

Multibody Dynamics Model of a VTOL Teetering Rotor

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Abstract

This paper presents the development of a multibody dynamics model of a VTOL teetering rotor. The developed model includes a teetering hub, containing a flexure and torque tube, rotor blades, pitch links, and swashplate system. A non-teetering rotor configuration, which modified the baseline teetering rotor by removing the teetering hinge, is also developed, and its aeromechanics characteristics compared to those of the baseline teetering design. The rotor aeroelastic responses and loads are studied under various flight conditions including the conversion flights. The rotor natural frequencies are calculated for two blade pitch angles, which represents respectively the rotor operating in helicopter and airplane modes. The MBDyn predictions of aerodynamics loading of the teetering rotor are compared with those of OVERFLOW in both helicopter and airplane modes. The comparison shows overall good agreements. The blade responses and loads in conversion flight are then compared between the baseline teetering rotor and the modified non-teetering version. Similar aeromechanical characteristics are shown for the two rotor configurations, such as the blade response, steady hub loads, and steady and oscillatory blade shear forces. However, the non-teetering rotor displays a much larger blade bending moments, both the mean and oscillatory components. Overall, the study shows that the multibody analysis has the capability to model complex rotor configurations, and helpful in establishing the requirement and criteria applied to VTOL proprotor load analysis in supporting the aircraft design.

Introduction

The computational model development is an indispensable part of the modern design process. With the emergence of cheap and computational capable PC, comprehensive, multibody-based analyses of rotorcraft enable the modeling of the rotor system to a high level of details. As the fidelity of analytical model improves, the systematic use of advanced simulation and modeling becomes a valuable tool to guide and assess the proposed design. Such analysis can be employed to investigate the underlying physics, carry out sensitivity study of important design parameters, and conduct trade-off study. As the design process moves forward to detail design, the analytical model can be further developed to provide design validation to supplant hardware testing. A successful design project should include a systematically developed analytical model, and fully utilize the assistance of the numerical

simulation.

This paper presents the development of a multibody dynamics model of a proposed VTOL teetering rotor. This study is part of a detailed conceptual design of an innovative, electric propulsion VTOL aircraft. The multibody dynamics code used is MBDyn (Ref. 1), a general-purpose Multibody Dynamics analysis software. The multibody dynamics model developed in this effort includes the teetering hub, rotor blades, and swashplate system. The natural frequencies, mode shapes, aeroelastic characteristics of rotor system are obtained using the MBDyn analyses, and aerodynamics loads will be compared with the predictions of another CFD analysis. The rotor aeroelastic response and loading will be studied for various flight conditions, including the conversion mode.

Analytical Model

A bi-planar teetering proprotor design is proposed to be used on an electric propulsion VTOL aircraft (Fig.1.) The typical flight operation of this VTOL aircraft consists of

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several stages: hovering and climbing (tail-sitting position), transition to forward flight mode, cruise, transition to hover mode, and descending and hovering back to tail-sitting position. In addition, the rotor speed will be switching between hover and forward mode. An analysis of the proprotor aeromechanics is carried out for these flight conditions. The proprotor aeroelastic response and loading is examined for any detrimental characteristics across the operating range.



Figure 1: An innovative, electric propulsed VTOL.

Multibody Dynamics Code

Analytical model of the teetering rotor has been developed using MBDyn. MBDyn is a general-purpose multibody dynamics simulation software, developed at the Dipartimento di Ingegneria Aerospaziale of the University “Politecnico di Milano”, Italy. It features the integrated multi-disciplinary analysis of multibody, multi-physics systems, including nonlinear mechanics of rigid and flexible constrained bodies, smart materials, electric networks, active control, hydraulic networks, essential fixed-wing and rotorcraft aerodynamics. It allows to simulate the behavior of heterogeneous mechanical, aeroservoelastic systems based on first principles equations. The deformable components in MBDyn include lumped components, geometrically exact, nonlinear beams which utilize a C^0 beam discretization based on the finite volume concept. A general-purpose component mode synthesis element is also provided in MBDyn. The DAE are solved using an original implicit multi-step integration scheme that allows to tune the algorithmic dissipation, and achieves second-order accuracy (Ref. 2). MBDyn provides several aerodynamic models with different levels of fidelity, which include the blade element theory and coupling with an external CFD code.

