

AN INVESTIGATION OF SOFT-INPLANE TILTROTOR AEROMECHANICS USING TWO MULTIBODY ANALYSES

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ABSTRACT

This investigation focuses on the development of multibody analytical models to predict the dynamic response, aeroelastic stability, and blade loading of a soft-inplane tiltrotor wind-tunnel model. Comprehensive rotorcraft-based multibody analyses enable modeling of the rotor system to a high level of detail such that complex mechanics and nonlinear effects associated with control system geometry and joint deadband may be considered. The influence of these and other nonlinear effects on the aeromechanical behavior of the tiltrotor model are examined. A parametric study of the design parameters which may have influence on the aeromechanics of the soft-inplane rotor system are also included in this investigation.

APPROACH

The objective of this investigation is to develop and refine multibody analytical models to predict the dynamic response, aeroelastic stability, and blade loading of a soft-inplane tiltrotor wind-tunnel model. Comprehensive rotorcraft-based multibody analyses enable modeling of the rotor system to a high level of detail such that complex mechanics and nonlinear effects associated with control system geometry and joint deadband may be considered. The influence of these and other nonlinear effects on the aeromechanical behavior of the tiltrotor model will be examined. A parametric study of the design parameters which have influence on the aeromechanics of the soft-inplane rotor system are also included in this investigation. This research is being performed as a cooperative agreement between the U.S. Army, NASA

Langley Research Center, and the University Politecnico di Milano.

A new four-bladed semi-articulated soft-inplane (SASIP) rotor system, designed as a candidate for future heavy-lift rotorcraft, was tested at model scale on the Wing and Rotor Aeroelastic Testing System (WRATS), a 1/5-size aeroelastic wind-tunnel model based on the V-22. Previous investigations involved a three-blade soft-inplane hub and mainly addressed the stability properties of this configuration (1, 2). Soft-inplane design implies reduced hub loads and should allow significant weight reduction in large scale tiltrotor aircraft. However, there is significant potential for reduced whirl-flutter stability margins in comparison to the currently exploited stiff-inplane configurations, so extensive aeromechanical investigation is required to determine the feasibility and the requirements of soft-inplane design.

The experimental part of this investigation included a hover test with the model in helicopter mode subject to ground resonance conditions, and a forward flight test with the model in airplane mode

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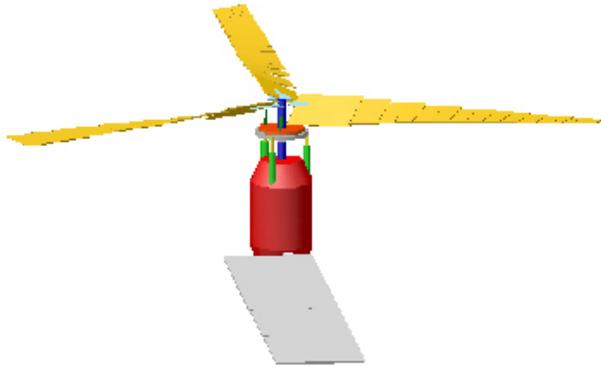


Figure 1: MBDyn multibody model of the three-bladed stiff-inplane tiltrotor system.

subject to whirl-flutter conditions. A three-bladed stiff-inplane gimbaled rotor system, used in several previous experiments, was examined under the same conditions as the four-bladed soft-inplane hub to provide a baseline for comparison.

Detailed analytical models of the SASIP tiltrotor have been developed using two multibody rotor codes, one known as MBDyn (Ref. 3) and one known as DYMORE (Ref. 4). The two codes have similar capabilities, but it is desirable to compare their results (with models created by two different researchers at two different institutions) as a test of robustness for the multibody approach. The multibody analyses include dynamic models for parts 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 and the hub (Fig. 1). 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.

A third analytical model of the SASIP tiltrotor has been developed using a classical rotorcraft analysis known as UMARC/G, and is based on the UMARC (Ref. 5) comprehensive rotor code. This analysis does not have the capability to model complex joints and extreme nonlinear behavior as do the multibody codes, but is useful to serve as an analytical standard for some portions of the current study.

The paper approaches the problem by directly comparing the results of the two multibody analysis codes, mainly focusing on those that are also available from the experimental campaign described in Ref. 6 and on a selection of test cases that help speeding up model correlation, e.g. modal analysis of the rotor in vacuo.

KEY RESULTS

Several experiments have been conducted using the SASIP rotor system and its subcomponents (Ref. 6). The following list presents an overview of tests that are included in the analytical comparisons presented in this paper:

1. Single blade cantilevered outside lag hinge: elastic mode comparison.
2. Single blade mounted on hub in pendulum configuration, flap and lag hinge with lag spring and lag damper included: elastic mode comparison.
3. Control system stiffness calibration: control stiffness and deadband comparison.
4. Pitch-flap coupling and pitch-lag coupling calibration: control system response comparison and analytical models.
5. Hover run-up: fan plot comparisons.
6. Hover performances: thrust, torque and blade angles as functions of collective at prescribed rpm; rpm sweep at prescribed collective setting.
7. Wing structural analysis and hover stability subject to ground resonance conditions: comparison of wing and rotor mode damping and frequencies.

