

STIFF-INPLANE TILTROTOR AEROMECHANICS INVESTIGATION USING TWO MULTIBODY ANALYSES

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Abstract. *This paper presents the development of two multibody dynamics models to predict the whirl-flutter stability of a stiff-inplane tiltrotor wind-tunnel model and correlates the predictions with experimental data. Comprehensive, multibody-based dynamics analyses of rotorcraft enable modeling and simulation of the rotor system at a high level of detail so that complex mechanics and nonlinear effects associated with control system geometry and various types of hinges and joints are able to be considered. A parametric study of key design variables, such as control system stiffness, pitch-flap coupling, and aerodynamic compressibility was completed as part of this investigation, which may help to determine suitable design criteria for future stiff-inplane tiltrotor systems. Analytical results indicate consistent capabilities of multibody dynamics analyses in predicting the stiff-inplane tiltrotor whirl-flutter stability and show generally good agreement with the experimental results. Both analytical and experimental results show the destabilizing effects of pitch-flap coupling and aerodynamic compressibility on the whirl-flutter stability of a stiff-inplane tiltrotor whereas both results also indicate that a reduction in control system stiffness has little effect on whirl-flutter stability.*

1 INTRODUCTION

This paper presents the development of a multibody dynamics model to predict the whirl-flutter stability of a stiff-inplane tiltrotor wind-tunnel model and correlates the predictions with experimental data. In view of the ever-increasing cost of flight or wind tunnel testing, the systematic use of advanced simulation and modeling for these complex tiltrotor configurations using multibody dynamics codes may prove to become, at least in part, an alternative to expensive experimental verifications.

Nonlinear elastic multibody dynamics analyses have received considerable interest among the rotorcraft analysis community because of their generality and flexibility, especially in modeling of tiltrotor aircraft [1, 2]. Helicopter rotor systems may be classified into stiff-inplane and soft-inplane rotors depending on whether the fundamental blade lag rotating frequency is above or below the rotor speed. Soft-inplane rotor systems, which have the blade lag frequency below one (normalized by the rotor speed), can greatly reduce the inplane blade loads in tiltrotor aircraft, thereby reducing strength requirements for the hub which in turn leads to reduced structural weight and improved aircraft agility [3]. However, soft-inplane rotor systems generally have reduced damping margins and lower stability boundaries than stiff-inplane rotor systems. Thus, current tiltrotor designs for production aircraft use gimballed stiff-inplane rotor systems [4, 5, 6]. Stiff-inplane rotor systems are desirable for tiltrotors because in hover there is no concern for ground resonance, and in high-speed airplane mode the stability boundaries associated with whirl-flutter have been established at velocities slightly beyond aircraft power limits, with adequate damping margins at sub-critical airspeeds. Ref [1] focuses on the development of two multibody analytical models, DYMORE [7] and MBDyn [8], to predict the dynamic response and aeroelastic stability of a four-bladed, soft-inplane tiltrotor wind-tunnel model. Good agreement is seen between analytical predictions and test results. Ref [2] uses a multibody dynamics DYMORE model of the same soft-inplane tiltrotor to carry out an aeroelastic stability and blade loads correlation study using wind tunnel test data. Refs [1] and [2] show that the DYMORE and the MBDyn models with drive train free-play captured the largely nonlinear wing beamwise damping change in the range of near-zero rotor mast torque. A parametric study of the design parameters which have influence on the aeromechanics of the soft-inplane rotor system is also included in those investigations. Refs [6, 9] present the development of multibody analytical models of a proposed unmanned stiff-inplane gimballed tiltrotor aircraft using CAMRAD [10] and DYMORE in support of the design process. The analytical models have been used to calculate the loads and stability margins of the tiltrotor UAV in helicopter, airplane, transition, and maneuvering flight. Gust loadings are investigated for some of the maneuvers. Rotor-wing stability is examined using DYMORE. A parametric study of wing beam mode damping with varying rotor and wing properties for semi-span and full-span models is presented.

The objective of the present study is to develop a sophisticated multibody stiff-inplane tiltrotor model component by component, to carry out correlations of the analytical models with experimental data, and to improve the current analytical accuracy of stiff-inplane tiltrotor whirl-flutter stability predictions. This study will also include parametric investigations of key variables that are crucial to the tiltrotor aeromechanical behavior. The computed sensitivities of tiltrotor whirl-flutter characteristics to parameters such as control system stiffness, pitch-flap coupling, and aerodynamic compressibility, will be compared to the experimental values to improve the physical understanding of tiltrotor aeromechanical characteristics.

2 WIND TUNNEL TEST DESCRIPTION

Ref [11] presents in detail the wind tunnel experimental investigation of whirl-flutter stability on the stiff-inplane tiltrotor, which results are used in this correlation study. The test procedure is briefly described here. The stiff-inplane, three-bladed rotor system was tested at model scale on the Wing and Rotor Aeroelastic Testing System (WRATS) in the NASA Langley Transonic Dynamics Tunnel (TDT) in 2000 (Fig. 1). The model was tested in airplane mode at forward flight conditions. The experimental investigation included a baseline whirl-flutter stability study, and a parametric investigation of key design parameters such as control system stiffness and pitch-flap coupling on the whirl-flutter stability boundary. The WRATS model is instrumented to provide loads, stability and rotor dynamics information. Instrumentation includes pylon and wing accelerometers; blade, wing, mast, pitch link, and hub loads via strain gauges; rotor flapping via an angular displacement transducer; and swashplate position and orientation via translational displacement transducers. For investigation of whirl-flutter stability, the wing bending and torsion moment strain gauge data were used.

