Loads Correlation of a Full-Scale Proprotor on the Tiltrotor Test Rig

Sesi Kottapalli
Aeromechanics Office
NASA Ames Research Center
Moffett Field, California, USA
sesi.b.kottapalli@nasa.gov

ABSTRACT

In 2017-2018, a full-scale isolated proprotor test was conducted in the USAF National Full-Scale Aerodynamics Complex (NFAC) at NASA Ames Research Center. The test article was the 3-bladed Bell 699 research rotor derived from the AW609 rotor. For this test, the NASA Tiltrotor Test Rig (TTR) and rotor were installed in the 40- by 80-foot test section. Correlations between the test data and predictions from the comprehensive analysis CAMRAD II for blade and yoke (flexbeam) loads and rotor torque are presented. The full operating range of tiltrotor conversion is covered: conversion 30-, 45-, and 60-deg TTR yaw, and helicopter 75- and 90-deg TTR yaw. The flap moment correlation is reasonable to good; the pitch link load and torsion moment are uniformly underpredicted. The measured 2P lag moment and 2P torque are not captured by the analysis. The inability to predict the 2P component is currently attributed to the analytical assumption of identical blades. The actual test rotor has dissimilar blades because only one blade is instrumented, thus introducing the 2P harmonic. To analytically bring in the 2P component, additional analysis with dissimilar blades could be undertaken.

NOTATION

hpp	½ peak-to-peak
JVX	Joint Vertical Experimental proprotor
MTW	multiple-trailer wake
*n*P	n per revolution (same as *n*/rev)
NFAC	National Full-Scale Aerodynamics Complex
PLL	pitch link load, lb
RW	rolled-up wake
TH	time-history
TTR	Tiltrotor Test Rig
40x80	40- by 80-Foot Wind Tunnel
A	rotor disk area, πR^2
C_T	rotor thrust coefficient, $T/\rho A V_t^2$
M_{tip}	tip Mach number
R	rotor radius, ft
T	rotor thrust, lb
V	airspeed, knots
V_t	tip speed, ΩR
Yaw	TTR yaw angle; cruise is 0 deg and helicopter mode is 90 deg
μ	advance ratio, V/V_t
ρ	air density
σ	rotor solidity ratio
Ω	rotational speed, rpm

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INTRODUCTION

In November 2018, a full-scale isolated proprotor test was completed in the USAF National Full-Scale Aerodynamics Complex (NFAC) 40- by 80-Foot Wind Tunnel at NASA Ames Research Center (Ref. 1). The test article was a 3-bladed research rotor, designated as the Bell 699 rotor. The 699 is derived from the right-hand rotor of the AW609 and was manufactured by Bell Helicopter under contract to NASA. (The 699 was referred to as '609' in earlier publications, notably Ref. 2.) Figure 1 shows the TTR/699 installed in the NFAC 40- by 80-Foot Wind Tunnel test section. The TTR rotor axis is horizontal and the rig rotates in yaw on the wind tunnel turntable for conversion between airplane and helicopter mode testing. This 699 proprotor loads correlation study uses wind tunnel test data from the checkout test.

This paper represents the fourth analytical study for this test program, coming after pre-test predictions of 699 performance and loads (Ref. 2), an aeroelastic stability analysis of the TTR/699 installed in the 40- by 80-Foot Wind Tunnel (Ref. 3), and a recent, post-test, initial performance and loads correlation study (Ref. 4). Reference 5 presents an overview of the entire TTR/699 test program (note that an earlier paper, Ref. 6, addressed the development and initial testing of the TTR). Reference 7 addresses testing techniques and facility effects on the vertical climb performance of the 699 rotor in the 40- by 80-Foot Wind Tunnel.

Figure 1. TTR/699 installed in the USAF NFAC 40- by 80-Foot Wind Tunnel (45-deg yaw).

The research reported in this paper represents follow-on work to the initial performance and loads correlation study noted above, Ref. 4. The current focus is on correlation of 699 isolated rotor loads; correlation of rotor torque is also included. The conversion (transition) and helicopter modes of operation are considered for analysis. The airplane (cruise) 0-deg yaw condition is not considered in this study.

Prior to the 2019 initial correlation study (Ref. 4), only a limited number of correlation studies have been published for full-scale proprotors. The 1971 report by Bell Helicopter (Ref. 8) contains XV-15 40x80 wind tunnel test data and theoretical predictions. A literature survey brought up several existing correlation studies, but these were either based on small-scale test data (for example, Refs. 9-10) or full-scale aircraft flight test data (for example, flight tests conducted by Bell Helicopter). Separately, the 2009 NASA study involving the JVX rotor is relevant (see Ref. 11). The JVX is similar to the 699 in size and aerodynamics and is accordingly a good reference for performance calculations. In Ref. 2 (as mentioned above), pre-test reality checks of the current analytical model were made by comparing JVX and 699 predictions in hover and forward flight (airplane mode).

The current correlation study covers the full range of conversion to helicopter modes, in 15-deg yaw increments: conversion 30-, 45-, and 60-deg, and helicopter 75- and 90-deg. Table 1 lists the five cases (in the table “Conv” And “Heli” refer to the conversion and helicopter modes, respectively). Yaw in the wind tunnel corresponds to nacelle angle on the aircraft. The conditions in Table 1 represent the approximate middle of the conversion corridor.

Table 1. Operating conditions considered for correlation.

Case	Mode	Yaw, deg	V, knots	μ	C_T/σ
I.	Conv	30	104	0.23	0.080
II.	Conv	45	92	0.20	0.080
III.	Conv	60	92	0.20	0.080
IV.	Heli	75	70	0.15	0.081
V.	Heli	90	57	0.13	0.080

The ½ peak-to-peak (hpp) quantities and time-histories are correlated for the blade, yoke, and pitch link loads; the mean rotor torque is also correlated (same as in Ref. 2 and 4). Additionally, for the first time, correlations for the harmonics and time-histories of the rotor torque are presented. Details are given in the Results section.

BELL 699 RESEARCH ROTOR

A brief description of the 699 research proprotor is given here. The 3-bladed rotor has non-linear twist (47.5 deg) and square tips, the rotor diameter is 26 ft and the geometric solidity is 0.097. The rotor is stiff in-plane with a gimballed hub and yoke (flexbeam). The conversion and helicopter mode rpm is 569 (100%) and the airplane mode (cruise) rpm is 478 (84%). See Ref. 5 for further details of the rotor and instrumentation.

The 699 rotor is based on the AW609 rotor and was manufactured by Bell Helicopter under contract to NASA. The main differences between the research and flight rotors are listed below. The research rotor:

- Does not have deicing capability
- Has additional instrumentation
- Has a different pitch horn arrangement, specific to the TTR control system
- Does not have pendulum absorbers

See Ref. 5 for further details of the rotor and instrumentation.

ANALYTICAL MODEL

The rotorcraft comprehensive analysis CAMRAD II Release 4.9, Refs. 12-14, was used for the analytical predictions. Performance and loads calculations in Refs. 2 and 4 and in this study were performed for the 699 rotor with flexible blades and hub, including the gimbal, but with no fixed system flexibility. Similar to the V-22 CAMRAD model (Ref. 15), a dual load-path model is used for the 699 rotor. The yoke (flexbeam) and the blade form the two load paths. The CAMRAD II aerodynamic model requires airfoil tables, which were provided by Bell Helicopter as C81 tables. The rotor model includes the gimbal and swashplate degrees of freedom. The blade and yoke are modeled using elastic beam elements. In the trim calculations, 40 elastic blade modes are used (torsion, flap and lag); there is no modal truncation at all, all modes are retained.

Correlations with both the CAMRAD II rolled-up wake (RW) model (single tip vortex) and multiple trailer wake (MTW) model (multiple far wake trailers, Ref. 16) are shown. Time-history predictions require more detailed wake modeling, so the MTW model may be more appropriate for those operational conditions for which the wake is located close to the rotor disk. This paper contains results from both wake models; for each operational condition, the relative performance of each wake model is noted in the Results section.

Finally, the analysis was performed for an ideal, constant-speed gimbal and identical blades. The current predictions use a comprehensive analysis (Ref. 12), with no wind tunnel wall effects (a completely isolated proprotor is considered). Inclusion of wall effects and the use of higher order airloads from a CFD analysis should improve the current correlation. A full CFD analysis of the TTR/699/40x80-test section configuration should improve the correlation.

RESULTS

Correlations of full-scale proprotor loads are presented in this paper; correlation of the rotor torque is also included. Six sets of results are shown: these include the five conditions listed in Table 1 and torque results for the full yaw range.

Results are shown for the thrust, torque, blade and flexbeam (yoke) bending moments, blade torsion moments, and pitch link load. The results include trim control angles. Mean, ½ peak-to-peak (hpp) quantities and loads time-histories are shown. For torque, the harmonics and time-histories are also shown.

Correlation parameters. The blade stations used for correlation and their corresponding radial locations are listed below:

inboard:	0.20R
midspan:	0.45R
outboard:	0.75R
yoke inboard:	0.08R
yoke outboard:	0.11R

The flap and lag moments refer to the bending moments about the local section normal and chord axes, respectively. The Bell 699 rotor hub has pitch bearings; the pitch bearings and the gimbal isolate the yoke from torsion loads. In this paper, only yoke flap and lag bending moment correlations are shown.

The sign convention is as follows:

pitch link load:	+ tension
flap bending moment:	+ tip bent up
lag bending moment:	+ tip bent toward trailing edge
torsion moment:	+ blade twisted leading edge up

The rotor was always trimmed to M_{tip}, μ, C_T/σ, and zero 1P flapping. At each operational condition, the analysis matched the following test quantities: density, temperature, Ω, TTR yaw, airspeed, and C_T/σ.