The experimental results for all seven of the listed comparisons have been obtained during several recent test campaigns; many of the data plots required for these comparisons were presented in Ref. 6. The analysis models have been refined through comparison with the experimental data in sequence with the above list.

Some of the key results of this investigation obtained to date are discussed in the following paragraphs. The multibody model developed for the three-bladed stiff-inplane wind-tunnel model is illustrated in Fig. 1. The figure shows the rotor blades, pitch link, swashplate, and hydraulic control actuators which are attached to the pylon, and an elastic wing that is modeled using finite elements. For the SASIP four-bladed rotor system the rotor blades, hub joints, and most of the control system have been developed. Figure 2 shows the DYMORE model of the SASIP setup.

The wing and pylon model used for the three-bladed model is the same as for the SASIP rotor, so the wing/pylon submodel simply needed to be joined to the SASIP rotor model for the stability investigations. The aeromechanical stability of the coupled system will be investigated in future works; this work addresses the hover case.



Figure 2: DYMORE model of the SASIP hub setup.

Cantilevered Blade Modal Analysis

A complete review of the blade structural properties has been conducted, to develop a reliable finite element model for subsequent analyses and accurate load recovery. Since both the multibody software codes allow for direct finite element modeling of rotor blades, this analysis permitted the determination of a reasonable trade-off between model accuracy and computational cost, leading to a reduced order model with respect to those used for detailed modal analysis in NASTRAN and UMARC/G.

Table I reports the frequencies of a single blade, cantilevered right outside the lead-lag hinge. MBDyn results refer to a 5 parabolic, 3 node C^0 beam element (7) blade model, with 11 structural nodes. DYMORE results refer to a 4 cubic beam FEM model, while in NASTRAN and UMARC/G 25 beam elements were used.

Hub-Mounted Blade Modal Analysis

A comparison of elastic blade frequencies, for the condition of an isolated blade mounted to the hub (experimental setup shown in Fig. 3), is listed in Table II; the blade pitch is rigidly constrained. This analysis fully exploits the capabilities of multibody software in dealing with the exact kinematics of the articulated blade attachment and of the control system. Different configurations in terms of collective setting, imposed flap or lag angles, lead-lag hinge and pitch link stiffness have been addressed within a single model. The results indicate consistent capabilities of modeling the elastic blade and hinge dynamics among the analyses and generally good agreement with the experimental results. Mode shape compar-

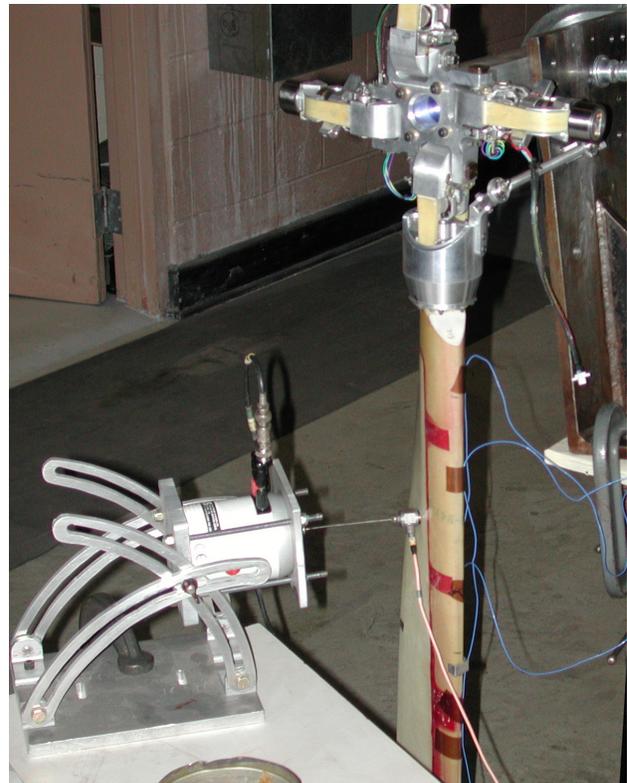


Figure 3: Ground vibration test of an isolated blade with hub fixed.

Table I: Frequencies of the elastic modes for a single cantilevered blade.

Mode		Frequency, Hz				
No.	Type	Experiment	NASTRAN	UMARC/G	MBDyn	DYMORE
1	F1	10.71	10.61	10.61	10.61	10.45
2	L1	29.20	29.11	29.46	29.03	29.28
3	F2	47.76	51.16	48.99	50.45	50.55
4	T1/F3	107.29	107.23	107.08	107.43	107.28
5	F3/T1	119.07	121.49	119.86	116.78	116.27
6	T2	141.83	177.19	140.19	162.69	166.67

Table II: Frequencies of the elastic modes for a single blade on a fixed hub.

