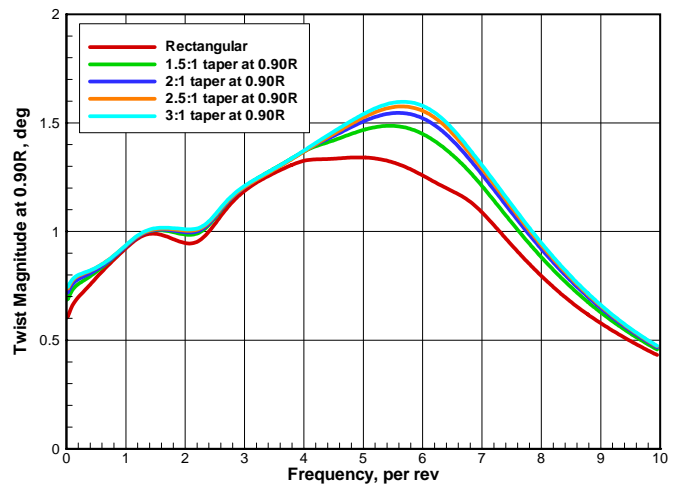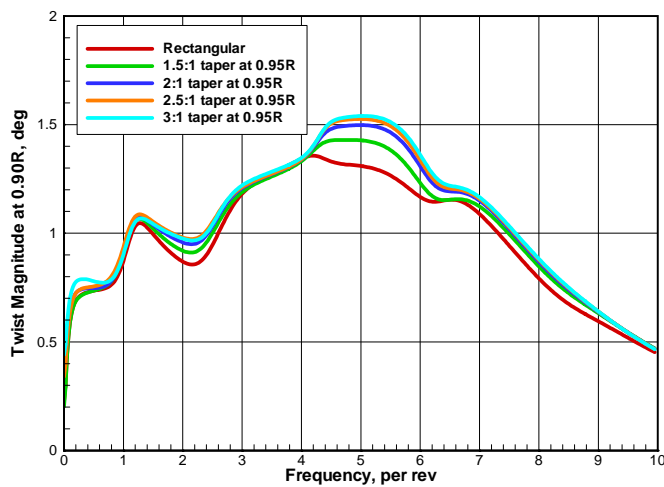
(b) 16° collective pitch.

Figure 13. Active-twist frequency response for varying taper ratios initiating at 0.95R.

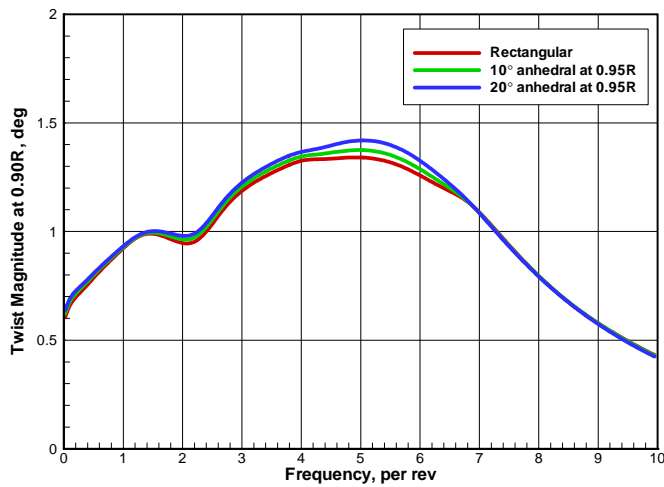

(a) 8° collective pitch.

(b) 16° collective pitch.

Figure 14. Active-twist frequency response for varying taper ratios initiating at 0.90R.