Case I. Conversion Mode, 30-deg yaw

The operating condition for this case is: 30-deg yaw, Ω=570 rpm, V=104 knots, μ=0.23, and C_T/σ=0.080.

30-deg mean and ½ peak-to-peak (hpp) correlation. The correlation for the mean quantities is shown in Figures 2-3 and the hpp correlation is shown in Figures 5-7, all as column charts. The torque is shown in Figure 2 and the trim controls are shown in Figure 3. The hpp blade (and yoke) flap and lag moment correlations are shown in Figures 4-5, respectively. The hpp pitch link load correlation is shown in Figure 6 and the hpp blade torsion moment correlation is shown in Figure 7.

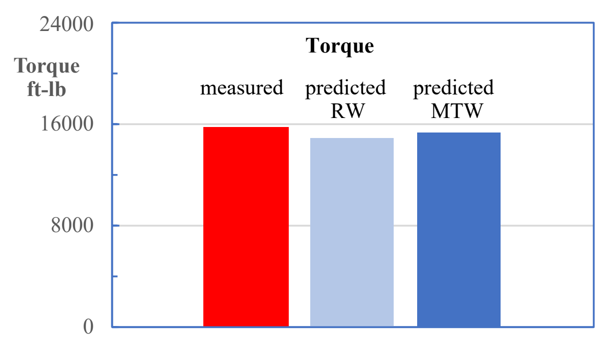
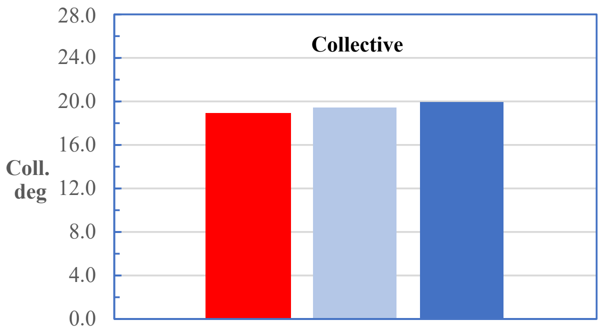
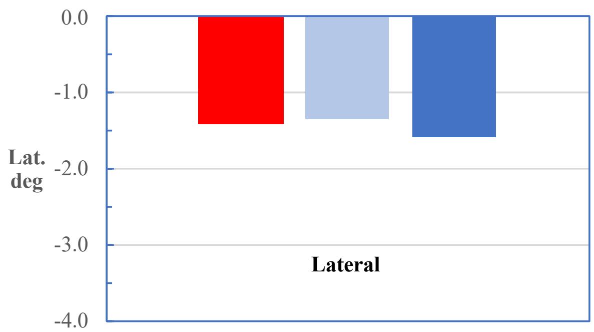


Figure 2. Measured and predicted torque, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.

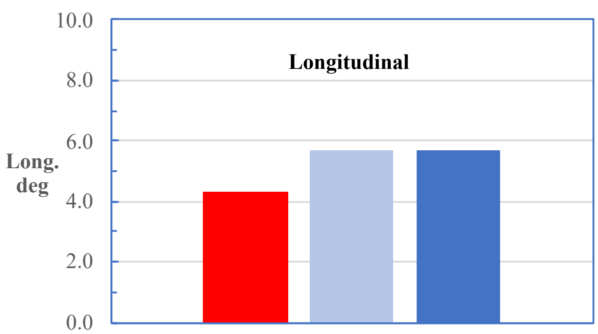
Specific observations are as follows. The torque is underpredicted by the RW model and predicted a bit better by the MTW model (Figure 2). The collective is predicted well by the RW model, the lateral cyclic correlation is reasonable, and the longitudinal cyclic correlation is not good (Figure 3). The blade and yoke bending moments, flap and lag, are overpredicted at all spanwise locations (Figures 4-5). The pitch link load and torsion moment are underpredicted (Figures 6-7, respectively). At this 30-deg conversion condition, the results are not significantly sensitive to the wake model.



(a) Collective

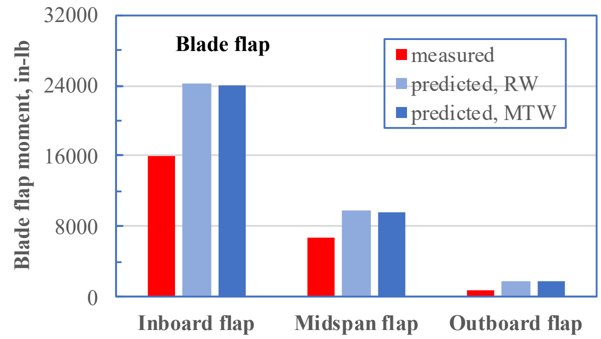


(b) Lateral cyclic

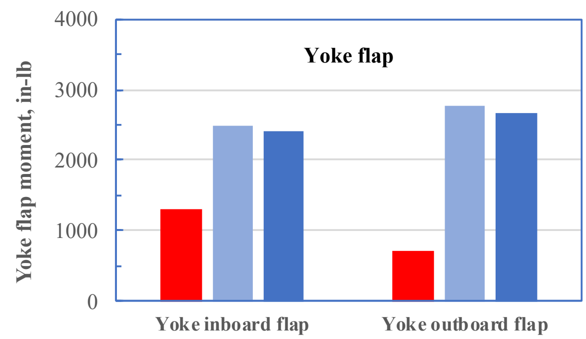


(c) Longitudinal cyclic

Figure 3. Measured and predicted control angles, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.

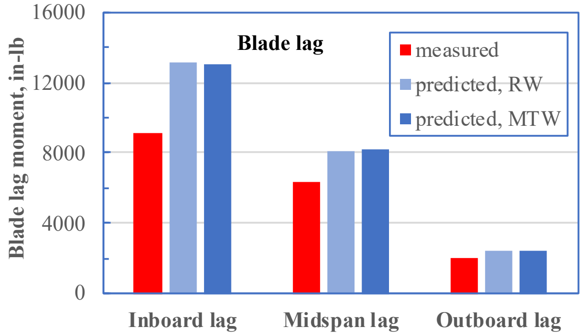


(a) Blade moments

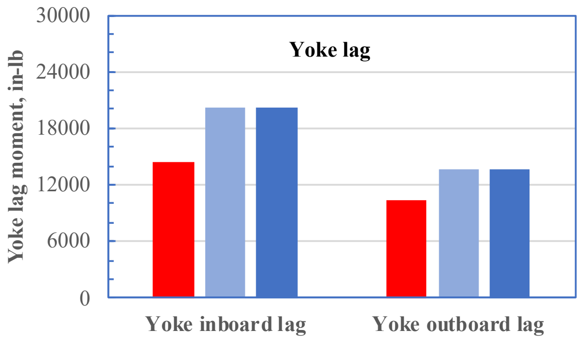


(b) Yoke moments

Figure 4. Measured and predicted blade and yoke hpp flap moments, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.



(a) Blade moments



(b) Yoke moments

Figure 5. Measured and predicted blade and yoke hpp lag moments, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.

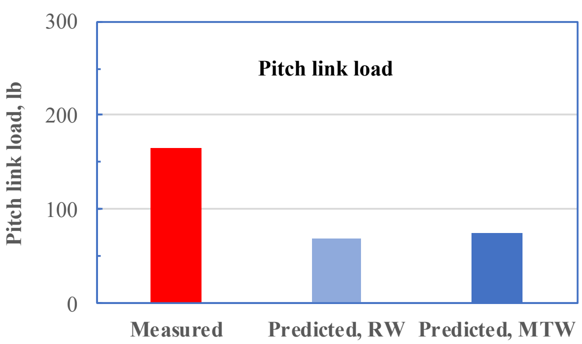


Figure 6. Measured and predicted hpp pitch link load, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.

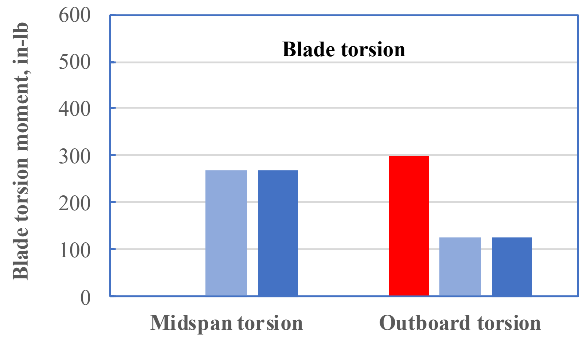
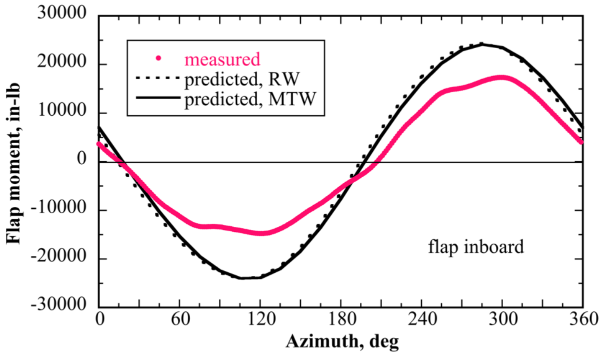


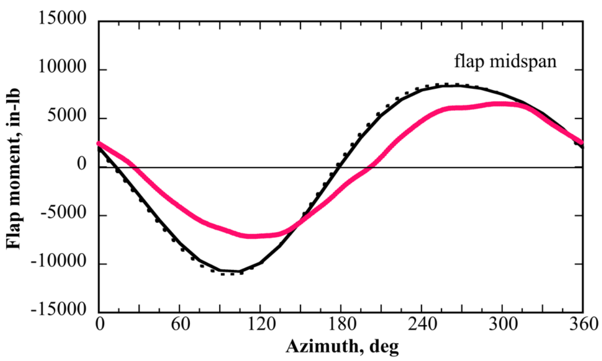
Figure 7. Measured and predicted hpp torsion moments, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.