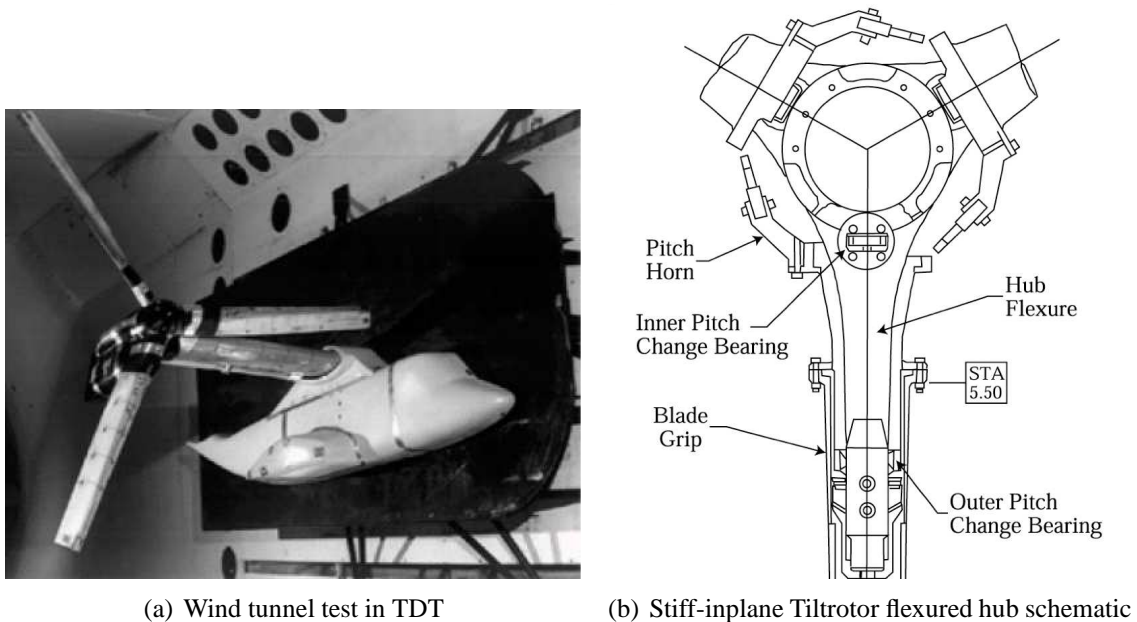


Figure 1: WRATS semi-span stiff-inplane rotor

3 ANALYTICAL MODEL

Detailed analytical models of the stiff-inplane tiltrotor have been developed using two multi-body rotor codes known as DYMORE [7], and MBDyn [8]. The two codes have similar capabilities, but in order to test the robustness of the multibody approach, their results were compared with models created by different researchers at different institutions. These multibody analyses can include dynamic models for components of the rotor system which are often not considered in classical rotor analyses such as the hydraulic actuator control system, the swashplate mechanics (rotating and non-rotating components), pitch links, pitch horns, the rotor shaft, the constant-velocity joint at the gimbal hub, and the hub kinematics. The rotor blades are modeled as elastic beams undergoing coupled flap, lag, and torsion deformation similar to the finite element methods used in classical rotorcraft analyses.

3.1 Stiff-Inplane Tiltrotor Model

The finite element based multibody dynamics models developed in this effort include the gimballed hub, rotor blades, pitch links, swashplate, hydraulic control actuators which are attached to the pylon, and an elastic wing (Figs. 2(a) and 3(a)). The DYMORE model of the stiff-inplane rotor also includes a model of the constant-velocity (CV) joint in the hub. This CV joint allows the rotating shaft to transmit power to the rotor through a gimballed angle at nearly constant rotational speed. The CV joint consists of two universal joints which are interconnected to each other. Through such an arrangement, the twice per revolution variation in the rotating speed, which would be present if only one universal joint were used, is mostly canceled out (the output rotating speed is exactly constant only when the deflection angle between both input and output universal joints are equal.) The DYMORE model simulates the CV joint hardware exactly using the universal joint model available in the multibody code, and as such captures the characteristics of the CV joint precisely. The MBDyn model uses an ideal analytical gimbal model [12], which saves modeling effort while producing the same results.

Property	Value
Rotor Type	Gimballed, stiff-inplane
Number of Blades	3
Rotor Diameter	7.6 ft
Twist	47.5°
Hover RPM	888
Cruise RPM	742
Lift curve slope (nom.)	5.9
Solidity	0.105
Geometric δ_3	-15.0°
Wing Span	55.0 in
Wing Chord	20.0 in
Wing Sweep	-6.0°
Wing Dihedral	3.5°

Table 1: Key Parameters of the WRATS Stiff-Inplane Tiltrotor [11]

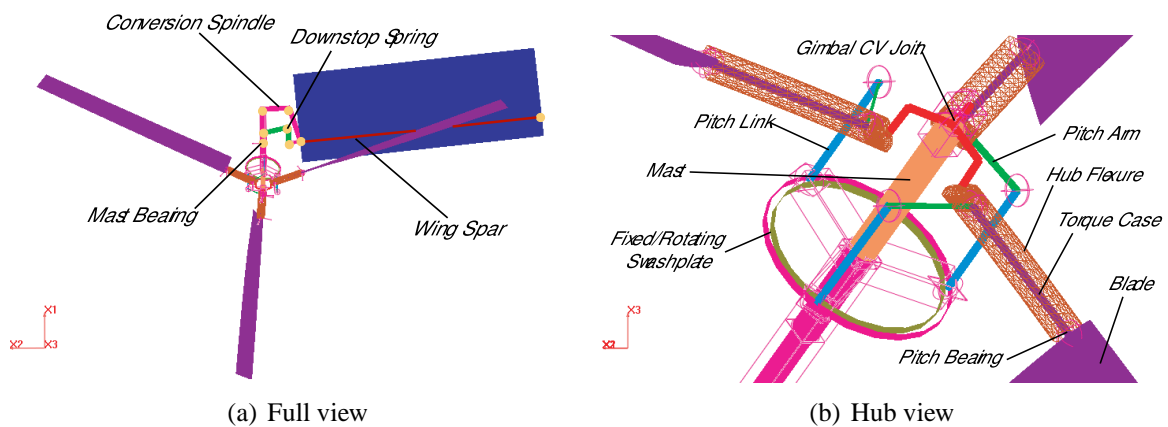


Figure 2: DYMORE model of WRATS semi-span stiff-inplane rotor

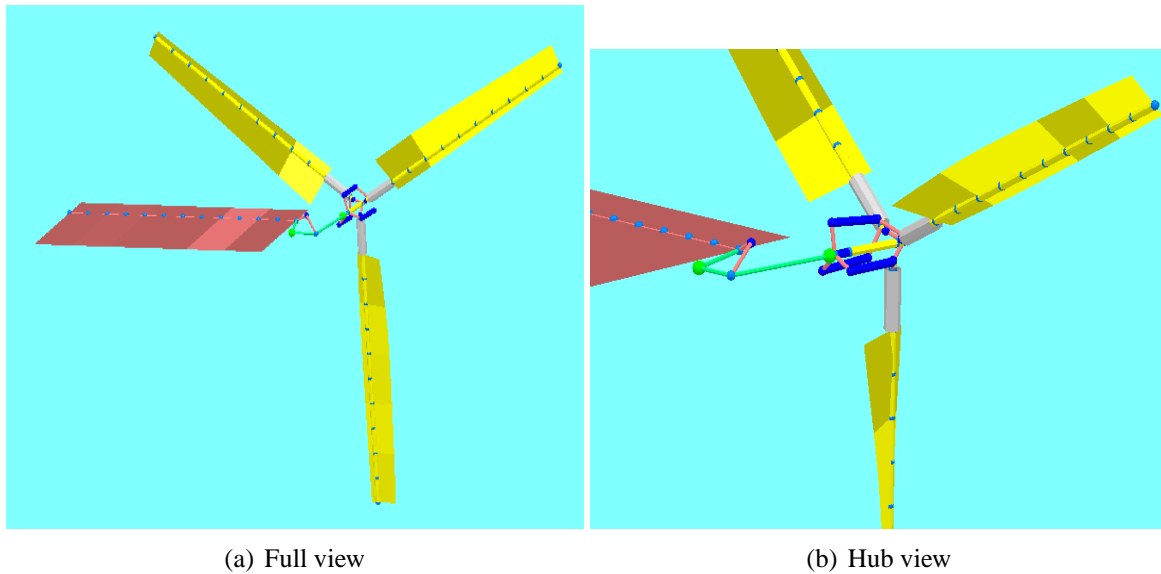


Figure 3: MBDyn model of WRATS semi-span stiff-inplane rotor

Figures 2 and 3 illustrate the key elements of DYMORE and MBDyn stiff-inplane tiltrotor models. The wing, rotor mast, and three blades, which each consist of a flexbeam, torque tube, and main blade, are modeled as elastic beam elements. Table 2 shows the details of the discretization of these beams [13, 14]. The aerodynamic forces on the rotor and wing are modeled with aerodynamic elements based on lifting line theory in the DYMORE model. The wing has five aerodynamic elements while each blade uses four aerodynamic elements. MBDyn model of rotor aerodynamics uses the built-in blade element theory. The aerodynamic interactions between rotor and wing are neglected in both models. The rotor hub, pitch links/horns, swashplate, and pylon are modeled as rigid bodies with their inertial properties properly input. The blade inner and outer torsion bearings are modeled as spherical joints matching the hardware precisely. The gimbal joint is modeled as a spherical joint, and the gimbal spring is simulated with springs in the CV joint.