results of this investigation, the tip geometry of many of the newer rotor system designs may prove to be troublesome if implemented in an active-twist application. Many other factors, however, would need to be explored fully, such as the associated structural design and its interaction with the tip shape, before a final conclusion regarding specific tip geometry may be reached. The tip shape that was deemed to perform the best in an active-twist environment is offered simply as a "first cut" in a more arduous design process. Of the active-twist phenomena explored in this paper, tip sweep – defined as a combination of the tip sweep angle and the radial initiation point -- is offered as the parameter of greatest significance to active-twist response. When considering the future development of active-twist rotor systems, designers should monitor closely the tip sweep angle, the radial extent of tip sweep, and the effect that each of these parameters has on rotor system active-twist response. As demonstrated in this

paper, this caution is of particular importance when tip sweep is coupled with tapered tip geometry.
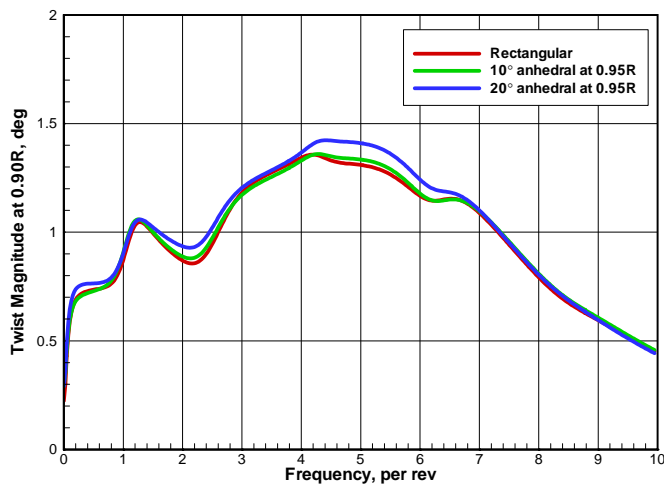
CONCLUSIONS

A parametric study of the effect of blade tip geometry on active-twist rotor response has been conducted using the comprehensive analysis CAMRAD II. The notional rotor system was patterned after a sub-scale rotor designed to be Mach and dynamically scaled for the Langley Transonic Dynamics Tunnel. The blade tip geometry was assumed to vary outboard of 0.90R, and tip sweep, taper, anhedral, nonlinear twist, and the associated radial initiation locations for each of these parameters were chosen for the study variables. All analysis was executed in a hovering flight environment with free wake geometry distortion.
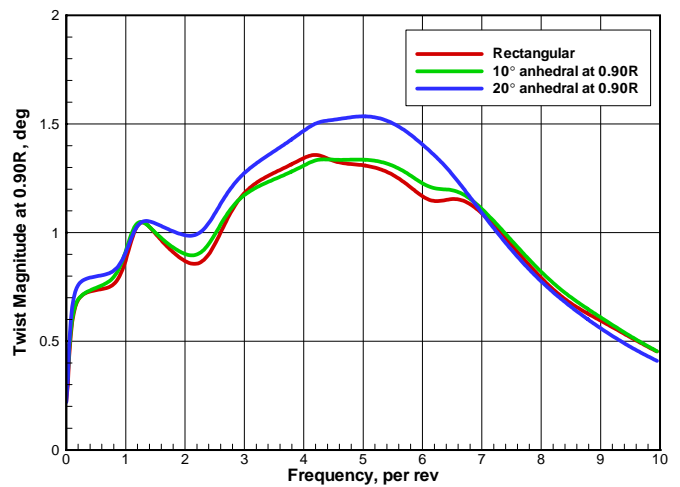
(a) 8° collective pitch.
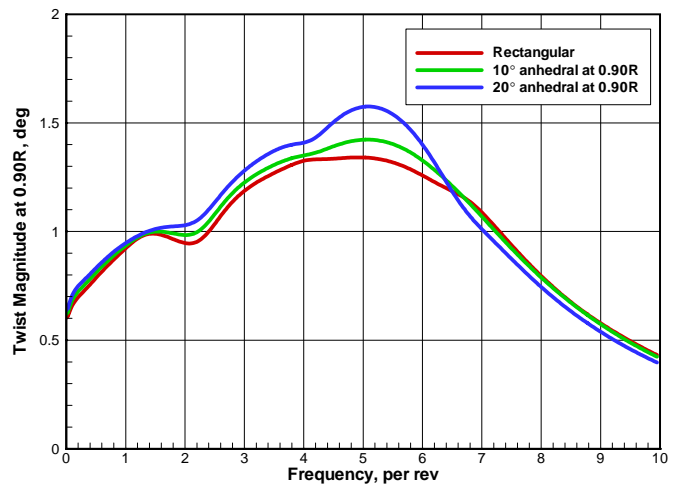
(a) 8° collective pitch.