30-deg time-history correlation. Figures 8-11 show the time-history correlations for the blade and yoke bending moments. Figure 12 shows the pitch link load correlation and Figure 13 shows the blade torsion moments for this conversion angle. These are consistent with Figures 4-7.

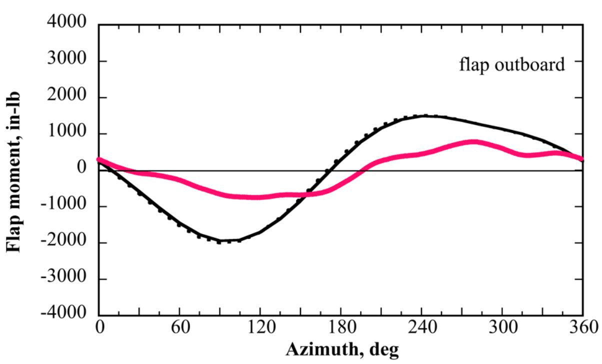
Specific observations on the current isolated rotor time-history correlation are as follows. The loads have mostly 1P variation (Figures 8-13). Some higher frequency content of relatively small magnitude is also present in the test data, especially in the blade lag moment (Figure 9), yoke flap moment (Figure 10), pitch link load PLL (Figure 12), and outboard torsion moment (Figure 13b). The loads time-history correlation shows that the basic 1P shape (and phase) is captured by the analysis (Figures 8-13). However, the analysis does not pick up the higher frequency content. The blade and yoke bending moments are overpredicted (Figures 8-11); the PLL and torsion moment are underpredicted (Figures 12 and 13b, respectively). The lack of correlation for the loads magnitudes is somewhat disappointing. The loads are not significantly sensitive to the wake model.



(a) Inboard

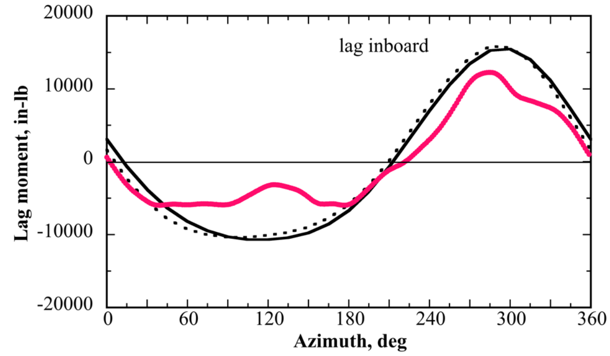


(b) Midspan

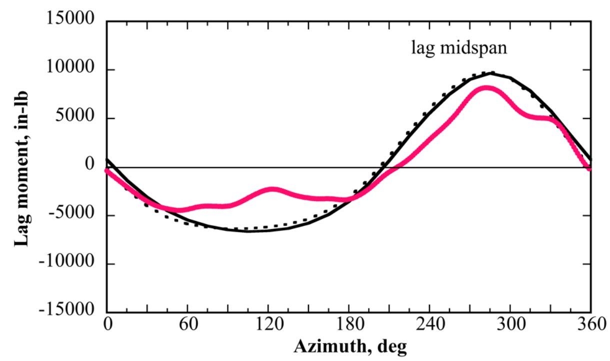


(c) Outboard

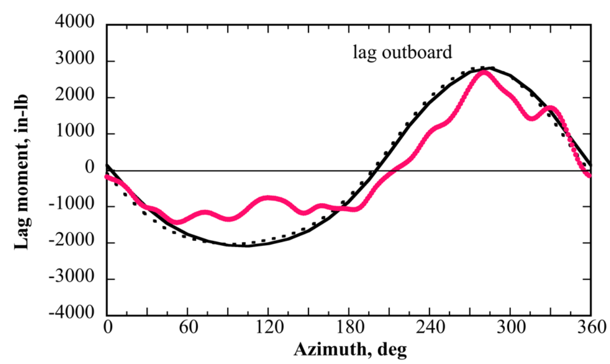
Figure 8. Blade flap moment time histories, conversion mode, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.



(a) Inboard

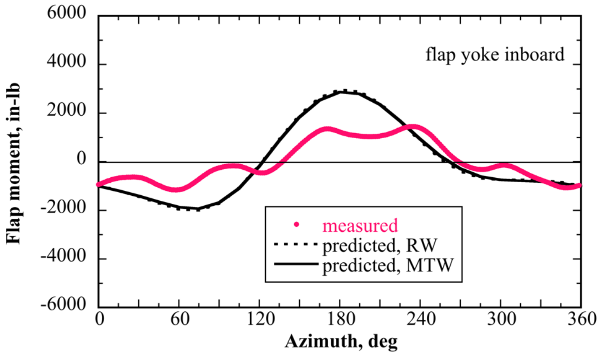


(b) Midspan

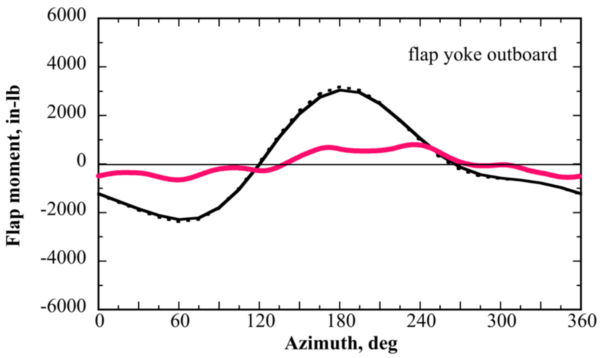


(c) Outboard

Figure 9 . Blade lag moment time histories, conversion mode, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.

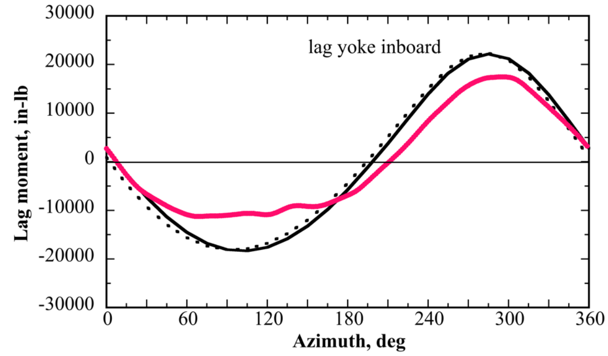


(a) Yoke inboard

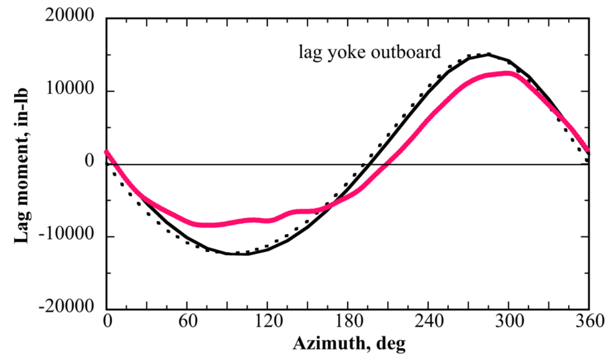


(b) Yoke outboard

Figure 10. Yoke flap moment time histories, conversion mode, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.



(a) Yoke inboard



(b) Yoke outboard (lag)

Figure 11. Yoke lag moment time histories, conversion mode, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.

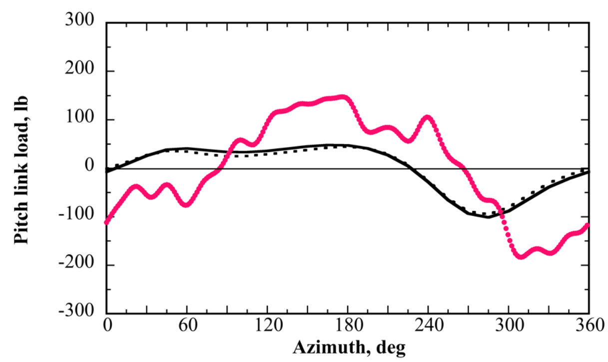
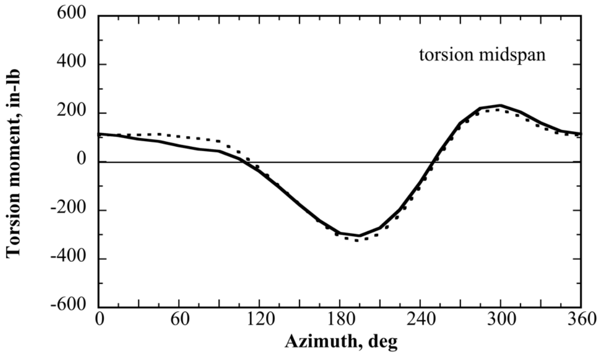
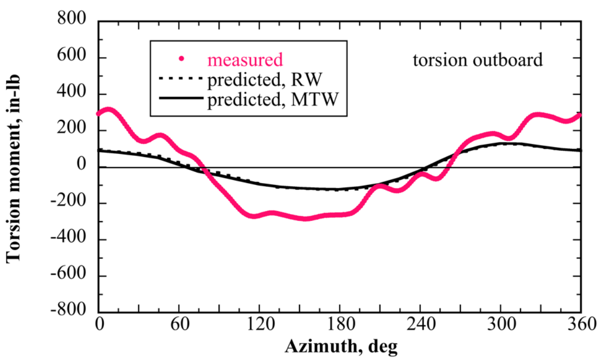


Figure 12. Pitch link load time history, conversion mode, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.