The pylon conversion actuator is modeled as a flexible joint, which consists of a set of co-located concentrated springs and dampers. There are two possible configurations when the tiltrotor is converted to airplane-mode. One is the off-downstop configuration, which simulates the pylon conversion actuator stiffness and damping in helicopter mode and during conversion. The other is the on-downstop configuration, which has higher pylon conversion actuator stiffnesses to simulate the “locked” pylon state after conversion to airplane-mode. It is important to model these two pylon conversion actuator states accurately because they determine the wing chordwise/torsional mode frequency, and this mode is critical in tiltrotor aeroelastic stability. In the DYMORE and MBDyn models, two sets of stiffness matrices for the flexible joint are properly tuned to model the on- and off-downstop configurations respectively.

The computational aspects of the two multibody analyses considered in this paper are summarized in Table 3. The data shown is for a typical case of identifying wing beamwise frequency and damping of WRATS stiff-inplane tiltrotor model using DYMORE and MBDyn simulations.

4 RESULTS

Several multibody dynamics simulations and experiments using the stiff-inplane tiltrotor system and its sub-components have been conducted. The key simulations and data correlations

Beam	DYMORE		MBDyn	
	Number of elements	Order of elements	Number of elements	Order of elements
Wing	10	3	6	2
Flex-beam	5	3	10	1
Torque-tube	1	3	1	1
Blade	10	3	15	2

Table 2: Finite element beams in the DYMORE and MBDyn WRATS model

Data	DYMORE	MBDyn
Degrees of freedom	3554	1873
Time step (s)	2.64e-4	2.50e-4
Time steps per rotor revolution	256	270
Real/simulated time ratio	700:1	70:1
Computer	Intel Xeon 3.20 GHZ	Intel Xeon 3.20 GHZ

Table 3: Numerical analysis figures

included in this paper are: 1) determination of baseline airplane mode whirl-flutter stability boundaries, and 2) parametric investigations of control system stiffness, pitch-flap coupling, and aerodynamic compressibility effects on aeromechanical stability characteristics.

4.1 Baseline Stability Boundaries

Fig. 4 shows the variation of wing beam mode frequency and damping characteristics with airspeed for the off-downstop pylon stiffness configuration at steady rotor speeds of 742 and 888 RPM. The 888 RPM condition represents hover rotor speed while 742 RPM is the maximum performance cruise flight rotor speed. The DYMORE and MBDyn analyses for sub-critical damping and flutter speed compares relatively well for both rotor speeds, but slightly underpredicts the wing frequency in both the 742 and 888 RPM cases. Fig. 5 presents the variations of wing beam mode frequency/damping with airspeed for the on-downstop pylon stiffness configuration at rotor speeds of 770 and 888 RPM. The 770 RPM is an alternate to 742 RPM for the on-downstop configuration because of the proximity to the experimental model's torsion frequency to 742 RPM in the on-downstop configuration. DYMORE and MBDyn predictions of flutter speeds compare fairly with the test data in both the 770 and 888 RPM cases; however, the predictions of sub-critical damping case show some discrepancies compared with the test data. As the off-downstop case, DYMORE also underpredicts the frequency in both the 770 and 888 RPM cases, especially at low speeds.

4.2 Effect of Reduced Control System Stiffness on Whirl-Flutter Stability

The blade torsion dynamics associated with negative pitch-lag coupling (lag back, pitch up) were analytically shown to have a destabilizing influence on whirl-flutter stability boundaries for a rigid rotor hub and the pitch-lag coupling was shown to be affected by control system stiffness and rotor precone. To assess the effect of control system stiffness on the stability of a flexured-hub tiltrotor, a softened pitch horn, which reduces the control system stiffness by

more than 50 percent, replaced the baseline pitch-horn and was tested in the wind tunnel. In Fig. 6, both the experimental results and analytical predictions show that softening the control system stiffness only slightly reduces the whirl-flutter stability in high speed flight conditions for the 742 RPM and off-downstop configuration. Further, reducing control system stiffness has no significant impact on wing frequencies either. In Fig. 7, experimental results show an increase in wing beam damping using the soft control system for the 888 RPM and off-downstop configuration, however, this increase is not significant in the analytical predictions.

Fig. 8 shows that analytical results predict a small decrease in wing beam damping in high speed flight using the soft control system for the 770 RPM on-downstop configuration whereas experimental results are not complete due to hardware limitations. Fig. 9 illustrates that the soft control stiffness again does not have a significant impact on wing beam mode damping and frequency for the 888 RPM on-downstop configuration. Overall, both experimental and analytical results show that there is little or no change in whirl-flutter stability when the rotor control system stiffness of the stiff-inplane tiltrotor is reduced. Because of this, no comparison with MBDyn model simulation was attempted in this study of the effect of control system stiffness on whirl flutter stability.

4.3 Effect of Pitch-Flap Coupling on Whirl-Flutter Stability

Kinematic pitch-flap coupling (δ_3s), which is related to the orientation of the blade pitch link with respect to the hub gimbal, is an effective means of reducing the flapping response of a tiltrotor during maneuvers. Although both positive and negative δ_3s (an increase in blade pitch as the blade flaps up is defined as positive pitch-flap coupling and as negative δ_3) reduce blade flapping [15], they will reduce tiltrotor whirl-flutter stability, too. In Fig. 10, both the experimental results and analytical predictions show that the on-downstop whirl-flutter stability is significantly degraded when the magnitude of pitch-flap coupling is increased from the baseline δ_3 of -15° up to -45° . Compared to the experimental results, a larger reduction in wing beam damping is observed in the analytical predictions when δ_3 of -45° is used. Fig. 10 also shows that the wing beam frequency is slightly reduced when the magnitude of pitch-flap coupling is increased.

4.4 Effect of Aerodynamic Compressibility on Whirl-Flutter Stability

The effect of aerodynamic compressibility on the whirl-flutter stability of the WRATS stiff-inplane tiltrotor was investigated in the wind tunnel test by using a heavy gas test medium (R-134a). The tunnel pressure was reduced to match the gas density to standard atmospheric air density at sea level. The Mach number of the WRATS stiff-inplane tiltrotor model at 888 RPM is 0.65 when tested in R-134a at a density of $0.002378 \text{ slug}/ft^3$. Fig. 11 shows that the degradation in whirl-flutter stability is observed in both the experimental results and the analytical predictions for rotor speed of 770 RPM and the on-downstop configuration. This degradation is caused by an increase in aerodynamic forces at the same airspeed and rotor speed when aerodynamic compressibility is present with high Mach number, and these larger aerodynamic forces have a destabilizing effect on whirl-flutter stability. Fig. 11 also shows the reduction in flutter speed is larger in the simulations than in the test results. Similar results are observed for a rotor speed of 888 RPM and on-downstop configuration as shown in Fig. 12.