(b) 16° collective pitch.

Figure 15. Active-twist frequency response for varying anhedral initiating at 0.95R.

(b) 16° collective pitch.

Figure 16. Active-twist frequency response for varying anhedral initiating at 0.90R.

The conclusions from this parametric investigation are:

1. Of the tip geometry parameters, tip sweep has the greatest impact on active-twist frequency response. Increasing tip sweep angles and increasingly inboard sweep initiation locations tend to decrease active-twist blade response and increase blade flap-torsion coupling.

2. Increasing taper and anhedral tend to provide an increase in active-twist response. Taper is noted to be slightly more effective in increasing the active-twist response. Moving the initiation location inboard is effective in providing increased response for both taper and anhedral.

3. Nonlinear twist has little impact on active-twist frequency response.

4. When combined to generate tip shapes with multiple parameters, each parameter tends to affect active-twist response in a manner similar to that observed for the parameter alone. Often, however, an increased sensitivity of the active-twist response is noted.

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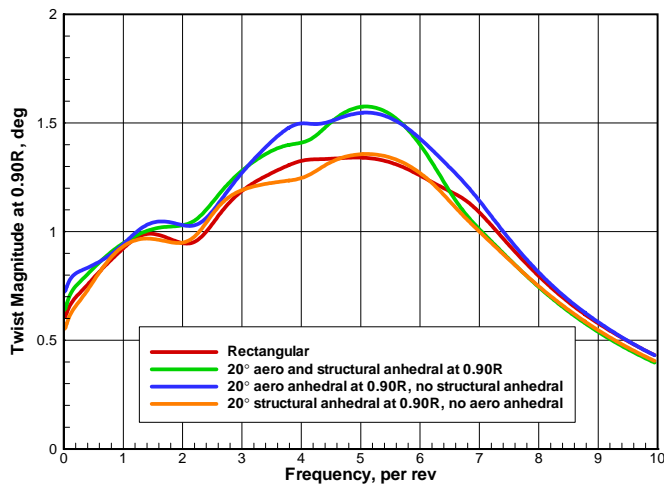
Figure 17. Results of blade anhedral investigation showing that aerodynamic loading on the tip is chiefly responsible for an increase in active-twist response.
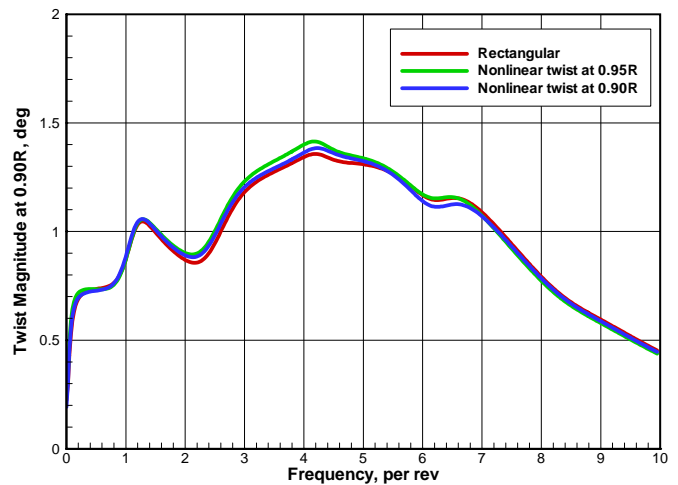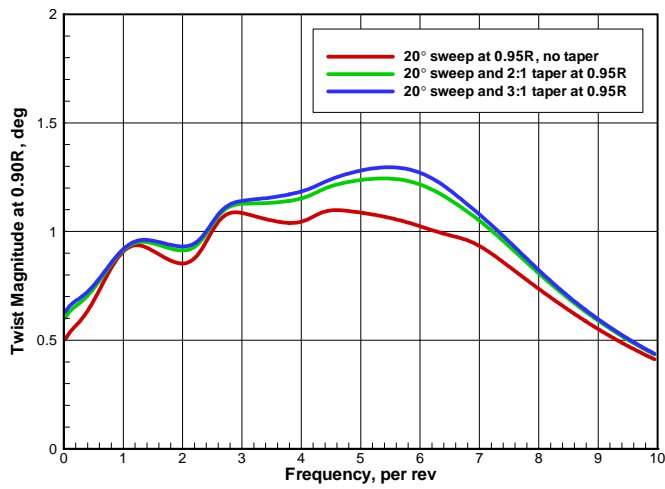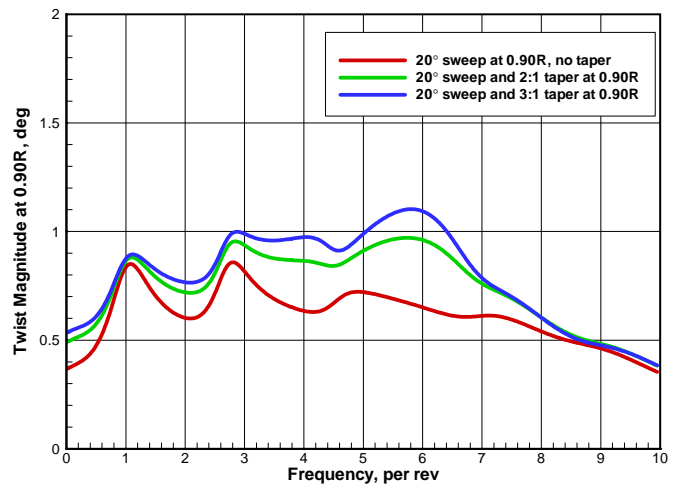