(a) Midspan (torsion)



(b) Outboard (torsion)

Figure 13. Torsion moment time histories, conversion mode, 30-deg yaw, Ω=570, V=104 knots, μ=0.23, C_T/σ =0.080.

The 30-deg (Case I) conversion correlation is summarized as follows. The mean and hpp correlations (Figures 2-7) and the loads time-history correlations (Figures 8-13) show that:

- The results are not significantly sensitive to the wake model.
- The collective and lateral cyclic are reasonably predicted. The longitudinal cyclic correlation is not good.
- The blade and yoke bending moments (flap and lag) are overpredicted.
- The pitch link load and torsion moment are underpredicted.
- The analysis captures the basic 1P azimuthal shape (and phase) of the loads.
- Finally, the lack of correlation for the loads magnitudes is somewhat disappointing.

These predictions are based on a comprehensive analysis. The analysis has been performed for an ideal, constant-speed gimbal and identical blades. A completely isolated rotor is modeled. The airflow around the TTR (a relatively large structure, extending over 30 ft in length) is not modeled and as noted earlier, wind tunnel wall effects are not included. It has not yet been determined whether the proximity of the TTR and rotor to the wind tunnel walls has a significant effect or not. A CFD analysis of the complete TTR/699/40x80-test section configuration should resolve this uncertainty. In any case, such considerations are outside the scope of the present study.

Case II. Conversion Mode, 45-deg yaw

The operating condition for this case is: 45-deg yaw, Ω=568 rpm, V=92 knots, μ=0.20, and C_T/σ=0.080.

45-deg mean and hpp correlation. The correlation for the mean quantities is shown in Figures 14-15 and the hpp correlation is shown in Figures 16-19. The torque is shown in Figure 14 and the trim controls are shown in Figure 15. The hpp blade (and yoke) flap and lag moment correlations are shown in Figures 16-17 respectively. The hpp pitch link load correlation is shown in Figure 18 and the hpp blade torsion moment correlation is shown in Figure 19.

Specific observations are as follows. The torque is underpredicted by the RW model and predicted better by the MTW model (Figure 14). All three trim control angles are predicted reasonably well (Figure 15). The blade and yoke flap moments are overpredicted at all spanwise locations (Figure 16). The blade and yoke lag moment are reasonably predicted (all stations, Figure 17). The pitch link load and torsion moment are underpredicted (Figures 18-19, respectively). Similar to the 30-deg results, the current 45-deg angle results are not significantly sensitive to the wake model.

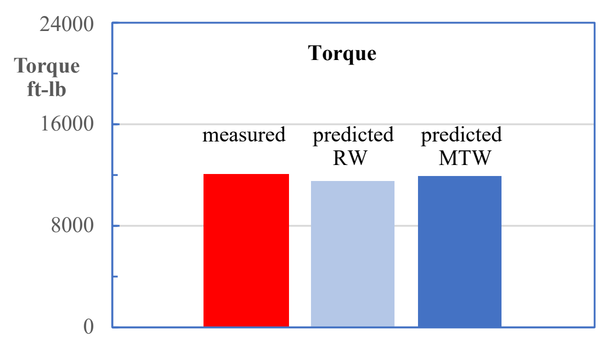
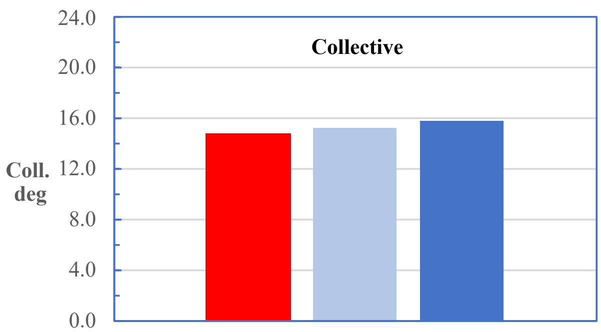
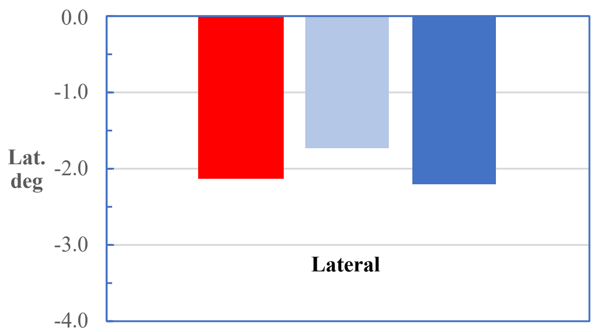


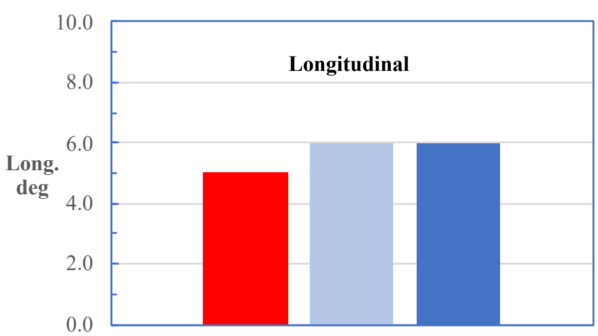
Figure 14. Measured and predicted torque, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Collective

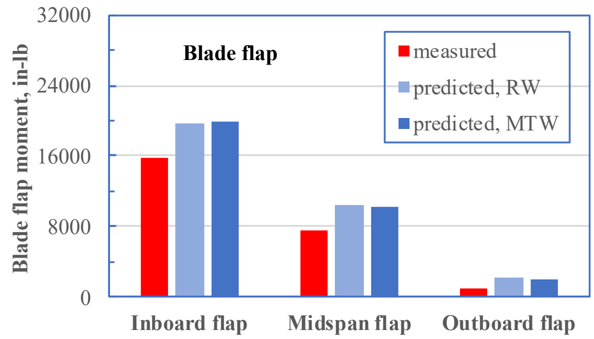


(b) Lateral cyclic

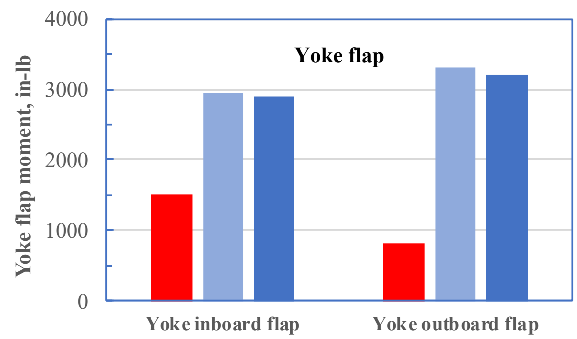


(c) Longitudinal cyclic

Figure 15. Measured and predicted control angles, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.

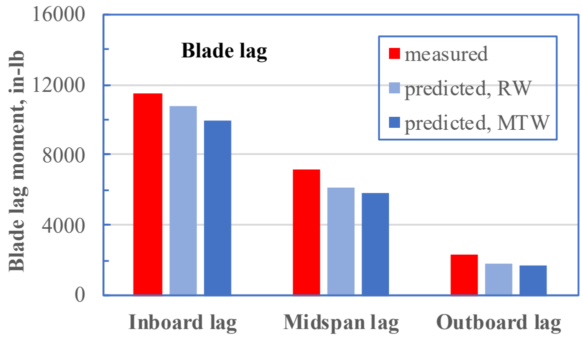


(a) Blade moments

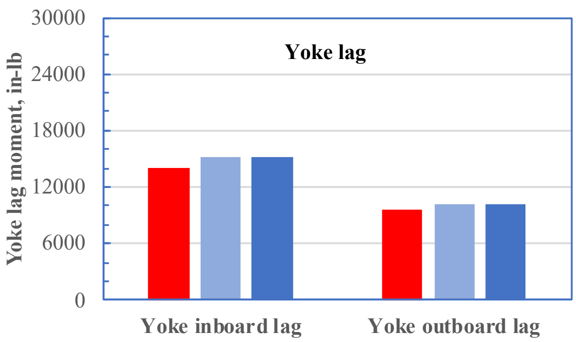


(b) Yoke moments

Figure 16. Measured and predicted blade and yoke hpp flap moments, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Blade moments



(b) Yoke moments

Figure 17. Measured and predicted blade and yoke hpp lag moments, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.

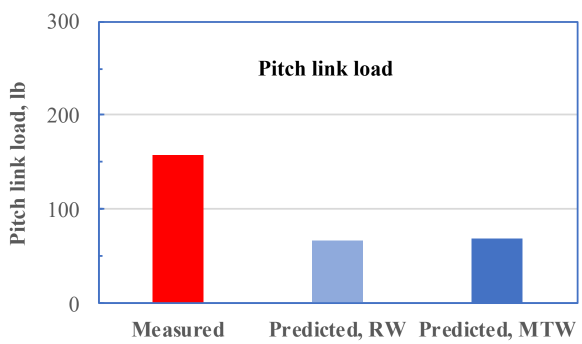


Figure 18. Measured and predicted hpp pitch link load, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.