VTOL Teetering Rotor

The multibody dynamics model developed in this effort includes the teetering hub, rotor blades, pitch links, and swashplate system (Fig. 2.) The pylon base is connect to a clamp. The rotor rotation is prescribed by a rotation hinge. The two rotor blades, hub flexure, and torque tube are modeled with the beam element, and teetering hub and the swashplate system is simulated with various rigid bodies and constraint elements. A modular approach is used in the model development, i.e. the model of key sub-structures are modular, and can be switched on and off, or assembled differently to study alternative configurations. For example, the teetering hinge can be removed from the model to investigate a non-teetering configuration (essentially, a hingeless rotor).

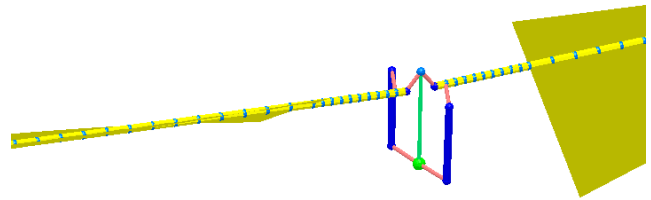


Figure 2: MBDyn model of the VTOL teetering rotor.

Eigenanalysis of a Rotating Rotor in Vacuum

The eigenanalysis of a rotating rotor is recently developed in MBDyn. The adopted methodology is described in this section. As soon as a steady state solution of the constrained mechanics problem of a rotor rotating at constant RPM can be computed, the natural frequencies and normal vibration modes of the system can be computed using standard eigenanalysis. The typical approach consists in projecting the problem in the space tangent to the kinematic constraints manifold (Ref. 3). However, similar results can be obtained by directly solving the generalized eigenvalue problem resulting from the linearization of the differential-algebraic equations of constrained system dynamics written according to the redundant coordinate set formalism (Ref. 4). The latter approach allows to extract eigenvalues directly from the Jacobian matrices resulting from the linearization of an arbitrary differential-algebraic

Table 1: Teetering Proprotor Parameters.

Property	Value
Rotor Type	Teetering
Number of Blades	4
Rotor Diameter	7.5 ft
Dual Twist Rate	48°/32°
Hover RPM	1019
Cruise RPM	624
Solidity	0.245

problem that represents the dynamics of a constrained mechanical and aeroelastic system. MBDyn adopts this latter approach that has the potential to study aeroelastic stability using the Floquet method.

Analytical Results

The paper presents the aeroelastic response and loading of the VTOL teetering rotor. The variation of rotor natural frequencies with rotor speed in vacuum is presented first. The MBDyn predictions of aerodynamics loading of the teetering rotor are compared with those of OVERFLOW (Ref. 5) in both helicopter and airplane modes. The blade responses and loads in conversion flight are then presented.

Rotor Natural Frequency

The prediction capability of the rotor structural characteristics is evaluated by comparing the WRATS stiff-in-plane tiltrotor (Ref. 6). The teetering rotor shares similar blade properties and geometries with the tiltrotor, and the tiltrotor was used as a prototype to validate the new eigenanalysis of a rotating rotor in MBDyn because of availability of predictions from its DYMORE model. Fig. 3 illustrates the variation of rotor frequencies with rotor speed in vacuum. The MBDyn predictions of the rotating rotor frequencies compare well with the DYMORE results except of some discrepancies at the higher modes, which may be due to differences in modeling assumptions since these higher order coupled modes are expected to be sensitive to them.

Fig. 4 shows the variation of rotor frequencies with rotor speed in vacuum ("fan plot"). The fan plots are illustrated at two blade collective angles: 11° and 63°, which represents respectively the rotor operating in helicopter and airplane modes. The lowest rotor mode is the rigid teetering mode, which is almost at one per rev for all the rotor rotation speeds. The teetering hub does not include a teetering hinge spring, and this makes the teetering mode at exactly one per rev. However, the effect