Mode		Frequency, Hz				
No.	Type	Experiment	NASTRAN	UMARC/G	MBDyn	DYMORE
1	F1	0.00	0.00	0.08	0.67	0.11
2	L1	6.46	6.54	6.43	6.32	6.51
3	F2	21.70	19.48	20.06	19.37	19.44
4	F3/L2	61.15	63.12	64.20	62.43	64.30
5	T1	107.94	107.44	103.50	106.58	107.07
6	F4	119.25	91.25	96.21	88.11	92.30

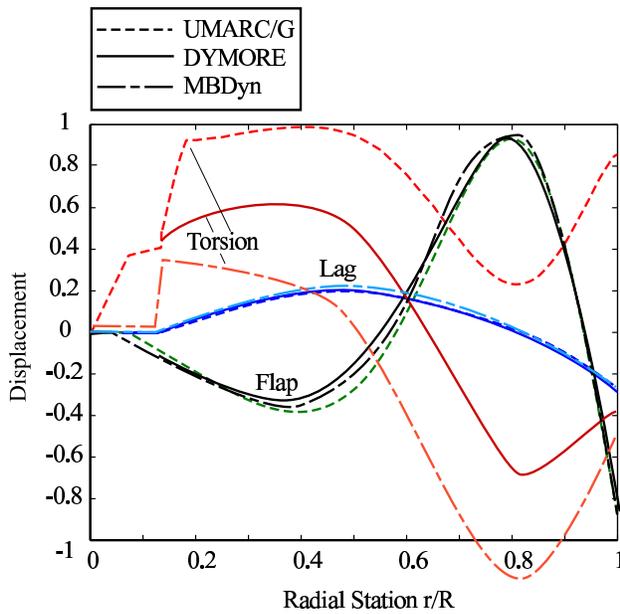


Figure 4: Mode shape comparisons for a non-rotating coupled flap-lag-torsion mode at approximately 64 Hz.

isons of the three analyses for the fourth mode are shown as an example because this mode has significant participation from flap, lag, and torsion. As shown, the agreement in the flap and lag deflections is excellent, but there is a prediction discrepancy in the torsion participation. This difference in torsion dynamics is currently under investigation.

Control System Calibration

Direct measurements showed that the control system may be regarded as rigid up to the rotating swashplate. Measurable compliance has been detected only between the blade pitch and the swashplate; moreover, an appreciable deadband (± 0.4 deg) results, possibly related to bearing and pitch link ball joints wear. From the multibody analysis standpoint, this has been modeled by concentrating the compliance and the deadband into the rod that represents the pitch link. The resulting analytical equivalent control system stiffness (blade root torsional moment per unit blade pitch) is strongly dependent on the collective setting (Fig. 5). Moreover, the experimental data apparently show that there is a strong dependency on the direction the control system is loaded; this can be partly related to a significant presence of deadband.

Control System Couplings

The nonlinear modeling capability of the multibody codes is highlighted in Fig. 6, which compares

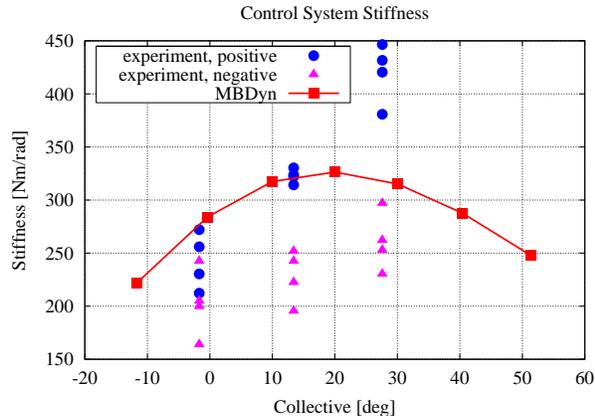


Figure 5: Equivalent control system stiffness; experimental data refers to measurements on each blade.

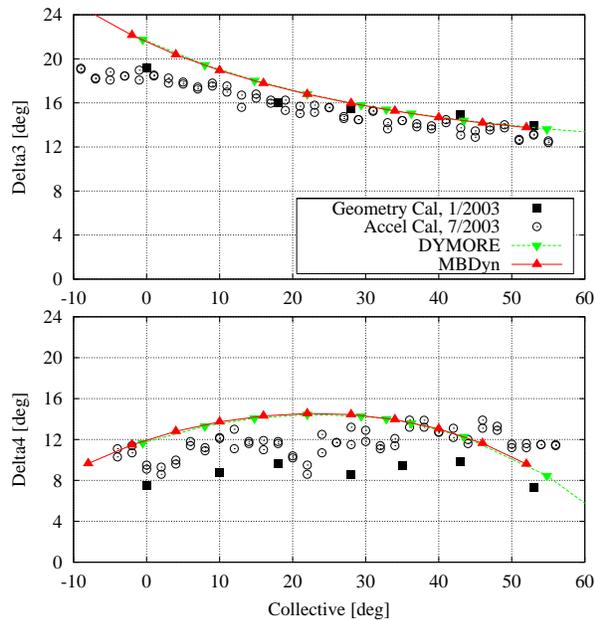


Figure 6: Pitch-flap (δ_3) and pitch-lag (δ_4) coupling comparison between experiment and analysis.

the experimental and predicted pitch-flap coupling response of the rotor system as a function of collective, at zero flap and lag angles. The comparison shows good trends, but a slight difference in magnitude. The control system model is currently being refined to produce a better comparison with the experimental data. It is worth noting that the kinematic couplings also depend on the reference configuration about which they are computed; the only alternative to multibody exact kinematics, with less than ideal accuracy, is represented by pitch, flap and lag tabulation, and 3 parameter table lookup.