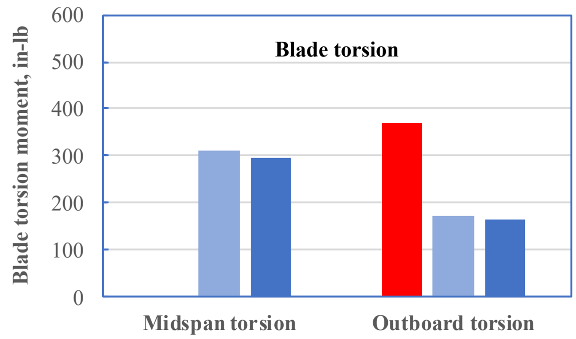
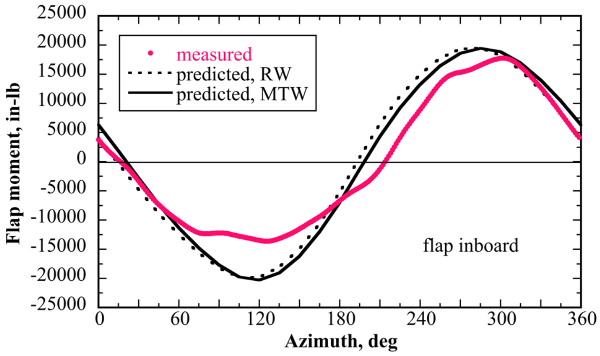


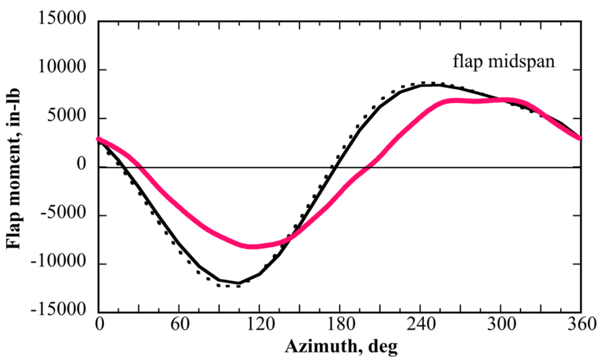
Figure 19. Measured and predicted hpp torsion moments, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.

45-deg time-history correlation. Figures 20-23 show the time-history correlations for the blade and yoke bending moments. Figure 24 shows the pitch link load correlation and Figure 25 shows the blade torsion moments. These are consistent with Figures 16-19.

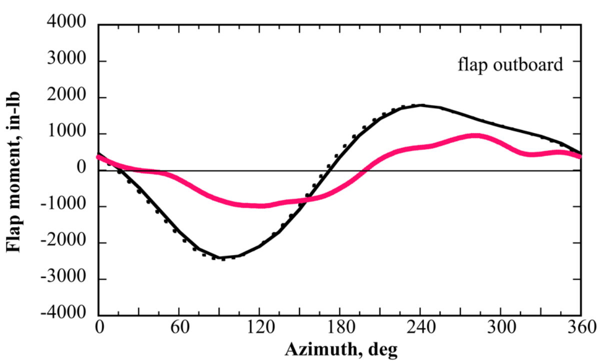
Specific observations on the current isolated rotor time-history correlation are as follows. The flap loads have mostly 1P variation (Figures 20 and 22). Some higher frequency content of relatively small magnitude is also present in the measured pitch link load PLL (Figure 24) and outboard torsion moment (Figure 25b). The test lag moment azimuthal variations (Figures 21 and 23) show that in addition to the 1P component a strong 2P component is also present. The analysis captures the basic 1P shape (and phase, Figures 20-25). The analysis does not pick up the higher frequency content. The blade and yoke flap moments are overpredicted (Figures 20 and 22). The 2P lag moment is not predicted. Except for the 2P component, the blade and yoke lag moments are reasonably predicted (Figures 21 and 23). The PLL and torsion moment are underpredicted (Figures 24 and 25b, respectively). Similar to the 30-deg results, the current 45-deg results are also not significantly sensitive to the wake model.



(a) Inboard

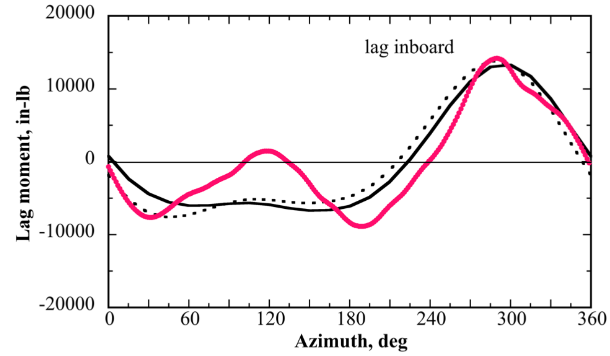


(b) Midspan

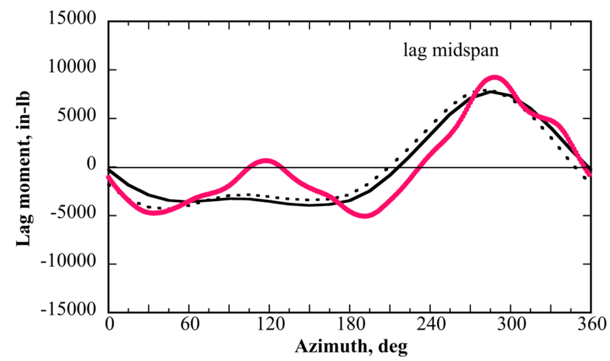


(c) Outboard

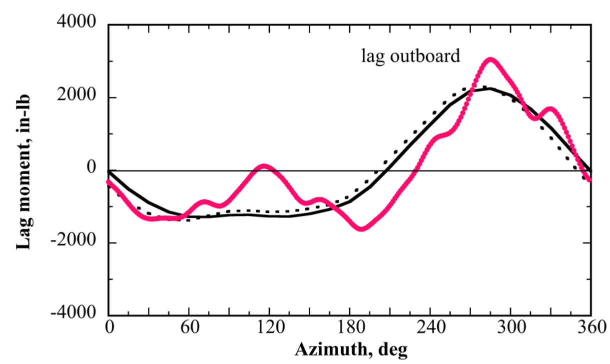
Figure 20. Blade flap moment time histories, conversion mode, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Inboard

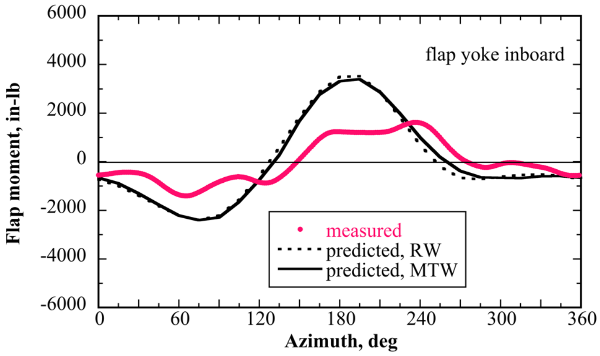


(b) Midspan

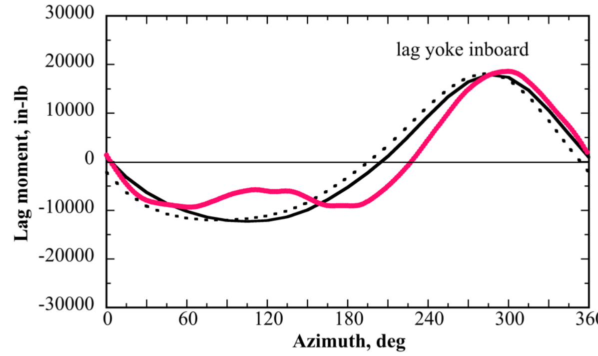


(c) Outboard

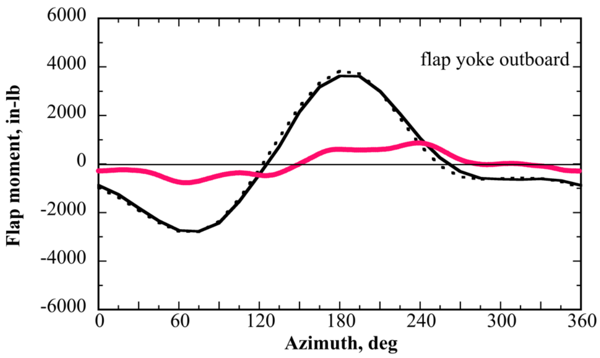
Figure 21. Blade lag moment time histories, conversion mode, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Yoke inboard

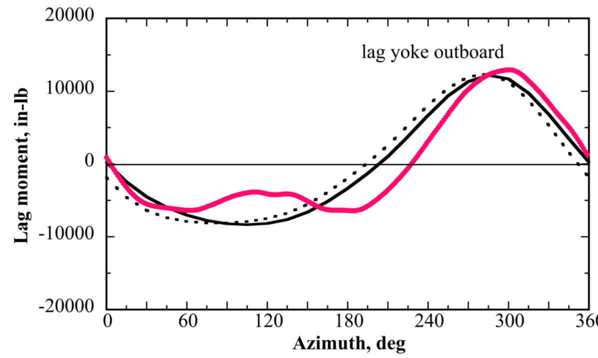


(a) Yoke inboard



(b) Yoke outboard

Figure 22. Yoke flap moment time histories, conversion mode, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.



(b) Yoke outboard (lag)

Figure 23. Yoke lag moment time histories, conversion mode, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.