Figure 18. Active-twist frequency response for nonlinear twist variation.

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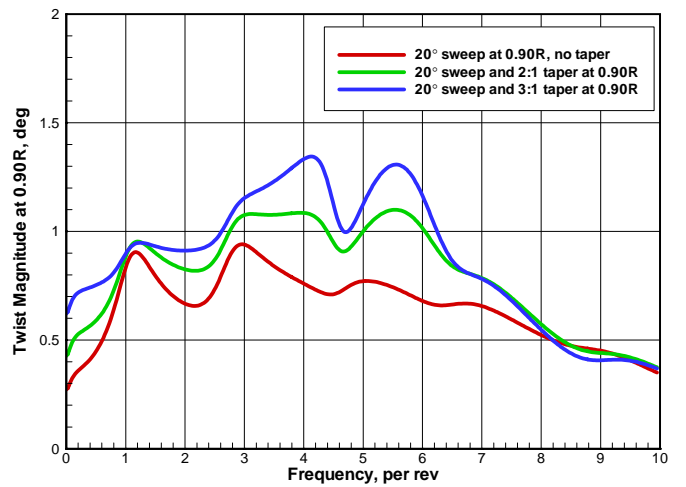
(a) 8° collective pitch.

(a) 8° collective pitch.
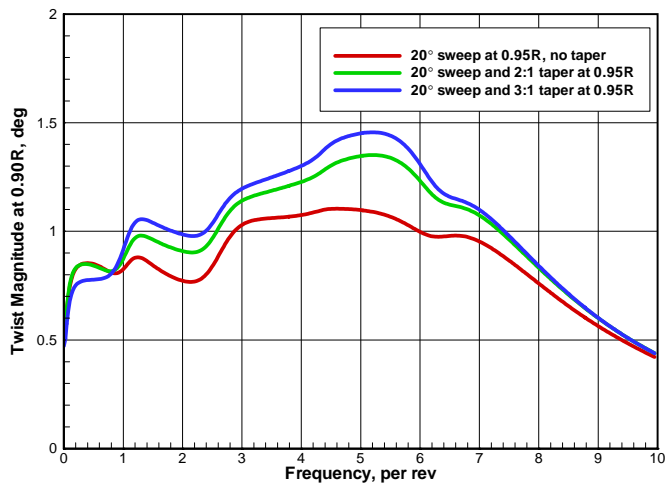
(b) 16° collective pitch.

(b) 16° collective pitch.

Figure 19. Active-twist frequency response for 20° sweep and varying taper ratio initiating at 0.95R.