5 SUMMARY AND CONCLUSIONS

The development of analytical models of WRATS stiff-inplane tiltrotor using two multibody dynamics rotor codes is presented in this paper. The finite element based multibody dynamics models developed in this effort include models of rotor blades, gimbal hub with constant-velocity joint, the pitch links, the swashplate, the hydraulic control actuators which are attached to the pylon, and the elastic wing. The analytical models are used to predict the dynamic response and aeroelastic stability of the stiff-inplane tiltrotor wind-tunnel model, and the results are correlated with experimental data. A parametric study of key design variables, such as control system stiffness, pitch-flap coupling, and aerodynamic compressibility is also completed as part of this investigation, which may help to determine suitable design criteria for future stiff-inplane tiltrotor systems. The following conclusions are offered, subject to the limitations of the analyses and the scope of this study:

- Analytical results indicate consistent capabilities of multibody dynamics analyses in predicting the WRATS stiff-inplane tiltrotor whirl-flutter stability and show generally good agreement with the experimental results.
- Both analytical and experimental results show insignificant changes in whirl-flutter stability for the WRATS stiff-inplane tiltrotor when rotor control system stiffness is reduced by more than 50 percent.
- The destabilizing effect of pitch-flap coupling on whirl-flutter stability is observed both in the analytical and the experimental results. However, the analytical model overpredicts the degradation in wing beam damping when the magnitude of pitch-flap coupling is increased.
- Analytical and experimental results show that aerodynamic compressibility has a destabilizing effect on whirl-flutter stability of WRATS stiff-inplane tiltrotor. Thus, it is important to match the full-scale blade Mach number in either analytical or experimental investigation of stiff-inplane tiltrotor whirl-flutter stability.

6 ACKNOWLEDGMENTS

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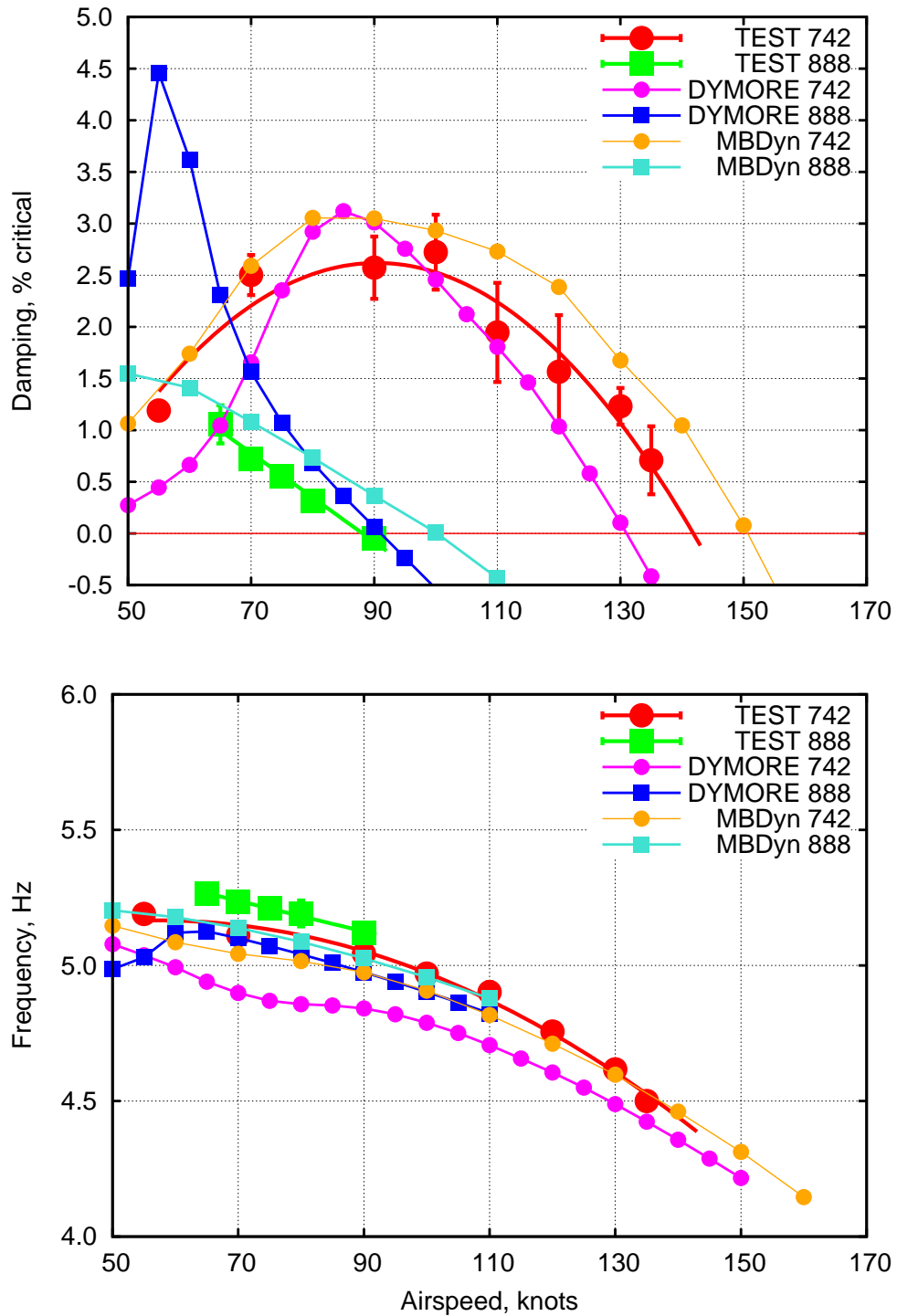


Figure 4: Comparison of analytical predictions with test data of the off-downstop wing beam frequency/damping variation with airspeed for the baseline configuration