Hover Run-Up

Figure 7 shows the dependency on the collective of the frequencies of the blade mounted on the hub, without aerodynamics, when the deformability of the pitch link is accounted for. Both the non-rotating and the 100% hover angular velocity cases are considered. While the flap and the lead-lag rigid modes appear to be very little affected by the collective setting, the higher modes show more pronounced changes. Modes labeled as F3/L2 and F4 change their nature when subjected to the centrifugal effect; their shape is now dominated by the torsional deformation, and their denomination rather reflects the prevailing participation of beam and chord bending.

A plot of the regressive rotor lag mode frequencies as function of rotor speed is shown in Fig. 8. The plot shows a difference between the predicted and experimental results, although agreement for the nonrotating condition is good. The lag hinge of the experimental system is a complicated mechanism, and the results obtained thus far represent a simple, constant stiffness equivalent spring hinge joint model. According to simple rigid blade theory, the regressive and the progressive lead-lag frequencies based on root stiffness and rotation speed is

$$\omega_{\xi} = \sqrt{\frac{K_{\xi}}{J_{\xi}} + \frac{f_{\xi} S_{\xi}}{J_{\xi}} \Omega^2} \pm \Omega$$

No unique lead-lag root stiffness could be found that matches the experimental results over the entire range of rotor rpm; Figure 8 shows the experimental results compared to the best fit obtained by calibrating the lead-lag root spring at the cross-over frequency, compared to those obtainable by calibrating the spring at each rpm. A detailed modal analysis showed a slight participation of blade chordwise bending in the mostly rigid lead-lag mode, resulting in a frequency reduction at 0 RPM of about 3.75%; this required an increase in the spring stiffness by

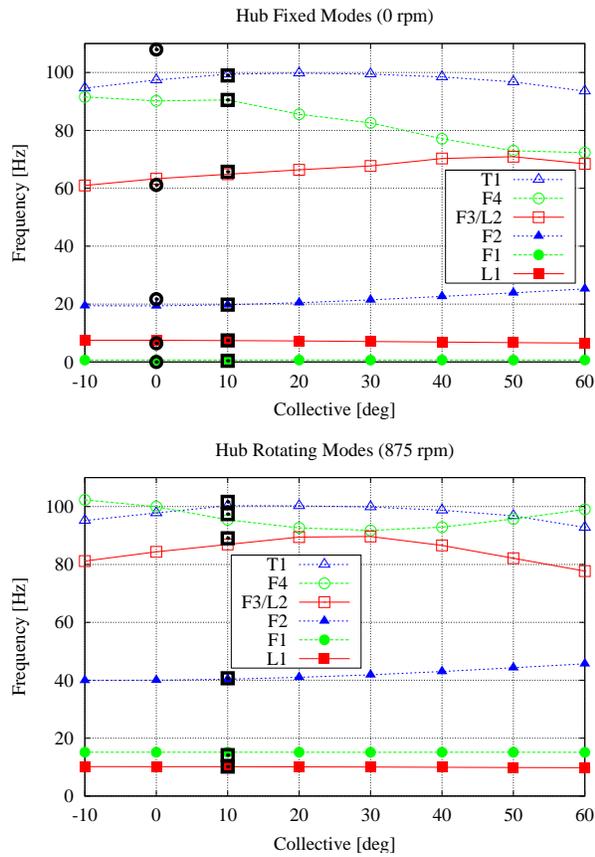


Figure 7: Dependency of isolated rotor *in vacuo* frequencies on collective settings; experimental results (thick hollow circles) refer to rigid pitch link; numerical results refer to deformable pitch link; thick squares represent DYMORE results at 10 deg collective.

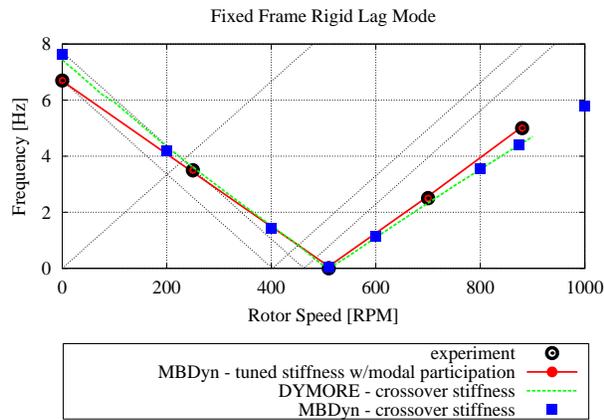


Figure 8: Regressive lead-lag mode frequency variation with rotor speed.