Figure 20. Active-twist frequency response for 20° sweep and varying taper ratio initiating at 0.90R.
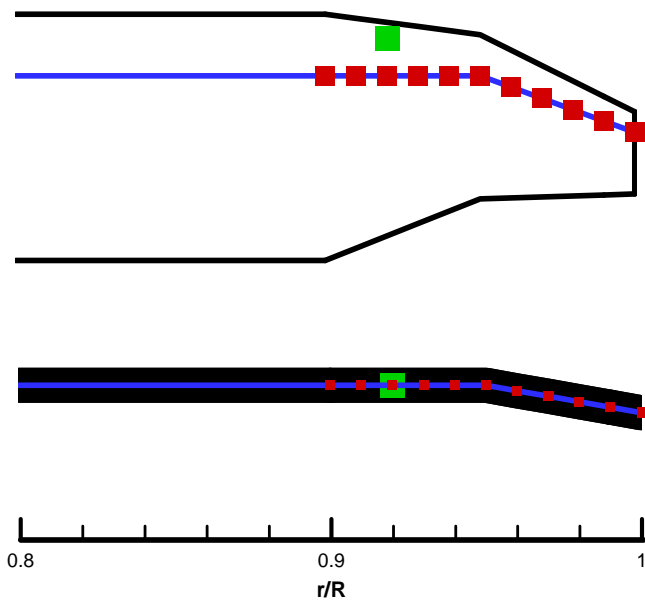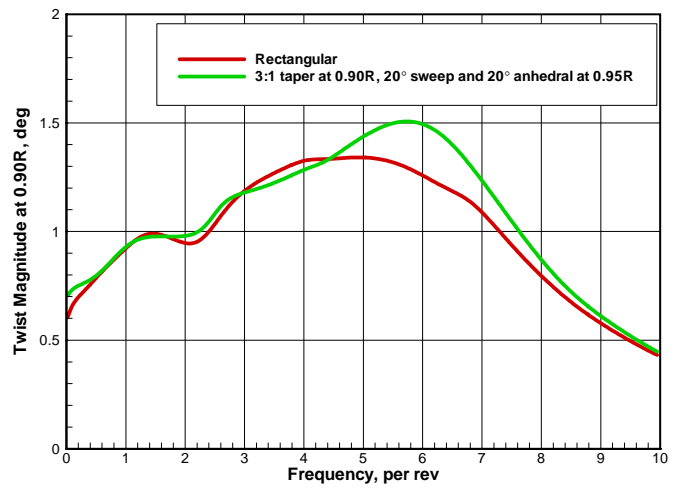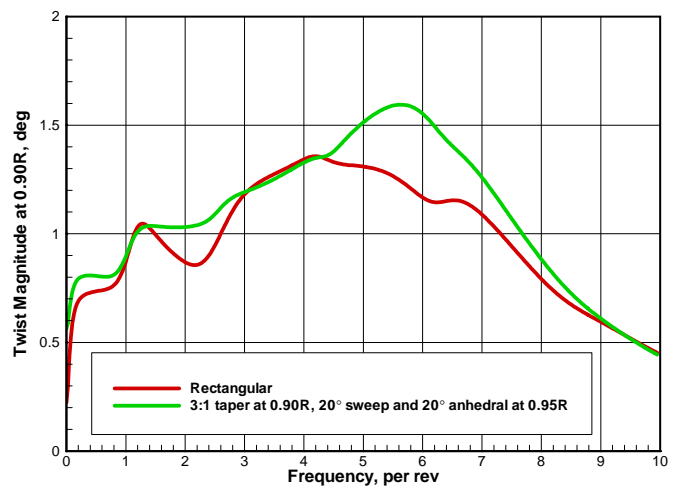
Figure 21. Tip configuration providing a good overall active-twist frequency response. Configuration incorporates 3:1 taper ratio initiating at 0.90R, and 20° tip sweep and 20° anhedral initiating at 0.95R.

(a) 8° collective pitch.

(b) 16° collective pitch.

Figure 22. Active-twist frequency response for tip shape with 3:1 taper ratio initiating at 0.90R, and 20° tip sweep and 20° anhedral initiating at 0.95R.