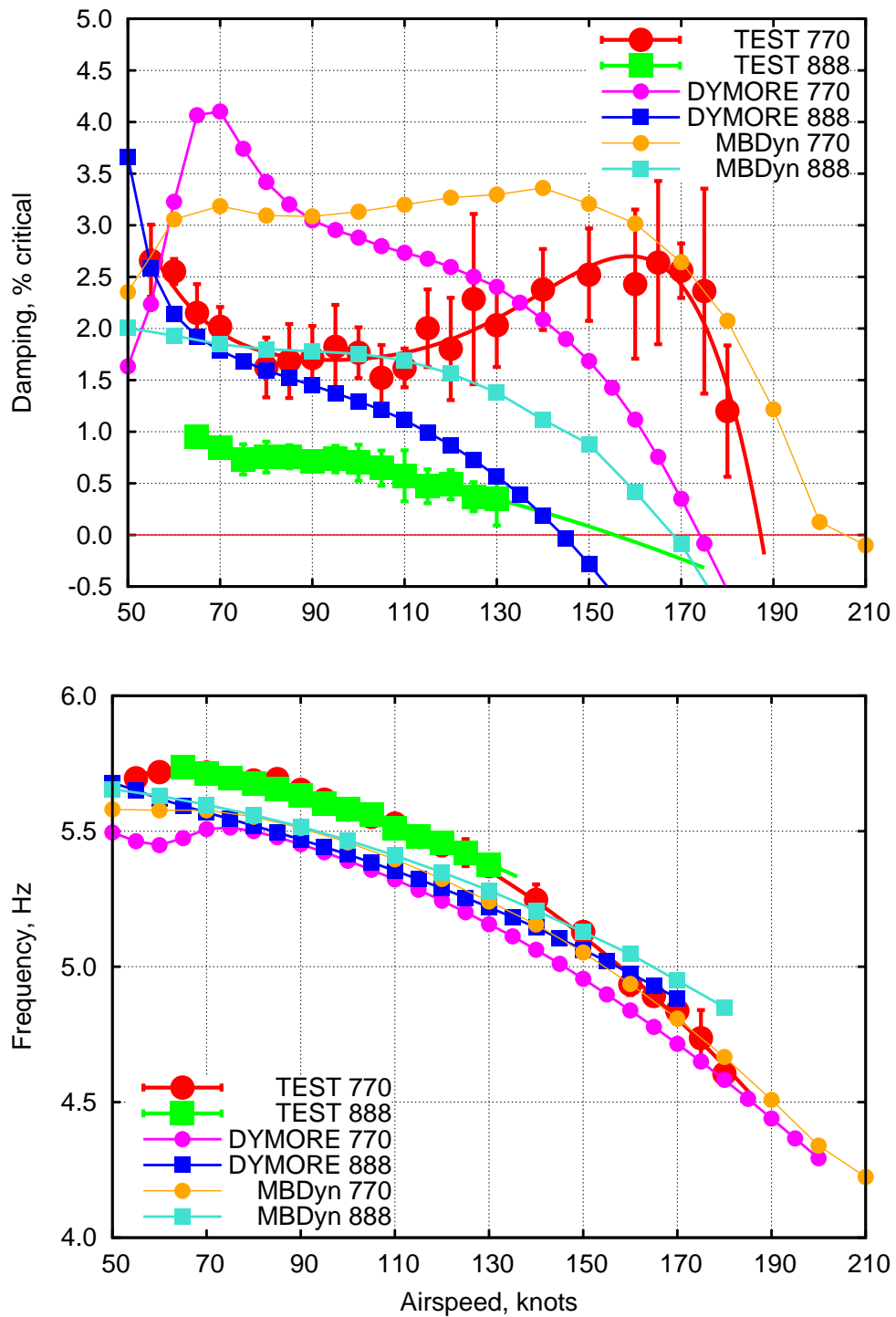


Figure 5: Comparison of analytical predictions of the on-downstop wing beam frequency/damping variation with airspeed for the baseline configuration

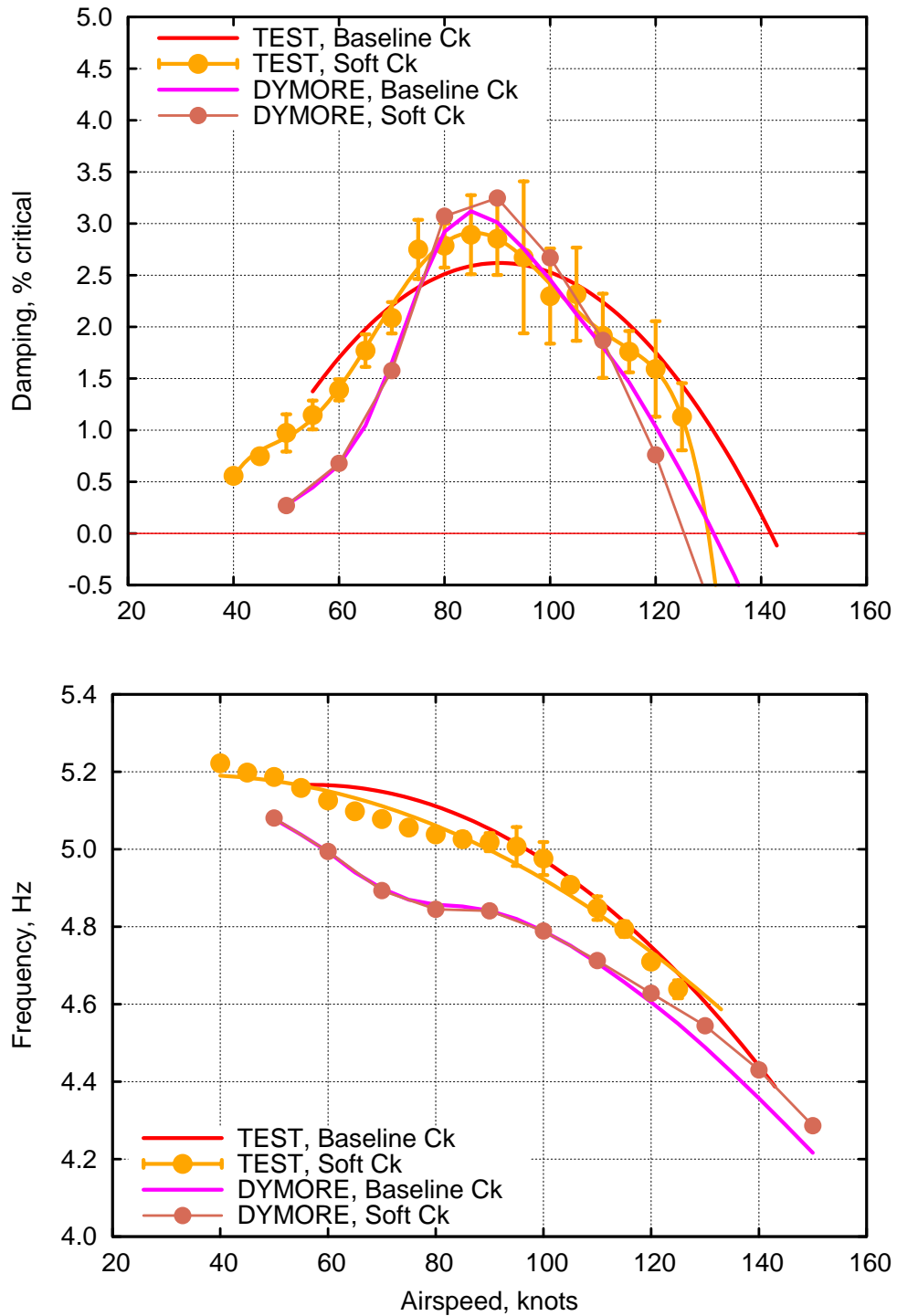


Figure 6: Damping and frequency of wing vertical bending mode vs. airspeed for the baseline and soft control system configuration (742 RPM, off-downstop, air)