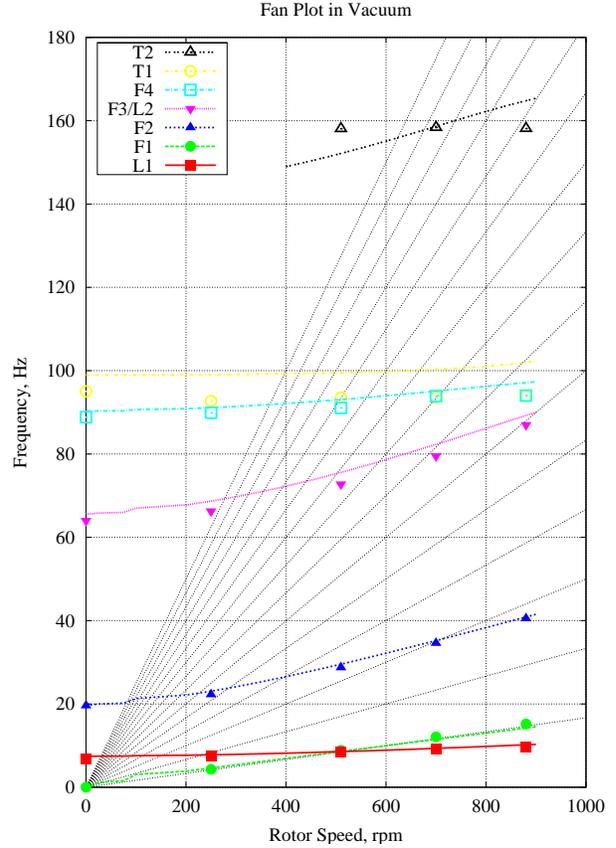


Figure 9: Fan plot of the isolated rotor *in vacuo* at 10° collective; lines: DYMORE, symbols: MBDyn.

about 7.5%. It is not yet clear what mechanism, if any, relates the lead-lag spring to the rotation speed.

A complete fan plot of the rotor at 10° collective is presented in Fig. 9; some sensitivity of the rotating modes of the rotor to the collective appears at the low angles that are typical of hover; a detailed rotating modal analysis at the higher collective settings of forward flight in a range of angular velocities will be the object of future analysis. The fundamental torsional mode is strongly dependent on the stiffness of the control system; the nominal frequency of about 106 Hz with rigid control system shown in Table II drops to less than 100 Hz when the pitch link is modeled as a deformable rod, according to the calibration described in Figure 5. The strong dependency of the control system stiffness on the collective setting is highlighted by the change in control/torsion frequency with the blade collective shown in Figure 7; note how the first torsion/control mode and the mode labeled as F4 cross at low and high collective.

Hover Performances

The hover performances of the SASIP rotor are detailed in Figs. 10–19. Experimental results are also shown, whenever available. The figures clearly show how the blade deformability highly affects the rotor performances. This is mostly related to blade torsion as a consequence of the offsets of the normal stress center, of the center of gravity and of the shear center of the blade sections. In fact, it has been verified that by artificially increasing the stiffness of the blade model, the curves shift towards those labeled as “rigid blade”. In the multibody analysis, simple uniform inflow was used without any empirical correction, and a standard 2% total tip loss was considered. The thrust was not directly measured, since the WRATS rotor does not have an internal balance; the values in the figures refer to measures of the wing root beam bending moment by means of strain gages, empirically corrected to account for wing download. It is estimated that wing download amounts to 10% of the nominal thrust.

Fig. 15 presents the actual blade pitch angle compared to the input collective. The differences between input and output angles mainly result from the contributions of the flap and lag angles through the control system couplings. While for low input collective the flap and the lag effects are comparable in magnitude but opposed in sign, and thus nearly cancel, for high input collective they add, resulting in an appreciable reduction in actual blade pitch.

Figures 16 and 18 have been corrected by arbitrarily shifting the cone angle, since there were uncertainties on the reference value; Figures 17 and 19 have been corrected as well by arbitrarily shifting the lead-lag angle, since the angle at rest was used as reference, but there is no guarantee that it corresponds to the nominal blade rest azimuthal orientation. It is reasonable to assume that the rest position should be as close as possible to the more critical operating condition from a structural design standpoint, since the main reason for developing soft-inplane tiltrotors is to reduce the hub loads that are typical of stiff-inplane tiltrotors. This can be achieved by carefully tuning the lead-lag hinge chordwise position and the lead-lag spring orientation.

Figs. 18 and 19, reported as a cross-check, show the expected rectilinear behavior that is typical of articulated rotors.