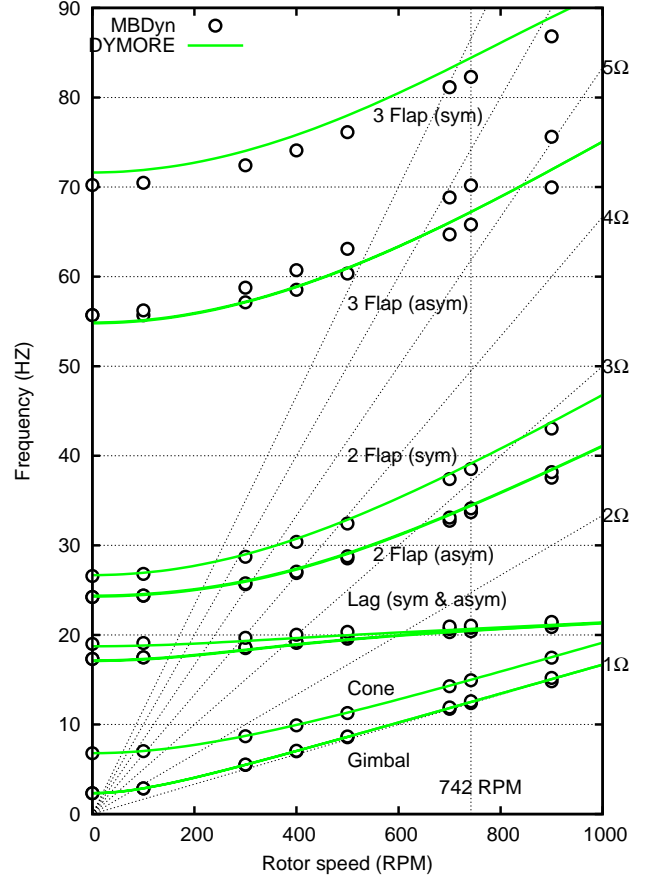


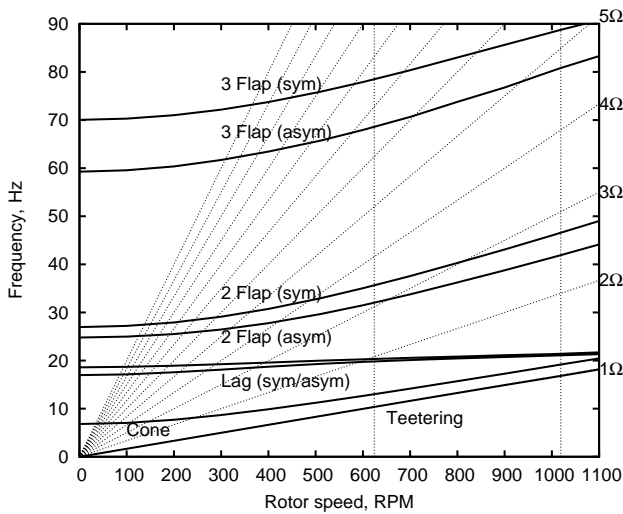
Figure 3: Variation of rotor frequencies with rotor speed. (WRATS stiff-inplane tiltrotor, collective at .75R of 11 degrees.)

of the hub moments of inertia causes the teetering frequency to be slightly less than one per revolution. The second rotor mode is the elastic coning, which shows a linear increase with the rotor speed after 500 RPM because of the dominance effect from the centrifugal force. The third and fourth modes are the asymmetric (may also be called collective) and symmetric (may be called cyclic) first lag modes respectively. Both modes show a small increase with the rotor speed because the effect of centrifugal force is much smaller in the lag modes than in the flap modes. The frequencies of the asymmetric and symmetric lag modes are very close to each other except a slight smaller asymmetric lag frequency. This is caused by the effect of the hub moments of inertia because the rotor hub is rotated inplane in the lag asymmetric mode. The second and third flap asymmetric and symmetric modes are the highest modes shown in Fig. 4(a). All the frequencies of these modes increase with rotor speeds. Again, the effect of the hub moments of inertia cause the flap asymmetric modes have smaller frequencies than those of the corresponding symmetric modes.

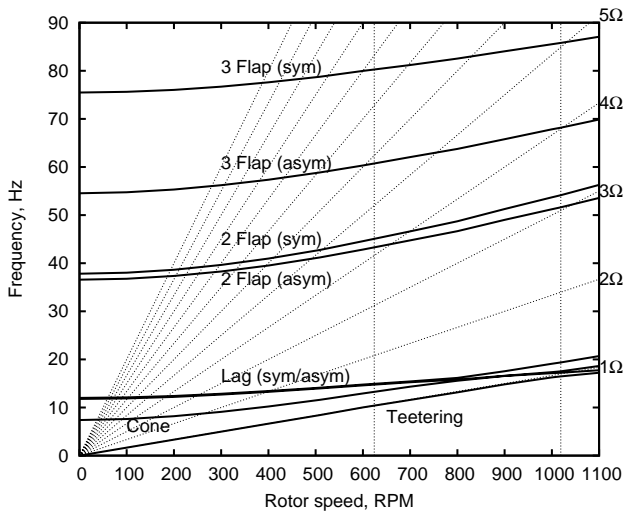
Fig. 4(b) illustrates the fan plot at blade collective pitch angle at 63° , which represents the rotor operating in airplane mode. The results show similar as those predicted at pitch angle at 11° (Fig. 4(a.)) Nonetheless, a higher pitch angle is achieved by pitch up the blade, and this causes the large stiffness at blade chordwise direction rotated to the flap plane, which decreased the frequencies of lag modes. In addition, the elastic cone and second flap modes are higher because of the corresponding increase of the stiffness in the flap plane. Natural frequencies of the baseline rotor are summarized in Table 2 for the nominal rotating speeds at 1019 RPM for pitch angles of 11 and 63 degrees.