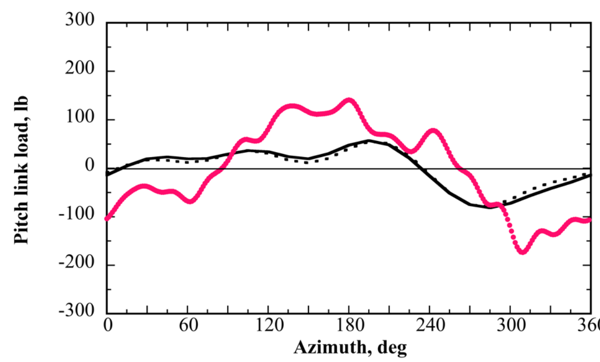
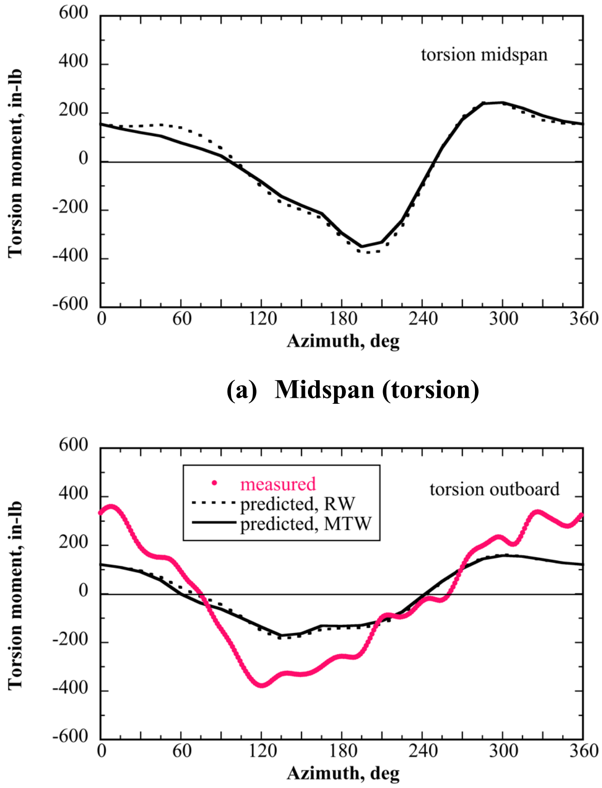


Figure 24. Pitch link load time history, conversion mode, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Midspan (torsion)

(b) Outboard (torsion)

Figure 25. Torsion moment time histories, conversion mode, 45-deg yaw, Ω=568, V=92 knots, μ=0.20, C_T/σ =0.080.

The 45-deg (Case II) conversion correlation is summarized as follows. The mean and hpp correlations (Figures 14-19) and the loads time-history correlations (Figures 20-25) show that:

- The results are not sensitive to the wake model.
- The trim control angles are predicted reasonably well.
- The blade and yoke flap bending moments are overpredicted.
- The predicted blade and yoke lag bending moments are reasonable except that the 2P lag moment is not picked up by the analysis. This 2P component is addressed later in detail in the torque correlation section (that appears after the Case V 90-deg helicopter mode results section).
- The pitch link load and torsion moment are underpredicted.
- The analysis captures the basic 1P azimuthal shape (and phase) of the loads.

The limitations of the present analytical model have been noted in the last paragraph of the 30-deg (Case I) results section; this caveat is applicable to the above 45-deg (Case II) results. Currently, it is believed that the presence of the strong 2P component in the lag moment is due to blade dissimilarity (and possibly due to nonuniformity in the flow field caused by the wind tunnel walls). This is discussed later under torque correlation.

Case III. Conversion Mode, 60-deg yaw

The operating condition for this case is: 60-deg yaw, Ω=566 rpm, V=92 knots, μ=0.20, and C_T/σ=0.080.

60-deg mean and hpp correlation. The correlation for the mean quantities is shown in Figures 26-27 and the hpp correlation is shown in Figures 28-31. The torque is shown in Figure 26 and the trim controls are shown in Figure 27. The hpp blade (and yoke) flap and lag moment correlations are shown in Figures 28-29, respectively. The hpp pitch link load correlation is shown in Figure 30 and the hpp blade torsion moment correlation is shown in Figure 31.

Specific observations are as follows. The torque is predicted well by the MTW model (Figure 26). All three trim control angles are predicted reasonably well (Figure 27). The blade flap moment prediction is reasonable, with the yoke flap moment overpredicted (Figure 28). The lag moments are underpredicted (Figure 29). The pitch link load and torsion moment are underpredicted (Figures 30-31, respectively). On wake models, it does not seem that MTW does consistently better than RW; they are comparable at this 60-deg angle.

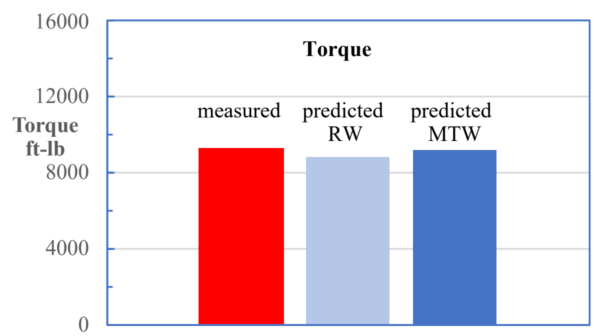
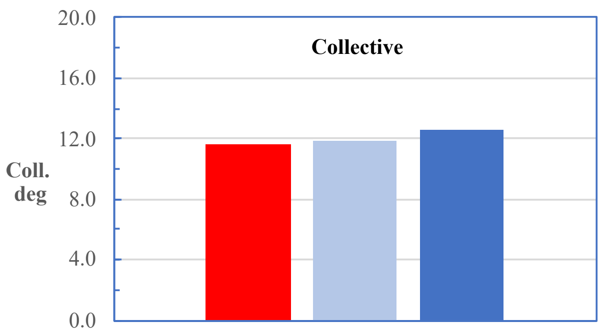
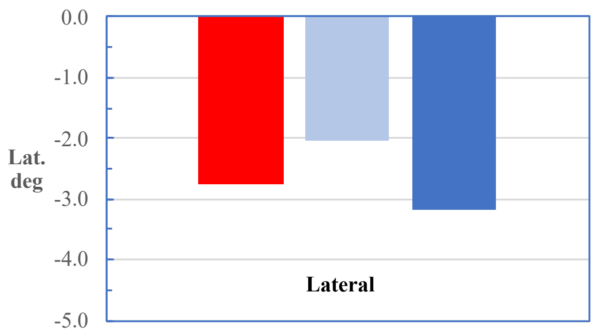


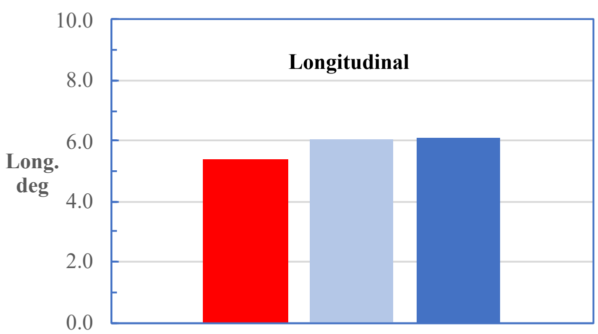
Figure 26. Measured and predicted torque, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Collective

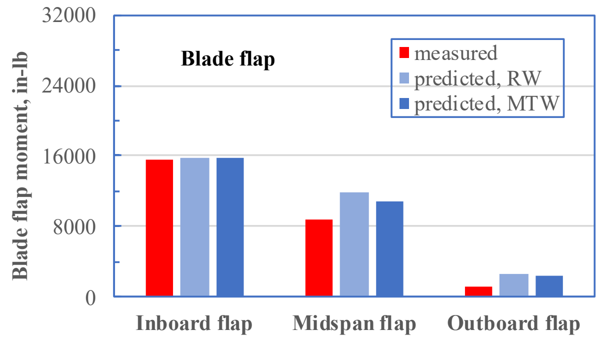


(b) Lateral cyclic

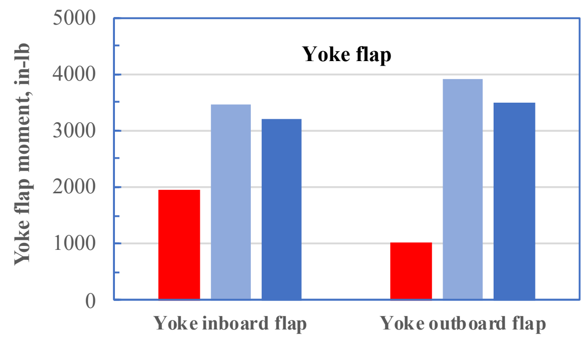


(c) Longitudinal cyclic

Figure 27. Measured and predicted control angles, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.

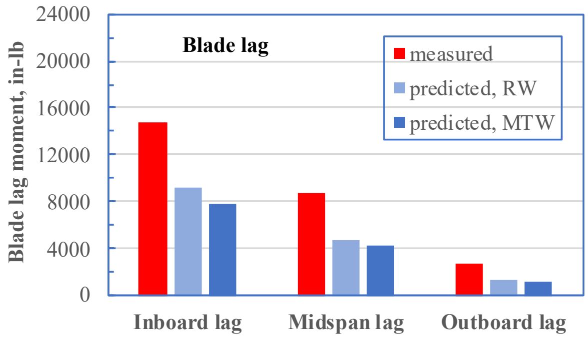


(a) Blade moments

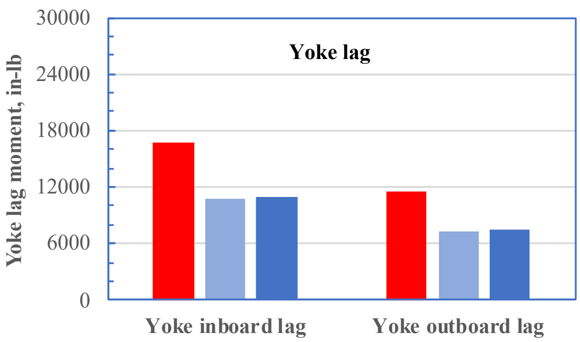


(b) Yoke moments

Figure 28. Measured and predicted blade and yoke hpp flap moments, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Blade moments



(b) Yoke moments

Figure 29. Measured and predicted blade and yoke hpp lag moments, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.