Wing Structural Model and Hover Stability

The wing model, in the case of hover and ground resonance analysis, in absence of significant sources

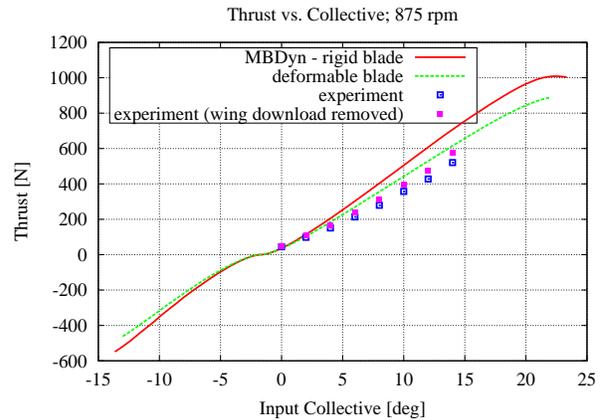


Figure 10: Thrust vs. input collective.

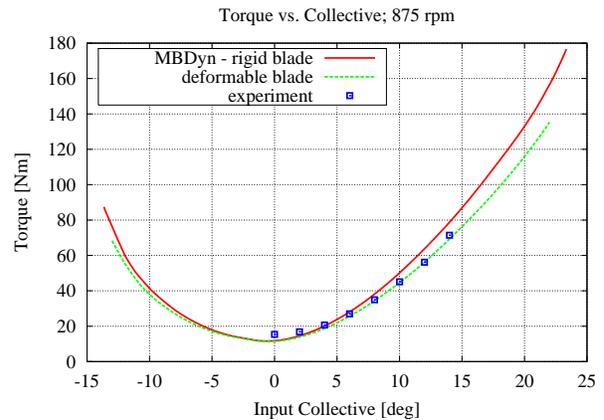


Figure 11: Torque vs. input collective.

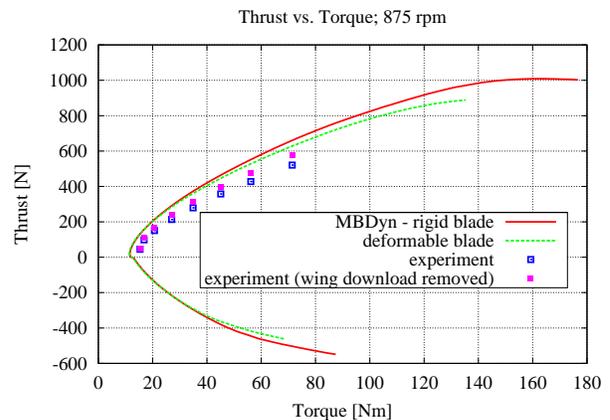


Figure 12: Thrust vs. torque.

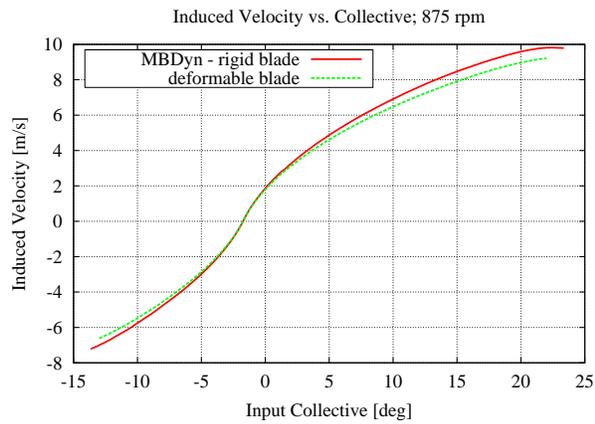


Figure 13: Induced velocity vs. input collective.

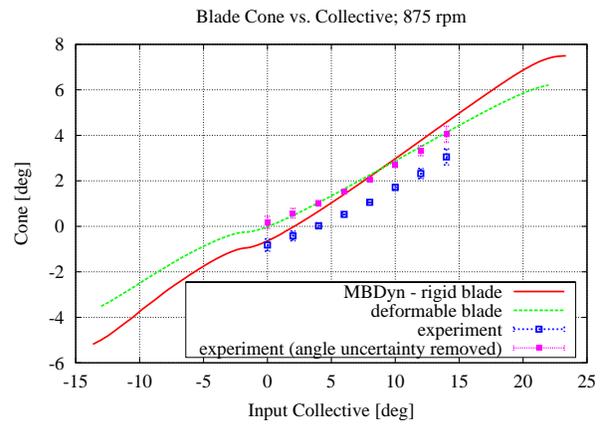


Figure 16: Blade cone vs. input collective.

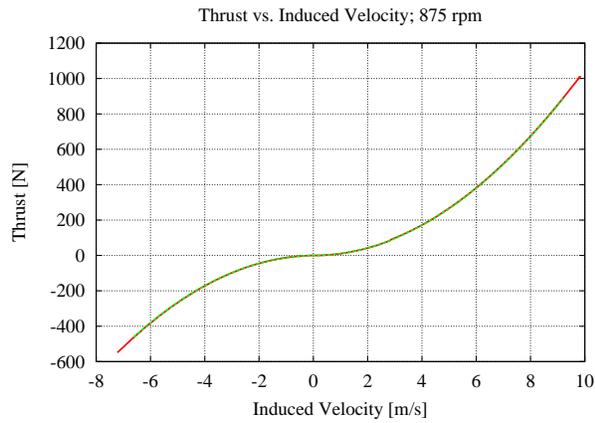


Figure 14: Thrust vs. induced velocity.