Table 2: Calculated normal mode frequencies for proprotor at rotating speed of 1019 RPM.

Mode	collective 11 (per rev)	collective 63 (per rev)
Teetering	0.99	0.97
Cone	1.13	1.14
Lag Asymmetric	1.24	1.01
Lag Symmetric	1.26	1.03
2nd Flap Asymmetric	2.47	3.04
2nd Flap Symmetric	2.74	3.19
3rd Flap Asymmetric	4.76	4.01
3rd Flap Symmetric	5.23	5.05



(a) Collective 11°



(b) Collective 63°

Figure 4: Fan plots of the teetering proprotor.

Validation of aerodynamics model

The MBDyn model of rotor aerodynamics uses the built-in blade element theory with the airfoil aerodynamics coefficient look-up in C81 format tables. Rotor inflow distribution is obtained with a uniform inflow model with correction parameters. The aircraft includes two bi-planar, two-bladed teetering rotors, which have a 90° phase, and rotate at the same direction. Since the aerodynamic interaction between the two rotors is not modeled in this study, the analytical results of the two bi-planar teetering rotors behave identically. Therefore, only one set of the teetering rotors is modeled for simplicity. The rotor hub loads and performance are then simply doubled to account the two teetering rotors. The inflow should, however, still be obtained for case of the two teetering rotors. A correction parameter in the amount of $\sqrt{2}$ is used (details in Ref. 7 and Ref. 8.) It is worthy to note, however, as typical with a tiltrotor, the induced inflow of the teetering proprotor is negligible in high speed airplane-mode and conversion flights. In addition, the aerodynamic interactions between rotor and wing are also neglected in this study.

The MBDyn aerodynamic model of the teetering proprotor is validated by comparing its predictions of aerodynamics loads with those of OVERFLOW. OVERFLOW is a general purpose overset grid based compressible Navier-Stokes CFD code. Ref 9 describes the current teetering proprotor OVERFLOW model in detail. For both analyses, air property is simulated at altitude of 6000 ft and ambient temperature of 95 F with the air density of $0.00178 \text{ slug/ft}^3$, and sound of speed at 1155.42 ft/sec.

Fig. 5 compares the rotor performance and blade aerodynamics load predictions among MBDyn, OVERFLOW, and another Blade Element Method (BEM) analyses. Figs. 5(a) and 5(a) show that the MBDyn predictions of rotor power and thrust compare well with the results of the other two analyses. Figs. 5(c) and 5(d) illustrate respectively the variation of blade vertical and edgewise shear forces, and torsional moments with blade radial station. These results are calculated at hover with rotor thrust at

about 300 lbs. Good comparison is seen for the shear force predictions except that the MBDyn model shows an under-prediction of vertical force on stations toward the blade tip. Fair agreement is seen for the blade torsional moment predictions. MBDyn model, which does not try to capture the effect of the rotor wake, apparently misses the small peak at the blade tip seen on the OVERFLOW results. This peak is caused by the tip vortex. MBDyn predictions of torsional moments also show larger values at blade inner stations. It is worthy to note, however, the predicted torsional moments are small for both analyses.

Fig. 6 shows the same results as Fig. 5, but for high speed forward flight condition instead of at hover. Overall, good comparisons are seen for the rotor power, blade shear forces, and torsional moment predictions between MBDyn and OVERFLOW analyses. Fig. 6(b) shows that the BEM and MBDyn over-predict the rotor thrust for the same blade pitch angle compared to OVERFLOW results. This is because the modeling difference between MBDyn and OVERFLOW analyses. For example, MBDyn and the BEM model have an abrupt airfoil switch at 0.5R while the OVERFLOW CFD grid has a smooth transition from 0.4R to 0.6R. When the high rotor inflow presents as in the high speed forward flight, these modeling difference will cause large prediction discrepancies.

Loads analysis in conversion flight

Fig. 7 illustrates the blade aeroelastic response and loads in conversion flight. The numerical results of two rotor configurations are shown. The first is the baseline teetering rotor. The other is a modification of the baseline rotor by removing the rotating hinge, which makes it essentially a four-bladed hingeless rotor. This comparison is for a design trade study which aims to simplify the rotor hub.