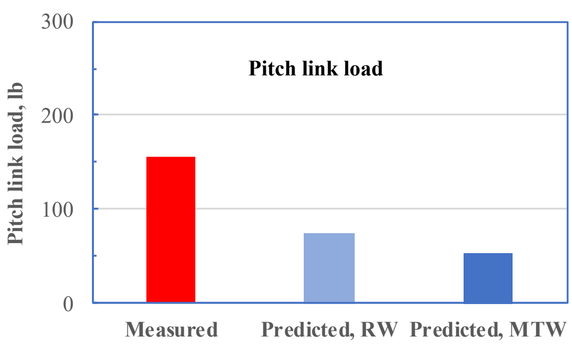


Figure 30. Measured and predicted hpp pitch link load, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.

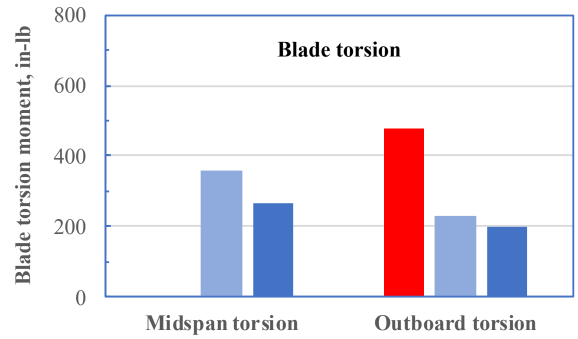
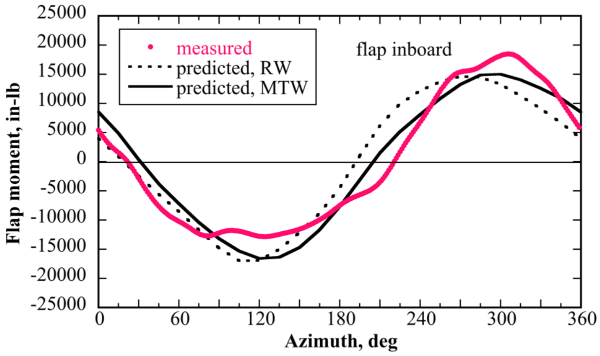


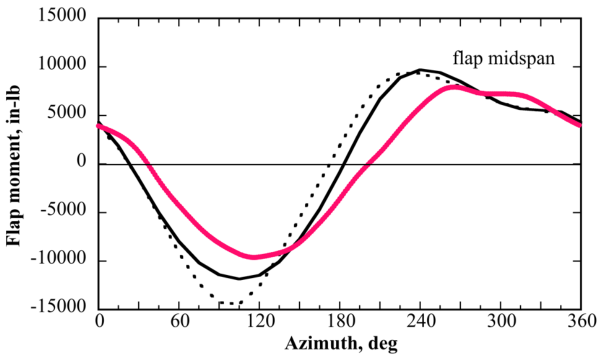
Figure 31. Measured and predicted hpp torsion moments, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.

60-deg time-history correlation. Figures 32-35 show the time-history correlations for the blade and yoke bending moments. Figure 36 shows the pitch link load correlation and Figure 37 shows the blade torsion moments. These are consistent with Figures 28-31.

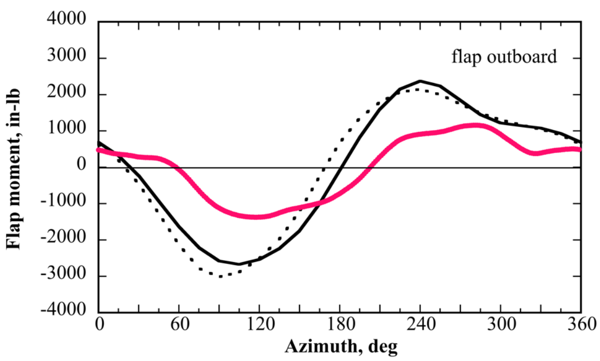
Specific observations are as follows. The test blade flap loads have mostly 1P variation, with higher frequency content of relatively small magnitude also present in the yoke flap moment and the pitch link load (Figures 34 and 36, respectively). The basic 1P shape (and phase) for the flap moments is captured by the analysis (Figures 32 and 34). The test lag moment shows the characteristic, large 2P variation (Figures 33 and 35); this has been observed earlier also at 45-deg (Figures 21 and 23). Relatively, the 60-deg 2P lag moment is larger than the 45-deg 2P lag moment. The current analysis, which assumes identical blades, does not capture the 2P lag moment (discussed later under torque correlation). The lag moment is underpredicted (Figures 33 and 35). On wake models, it does not seem that MTW does consistently better than RW; they are comparable at this 60-deg angle.



(a) Inboard

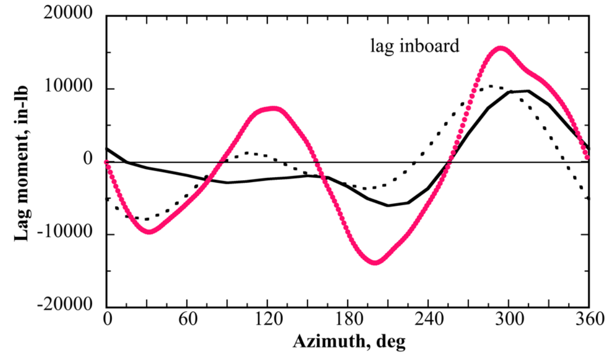


(b) Midspan

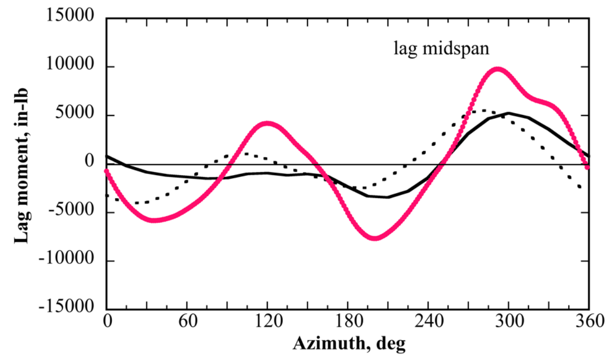


(c) Outboard

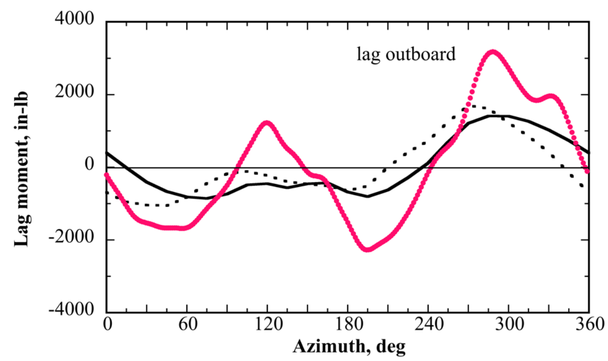
Figure 32. Blade flap moment time histories, conversion mode, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Inboard

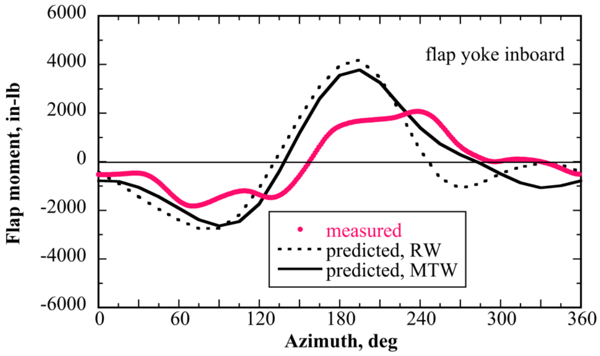


(b) Midspan

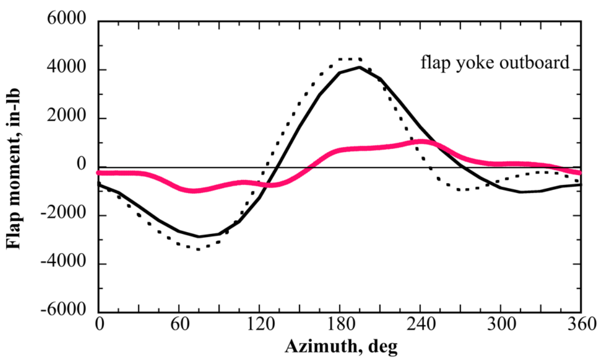


(c) Outboard

Figure 33. Blade lag moment time histories, conversion mode, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.

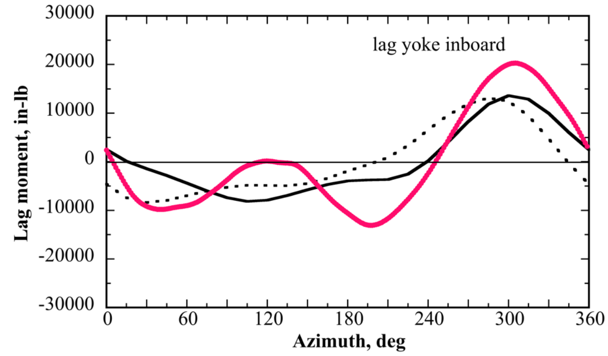


(a) Yoke inboard

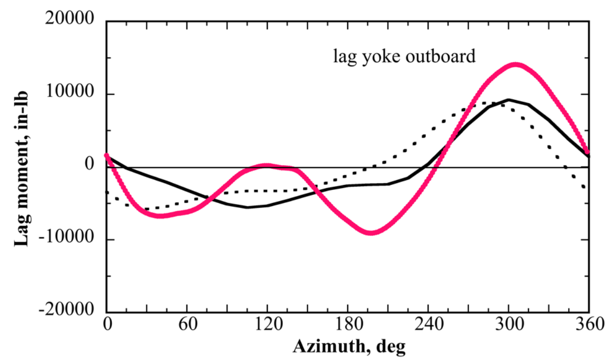


(b) Yoke outboard

Figure 34. Yoke flap moment time histories, conversion mode, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.