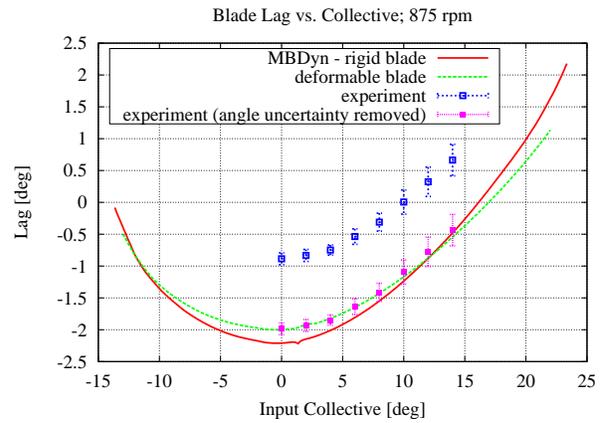


Figure 17: Blade lead-lag vs. input collective.

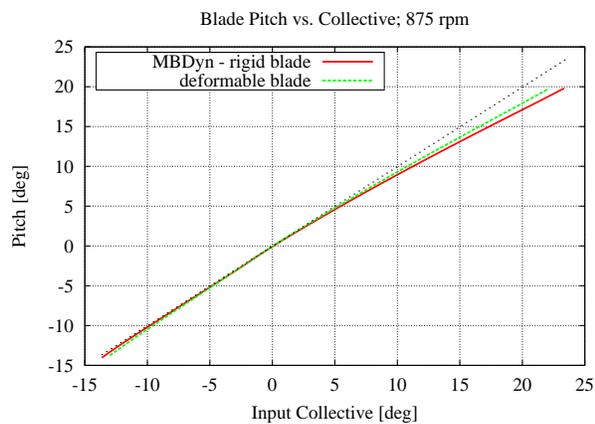


Figure 15: Blade pitch vs. input collective.

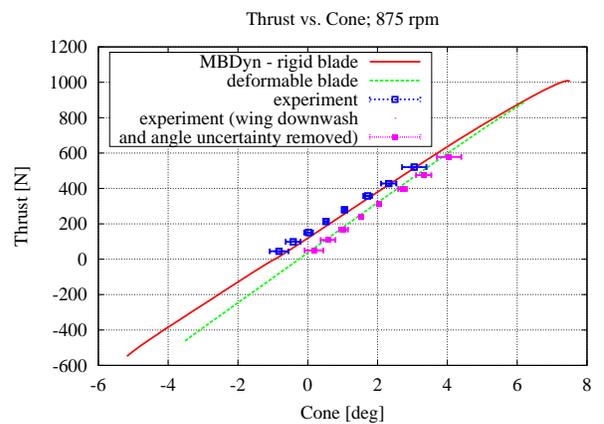


Figure 18: Thrust vs. cone.

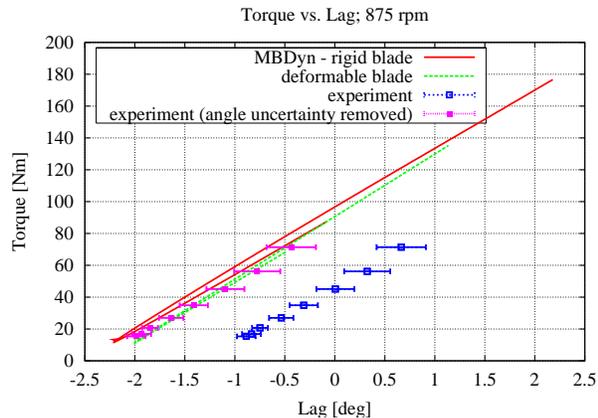


Figure 19: Torque vs. lead-lag angle (positive when lagging).

of nonlinear behavior, does not present any peculiar difficulties, as soon as the interaction of the rotor wake with the wing is not a concern. It is essential that the wing behavior, in terms of frequency and modal shapes at the interface with the rotor, is accurately modeled. The multibody formalism allows two different approaches to this problem: (a) the direct finite element modeling of the wing structure, and (b) a modal synthesis of the wing behavior. Within MBDyn both approaches have been considered, while with DYMORE the attention has been focused on the direct FEM modeling.

The hover stability of the SASIP model is a significant issue. In fact, the SASIP experimental system, by design, is prone to ground resonance, because the soft-inplane rotor is mounted on a deformable wing whose fundamental frequencies are right below the non-rotating regressive lead-lag frequency, and the damping of the support, significantly in hover, is inherently delegated to the structure. At the same time, the lead-lag motion of the blades is damped at a nominal damping ratio of 10–12%.