Fig. 7(a) compares blade coning and flapping responses between the teetering and non-teetering rotors. The coning and flapping is measured at blade root, about .16R. The flapping of the baseline teetering rotor includes both the rigid rotation at teetering hinge and the elastic flapping at hub flexure while the flapping of the non-teetering rotor only contains elastic flapping at the flexure. Similar coning deflections are shown for the baseline rotor and the modified non-teetering rotor except that the non-teetering rotor has a slightly larger coning angle at higher pitch angles. Fig. 7(b) displays the variation of steady hub forces with blade pitch angle. The predictions are similar for the two rotor configurations except that the non-teetering rotor shows a slightly larger vertical force than that of the teetering rotor. Figs. 7(c) and 7(d) show respectively the steady and oscillatory blade shear forces for a rotor thrust level about 300 lbs. Similar results are shown for the two rotor configurations. Fig. 7(e) illustrates the variation of mean blade bending moments with blade radial station.

As expected, the non-teetering rotor shows a larger bending moments than those of the baseline teetering rotor, especially for the edgewise bending moments. Fig. 7(f) compares the oscillatory blade bending moments between the two rotor configurations. Similarly, the non-teetering rotor shows a much larger loads than those of the teetering rotor. In selection of the rotor configurations between these two types of rotor hub, a design decision has to be made by compromising whether to choose a simplified hub or a lower rotor load level.

Summary and Conclusions

This paper presented the development of a multibody dynamics model of a VTOL teetering rotor. The aeroelastic response and loading of the teetering rotor was studied under various flight conditions including the conversion mode. In addition, a non-teetering rotor configuration, which modified the baseline teetering rotor by removing the teetering hinge, is also included, and its aeromechanics characteristics were compared to those of the baseline teetering design. The variation of rotor natural frequencies with rotor speed in vacuum is presented for two blade pitch angles, which represents respectively the rotor operating in helicopter and airplane modes. The MBDyn predictions of aerodynamics loading of the proprotor are compared with those of OVERFLOW, both in helicopter and airplane modes. Good agreements were shown overall. The blade responses and loads in conversion flight are compared between the baseline teetering rotor and the modified non-teetering version. Similar results are shown for the blade response, steady hub loads, and mean blade forces and moments between the two rotor configurations. However, the non-teetering rotor displays a much larger oscillatory blade loads than those of the baseline teetering rotor. Overall, the study shows that the MBDyn multibody analysis has the capability to model complex rotor configurations, and helpful in establishing the requirement and criteria applied to VTOL proprotor load analysis in supporting the aircraft design.