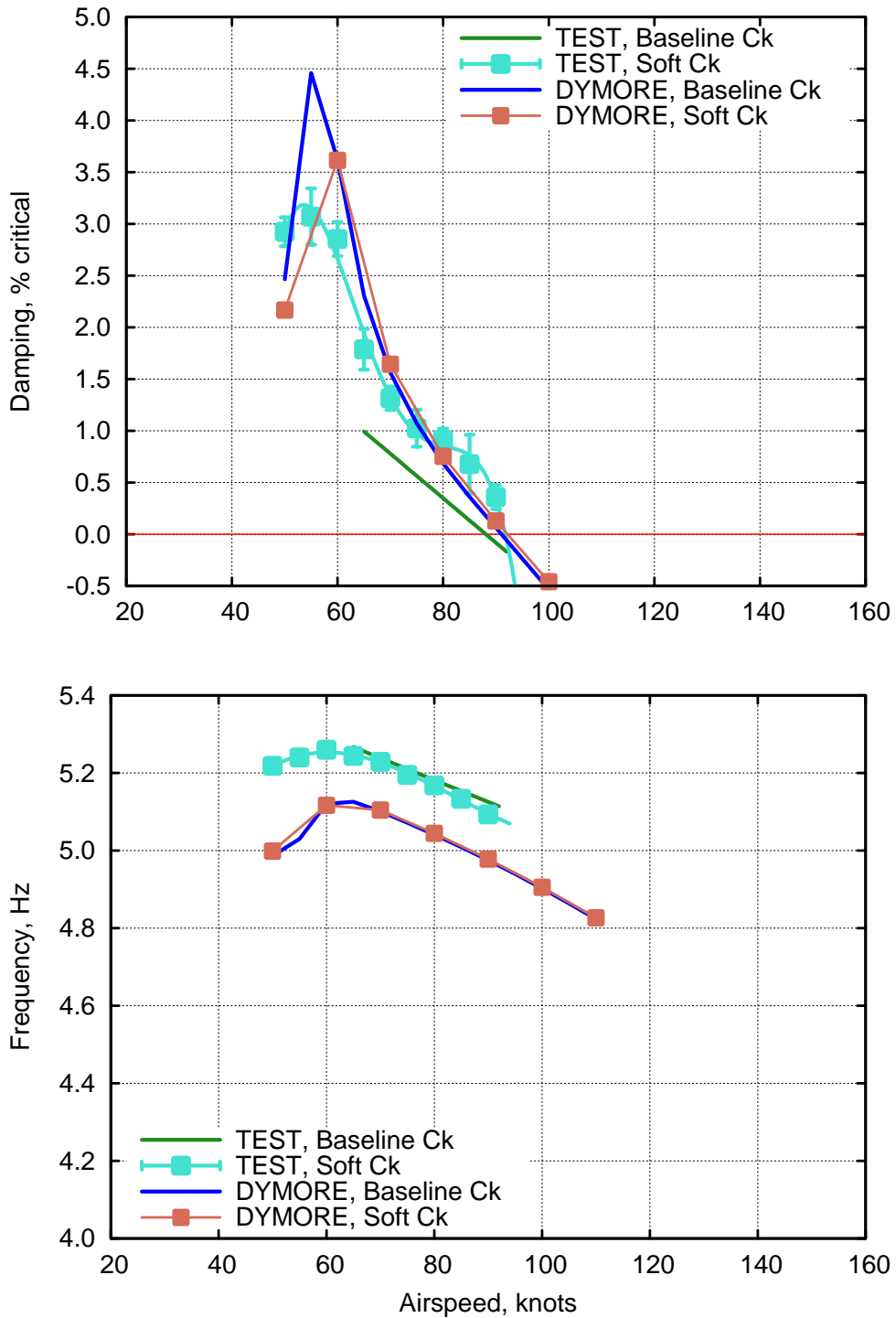


Figure 7: Damping and frequency of wing vertical bending mode vs. airspeed for the baseline and soft control system configuration (888 RPM, off-downstop, air)

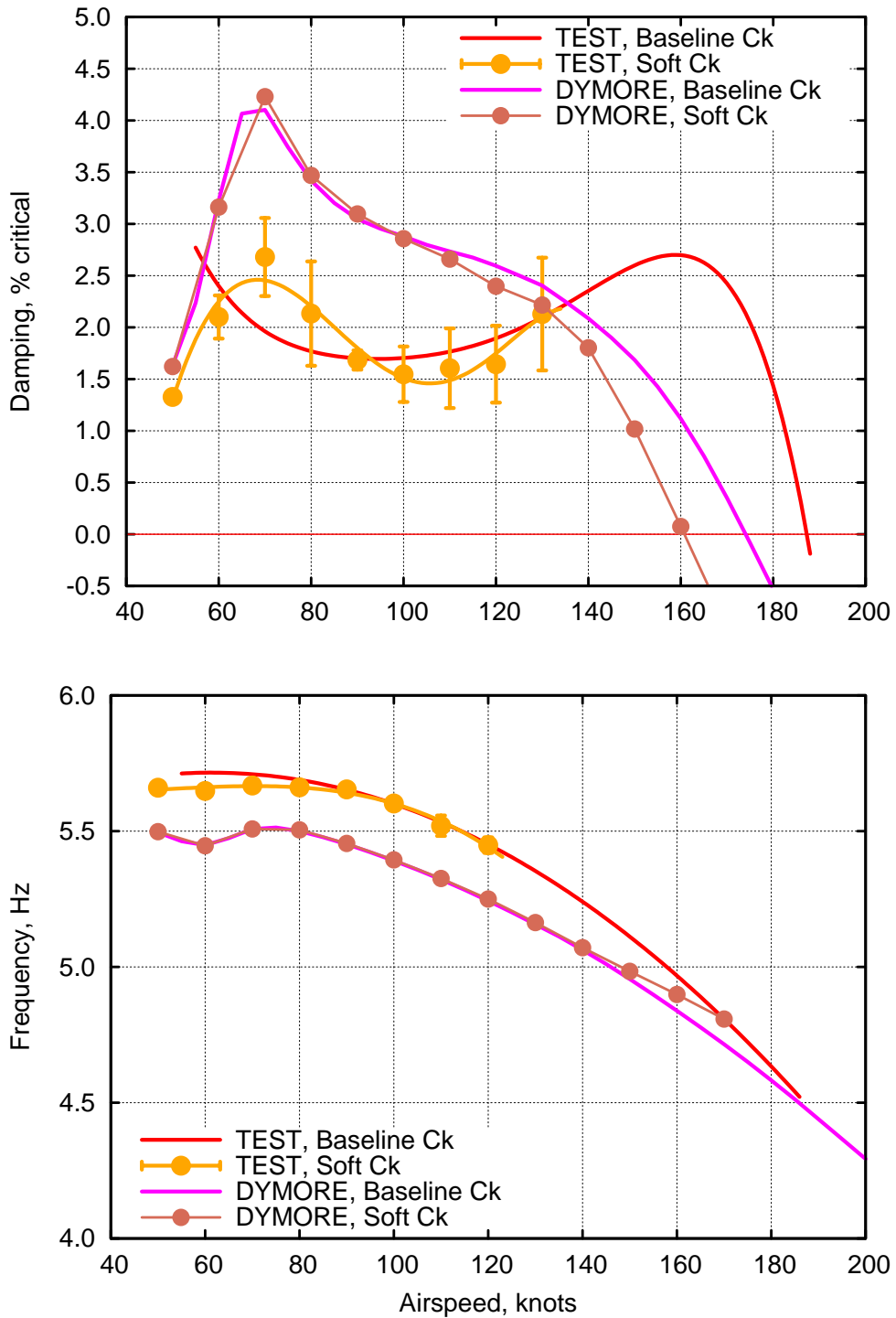


Figure 8: Damping and frequency of wing vertical bending mode vs. airspeed for the baseline and soft control system configuration (770 RPM, on-downstop, air)