Figure 21 shows the lead-lag angle rate that results from a transient analysis of the entire model, with and without aerodynamics, during a linear RPM sweep at a 100 RPM/s rate. It is compared to the plot of some significant system frequencies in the fixed frame. The time and the RPM abscissæ of the two subplots are proportional; this highlights interesting behavior patterns. At about $100 \div 200$ RPM there seems to be some interaction between the regressive lead-lag, the progressive flap and the wing beam/chord frequencies. At 510 RPM the rotor speed crosses the lead-lag frequency, resulting in significant resonant response when the aerodynamics are considered. Finally, above 800 RPM the regressive

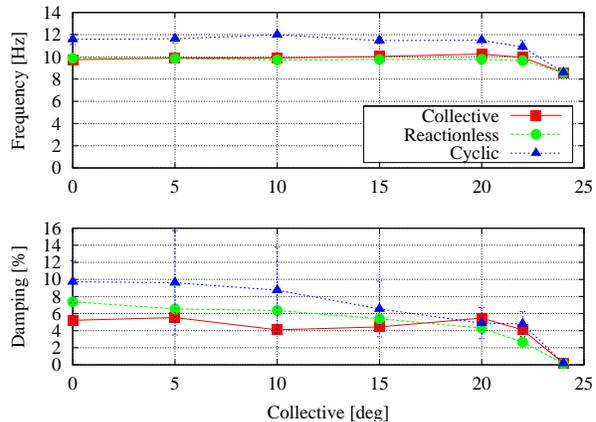


Figure 20: Lead-lag modes vs. collective in hover (875 rpm).

lead-lag frequency crosses again the wing beam/chord mode; this results in ground resonance when aerodynamics are neglected, because no wing structural damping was considered. The aerodynamics seem to provide enough damping to the system to prevent dynamic instabilities.

CONCLUDING REMARKS

This study shows that multibody codes can be used to successfully model complex mechanisms in rotorcraft and that this capability can improve predictions of dynamic behavior. How this improved modeling capability can influence load and stability predictions is an anticipated conclusion which has not yet been resolved. Key points that highlight the importance of exploiting the capabilities of multibody analysis software are:

- hub and blade root kinematics and dynamics
- control system kinematics and structural dynamics
- finite element and composite-ready blade structural modeling
- versatility in structural modeling of unusual components
- essential rotor aerodynamics capabilities

The two multibody analysis software show analogous capabilities when applied to rotorcraft modeling. The availability of two independently developed and validated multibody models of the WRATS SASIP represents an opportunity for future developments in the aeromechanical research on soft-inplane tiltrotor systems.

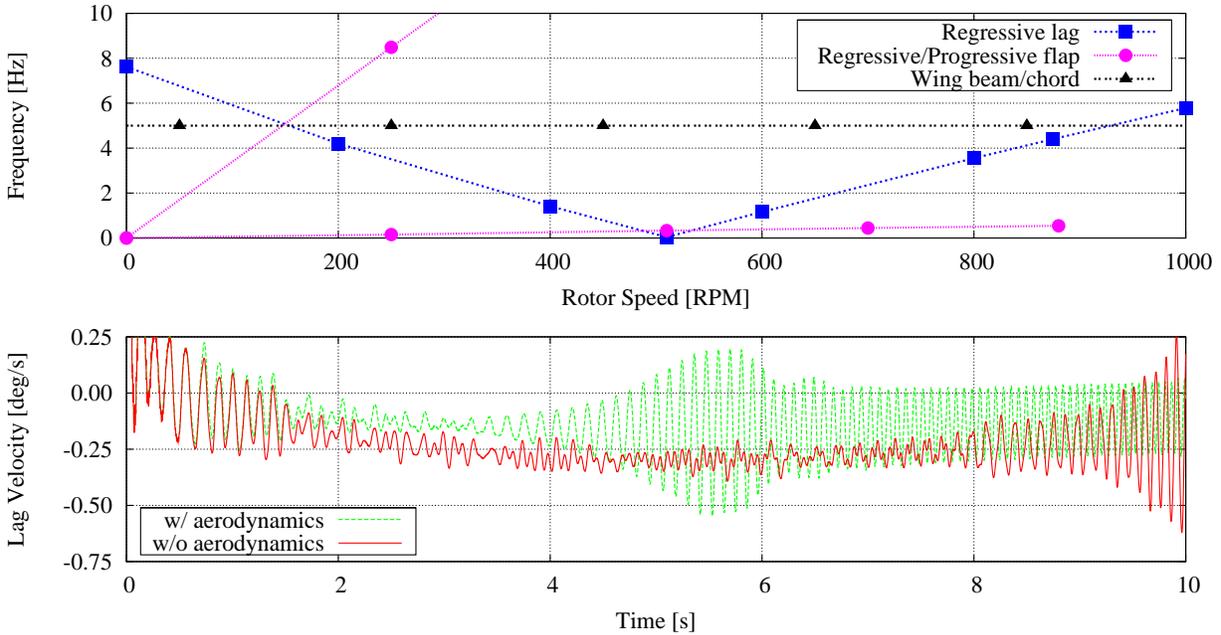


Figure 21: Lead-lag angular velocity during RPM sweep at 10 deg collective.

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