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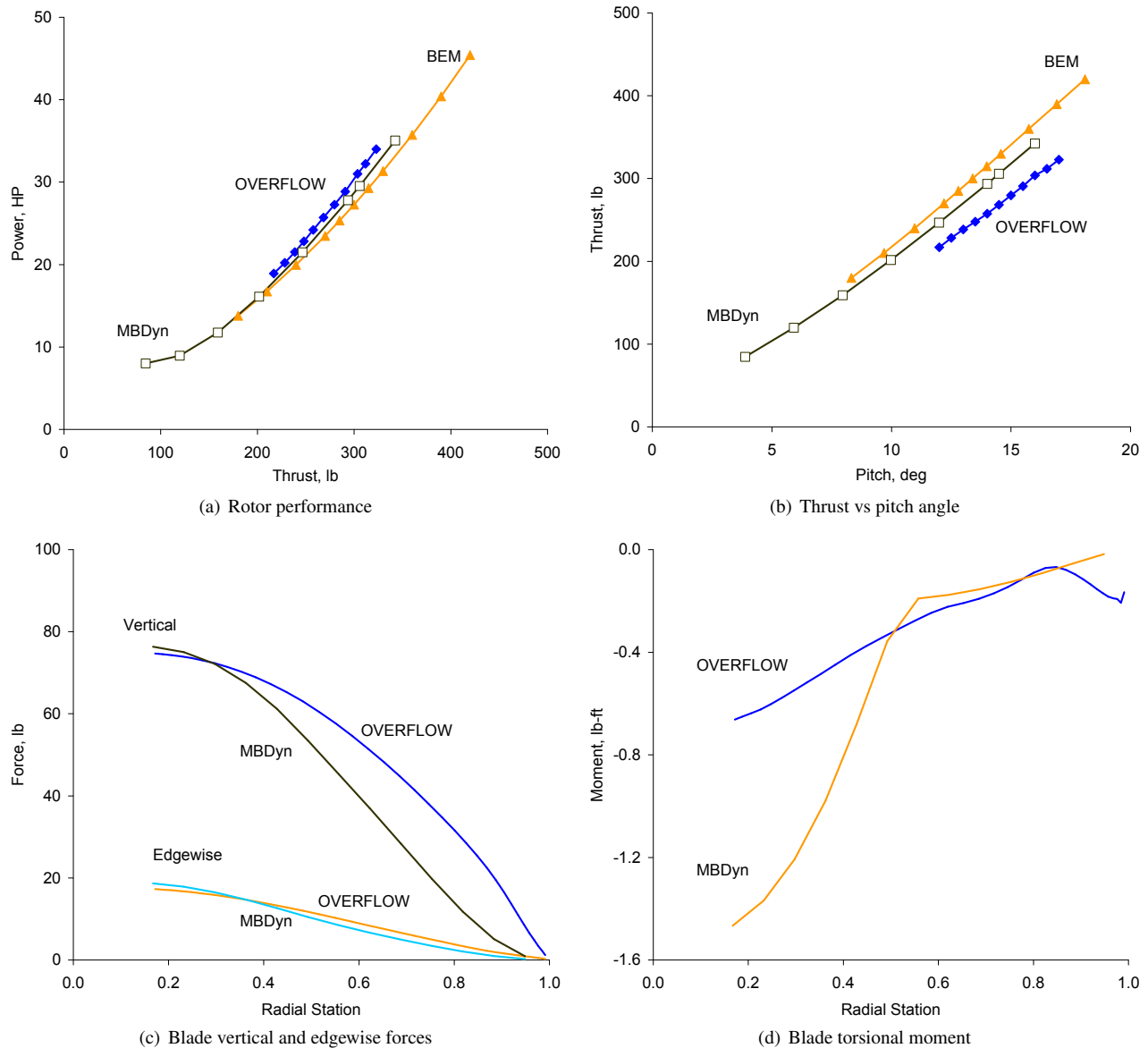


Figure 5: Comparison of MBDyn and OVERFLOW rotor performance and load