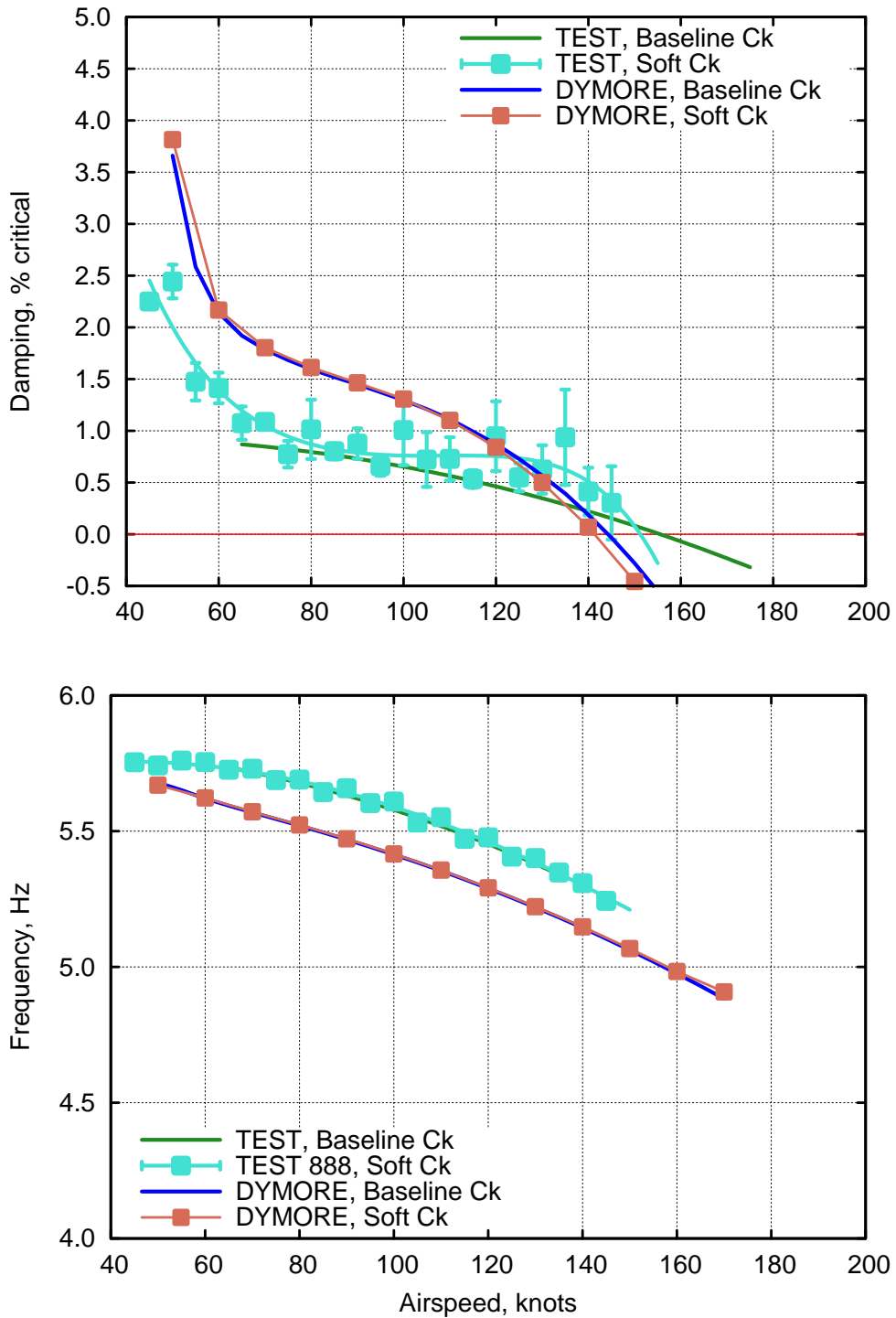


Figure 9: Damping and frequency of wing vertical bending mode vs. airspeed for the baseline and soft control system configuration (888 RPM, on-downstop, air)

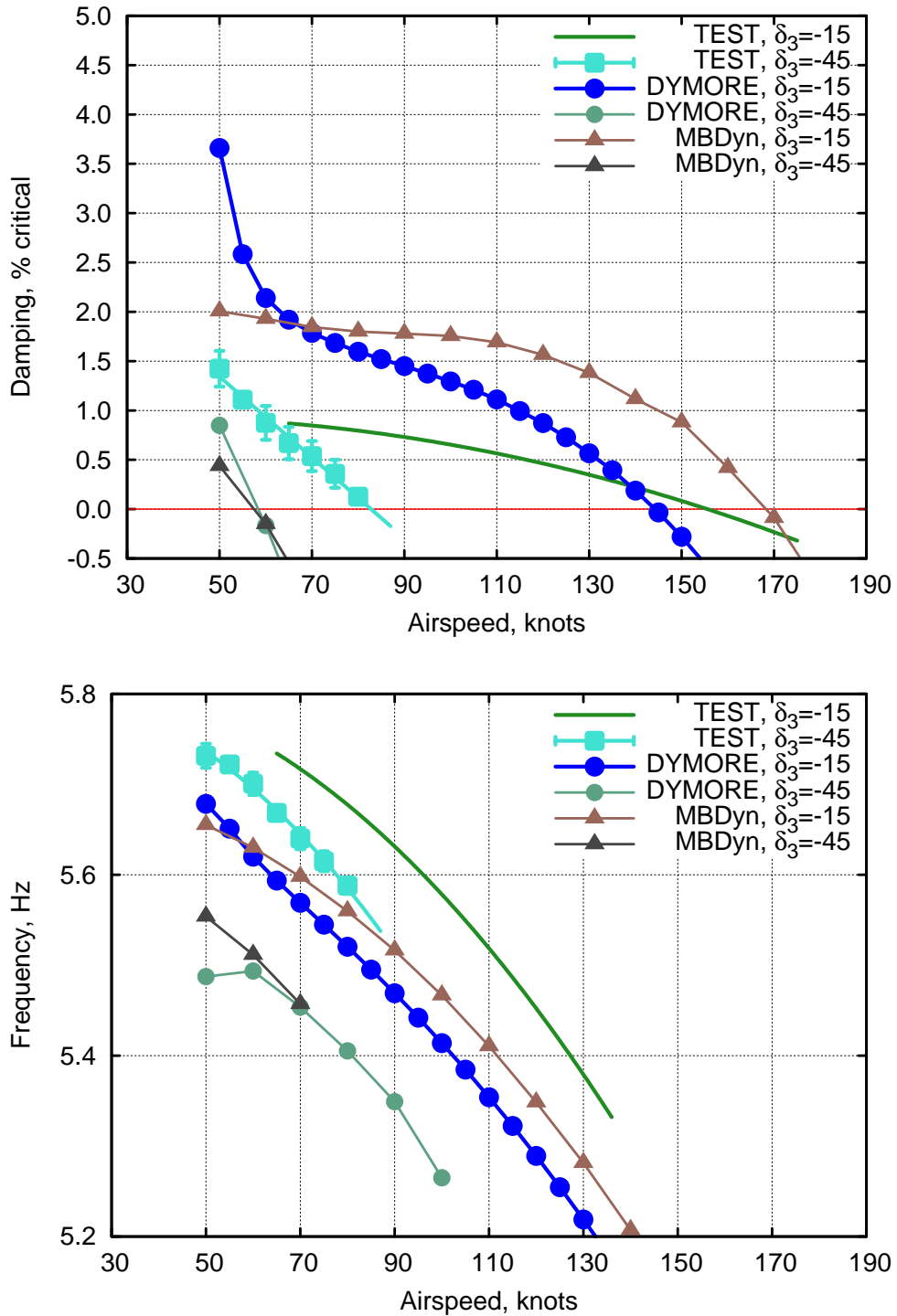


Figure 10: On-downstop wing beam mode damping and frequency versus airspeed for different δ_3 (888 RPM, air)