predictions in helicopter mode, 90° pylon angle, hover, 1019 RPM.

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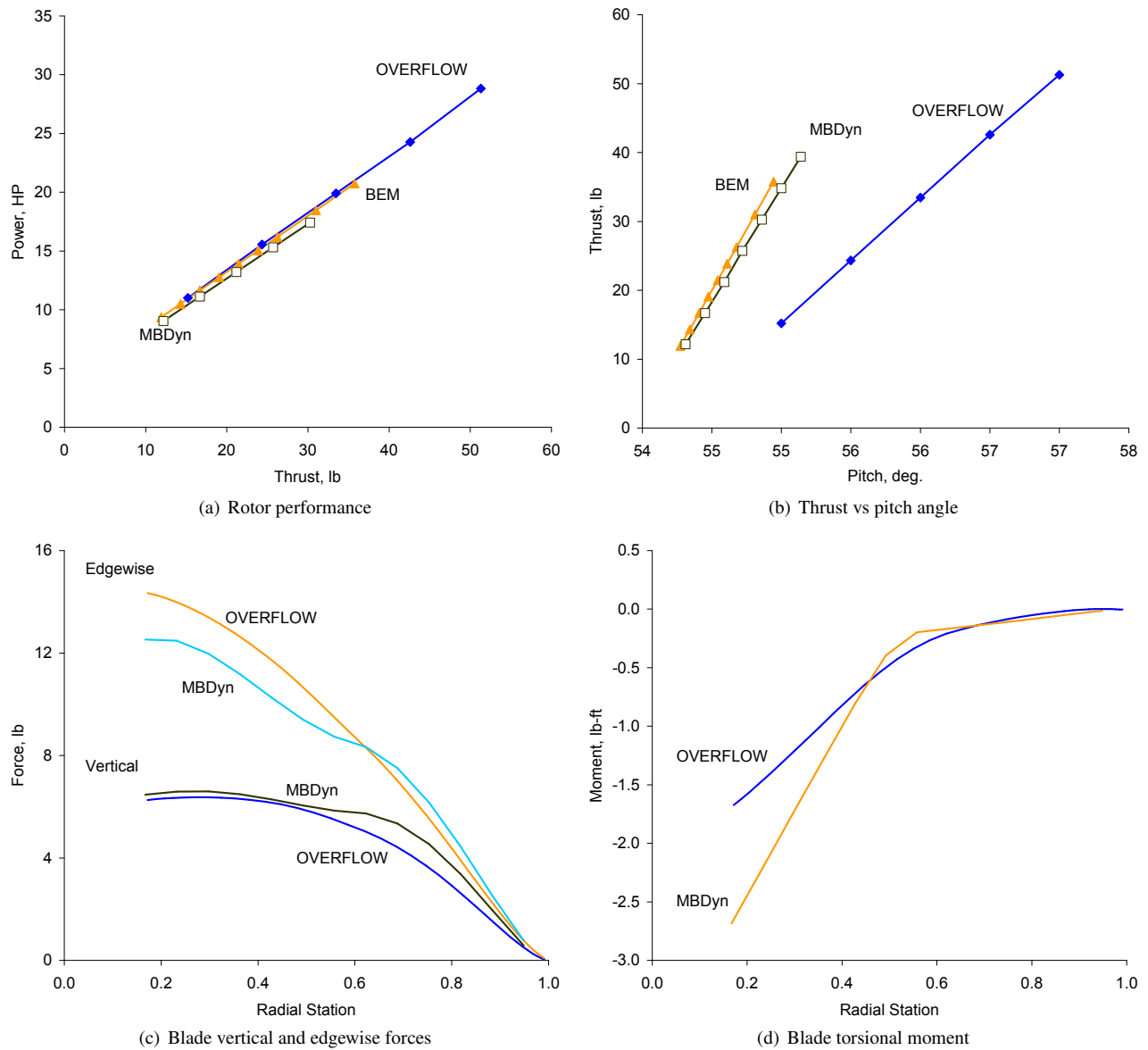