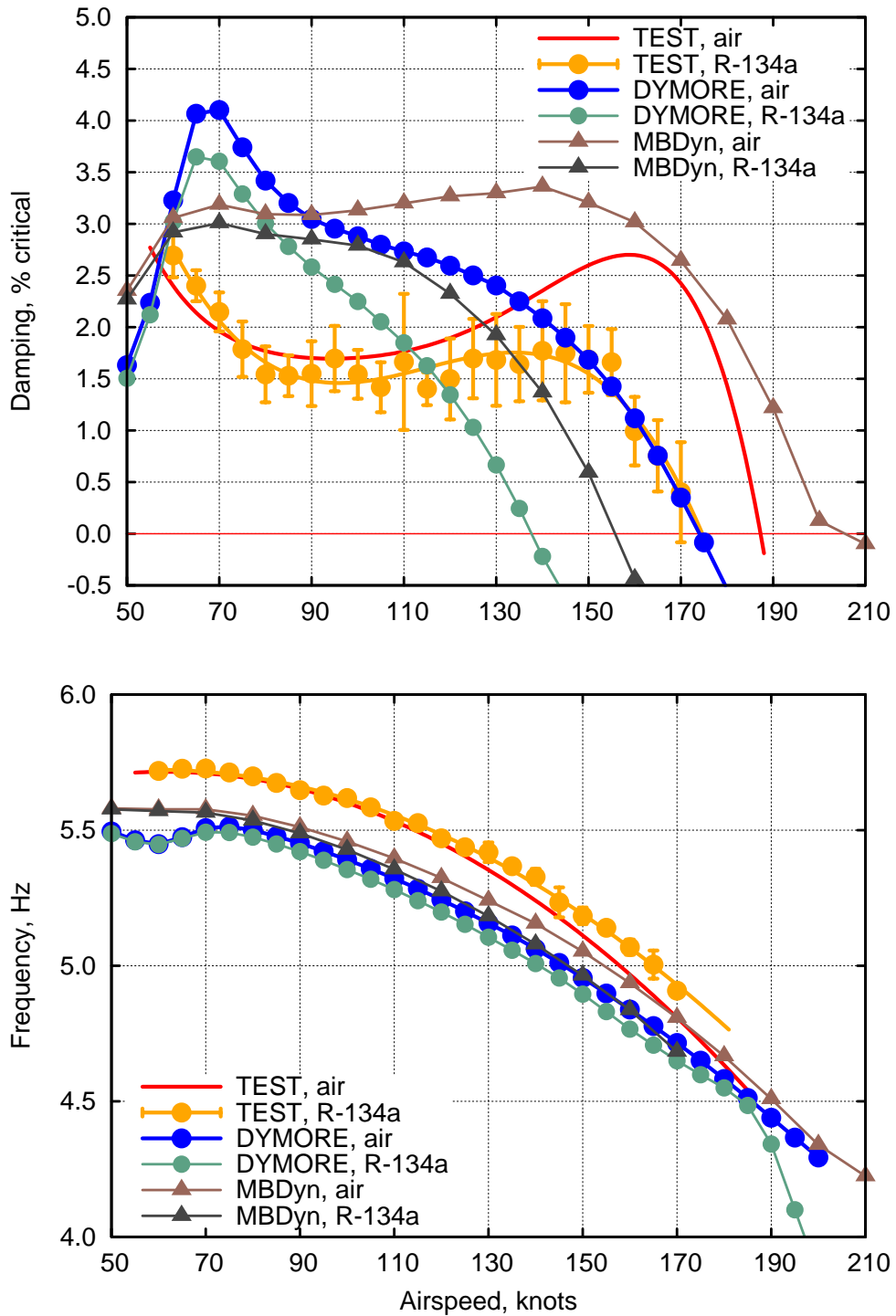


Figure 11: On-downstop wing beam mode damping and frequency versus airspeed in a R-134a and air test medium (770 RPM)

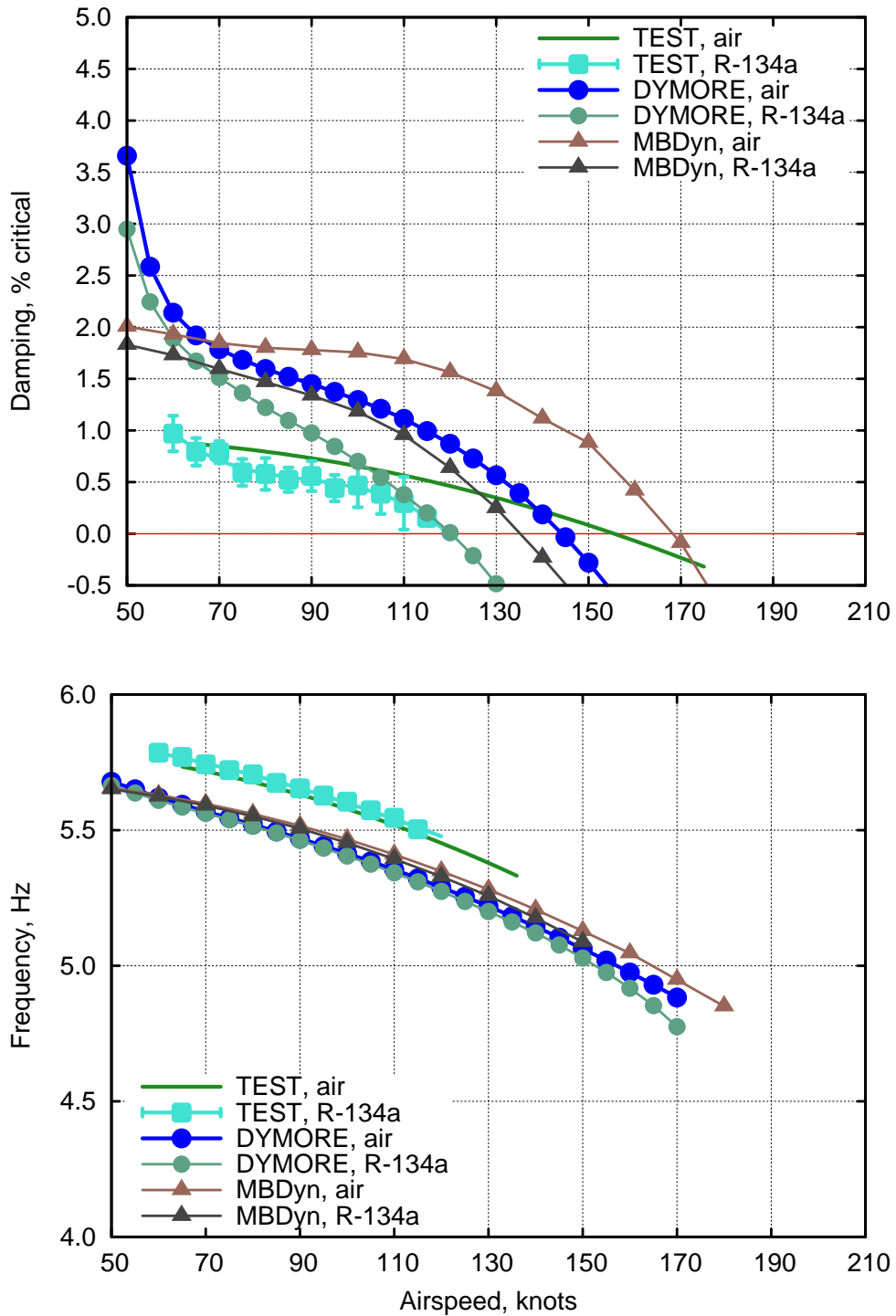


Figure 12: On-downstop wing beam mode damping and frequency versus airspeed in a R-134a and air test medium (888 RPM)