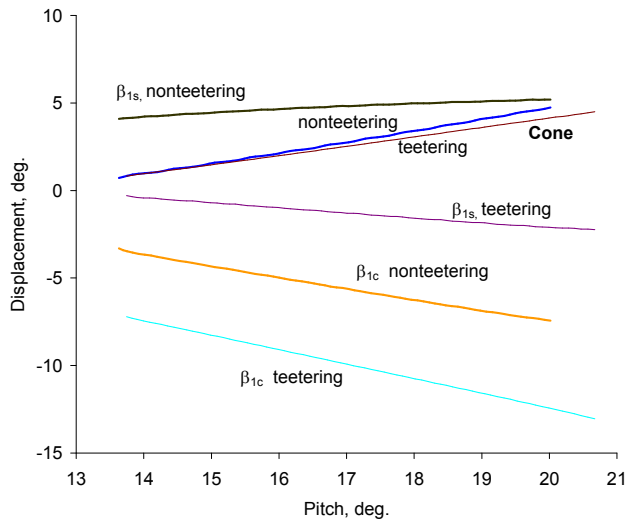
Figure 6: Comparison of MBDyn and OVERFLOW rotor performance and load predictions in airplane mode cruise, 0° pylon angle, 150 kts airspeed, 624 RPM.

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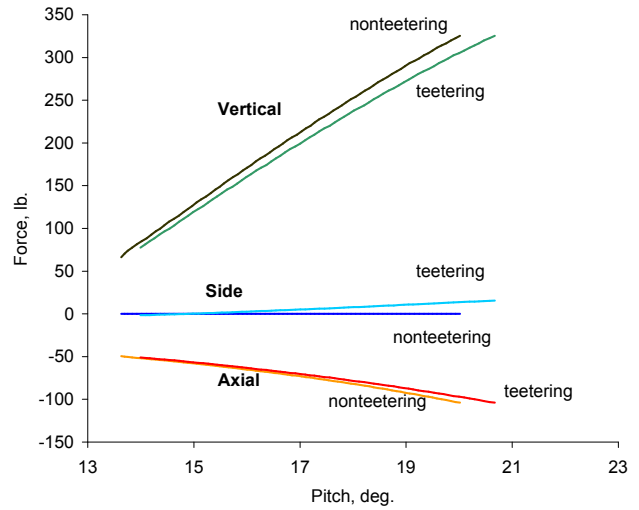
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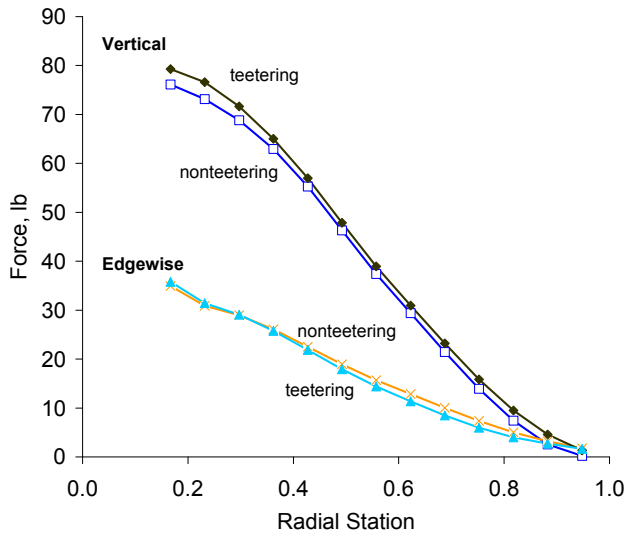
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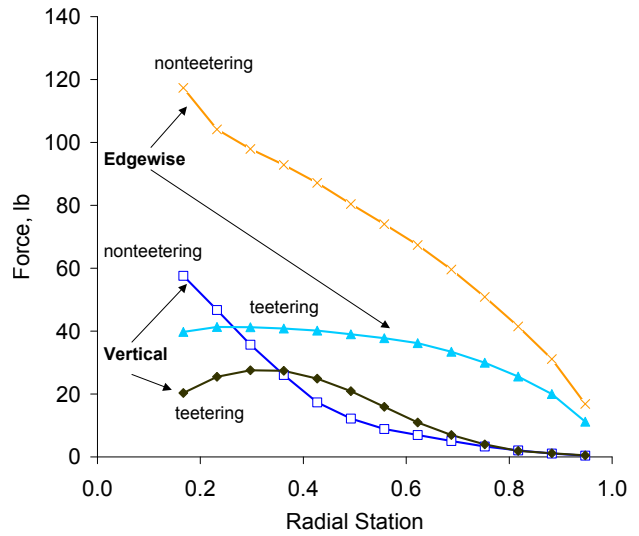
(a) Blade flapping and coning



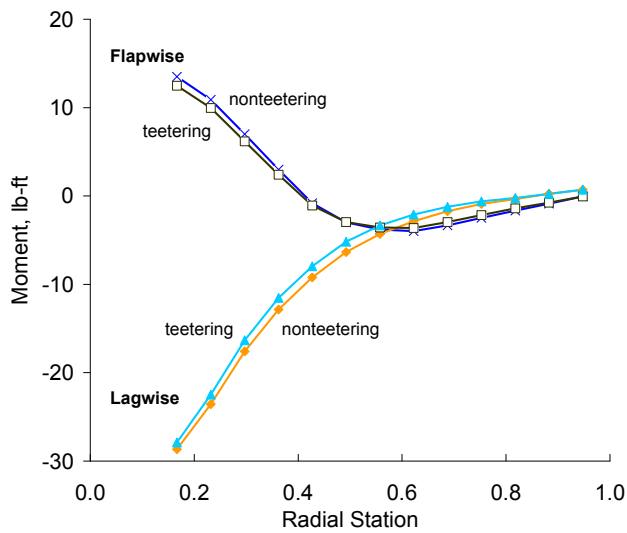
(b) Hub forces



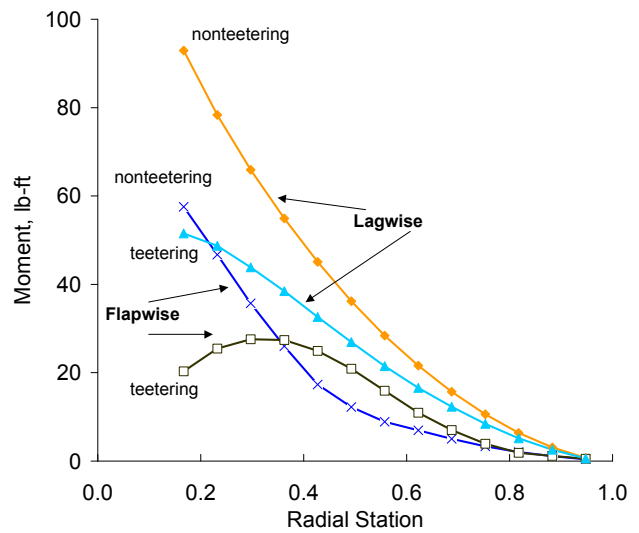
(c) Mean blade shear forces



(d) Oscillatory blade shear forces



(e) Mean blade bending moments



(f) Oscillatory blade bending moments

Figure 7: Blade displacements and loads in conversion flight, 60° pylon angle, 100 kts airspeed, 1019 RPM.