(a) Yoke inboard



(b) Yoke outboard (lag)

Figure 35. Yoke lag moment time histories, conversion mode, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.

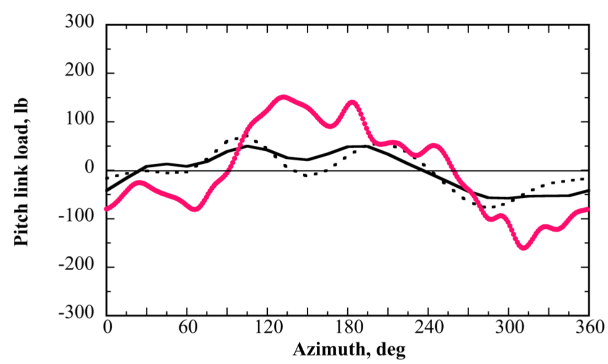
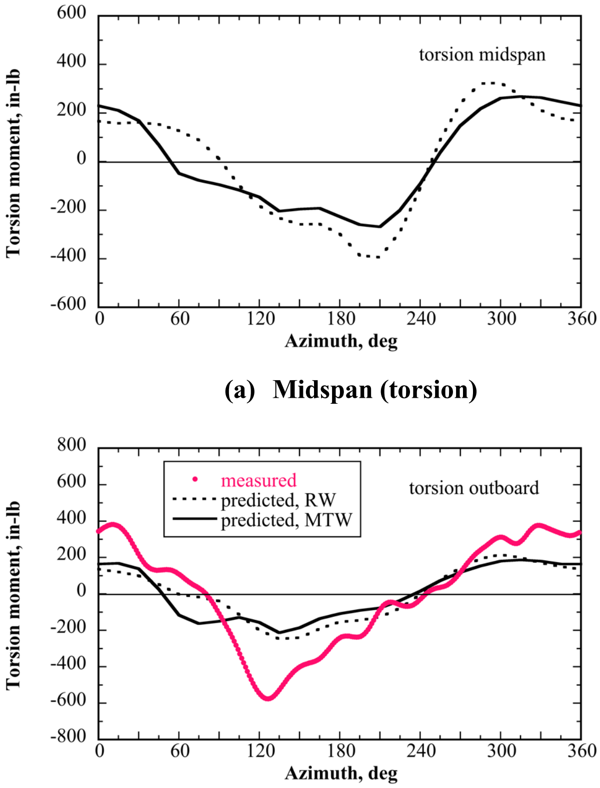


Figure 36. Pitch link load time history, conversion mode, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ=0.080.



(a) Midspan (torsion)

(b) Outboard (torsion)

Figure 37. Torsion moment time histories, conversion mode, 60-deg yaw, Ω=566, V=92 knots, μ=0.20, C_T/σ =0.080.

The 60-deg (Case III) conversion correlation is summarized as follows. The mean and hpp correlations (Figures 26-31) and the loads time-history correlations (Figures 32-37) show that:

- On wake models, it does not seem that MTW does consistently better than RW; they are comparable at this condition.
- The trim control angles are predicted reasonably well.
- The blade flap moment prediction is reasonable, with the yoke flap moment overpredicted.
- The lag moments are underpredicted. The 2P lag moment is not picked up by the analysis (addressed later in detail in the torque correlation section).
- The pitch link load and torsion moment are underpredicted.
- The analysis roughly captures the basic 1P azimuthal shape (and phase) of the flap loads.

The limitations of the present analytical model have been noted in the last paragraph of the 30-deg (Case I) results section and further expanded in the last paragraph of the 45-deg (Case II) results section; these caveats, which include the assumption of identical blades, are applicable to the above 60-deg (Case III) results; the 2P component is discussed later under torque correlation.

Case IV. Helicopter Mode, 75-deg yaw

The operating condition for this case is: 75-deg yaw, Ω=573 rpm, V=70 knots, μ=0.15, and C_T/σ=0.081.

75-deg mean and hpp correlation. The correlation for the mean quantities is shown in Figures 38-39 and the hpp correlation is shown in Figures 40-43. The torque is shown in Figure 38 and the trim controls are shown in Figure 39. The hpp blade (and yoke) flap and lag moment correlations are shown in Figures 40-41, respectively. The hpp pitch link load correlation is shown in Figure 42 and the hpp blade torsion moment correlation is shown in Figure 43.

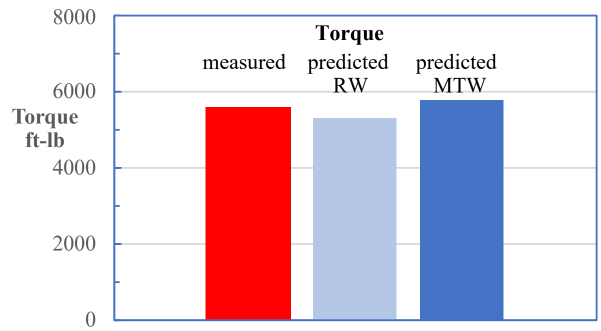
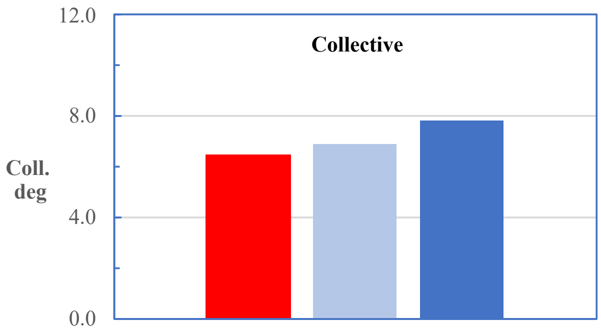
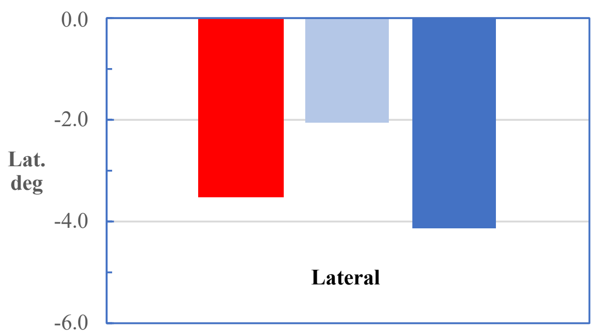


Figure 38. Measured and predicted torque, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.

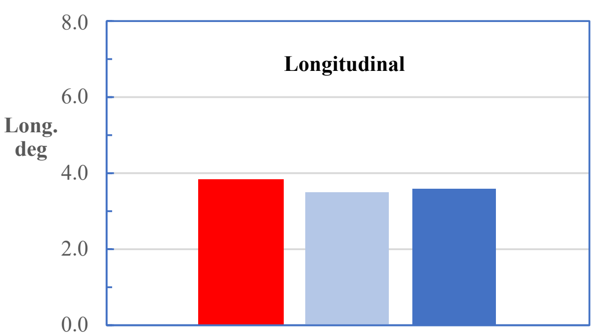
Specific observations are as follows. The torque is slightly underpredicted by the RW model but overpredicted by the MTW model (Figure 38). The trim control angles are predicted reasonably well (Figure 39). The blade flap moment correlations are reasonable, and the inboard yoke flap moment is predicted well (Figure 40). The lag moment is underpredicted, with MTW improving the correlation slightly (Figure 41). The pitch link load and torsion moment are underpredicted (Figures 42-43, respectively).



(a) Collective

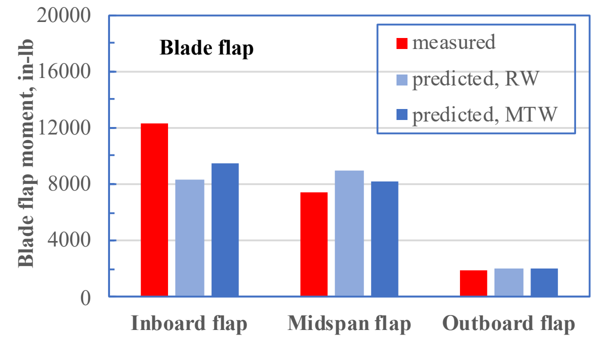


(b) Lateral cyclic

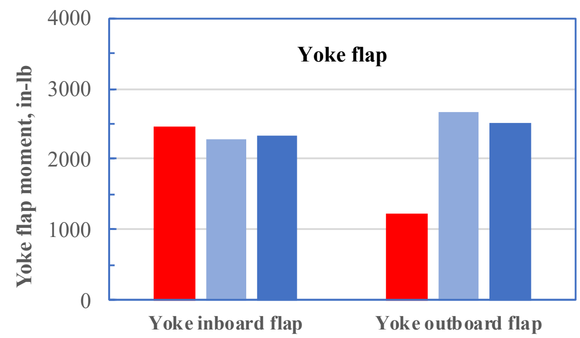


(c) Longitudinal cyclic

Figure 39. Measured and predicted control angles, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.

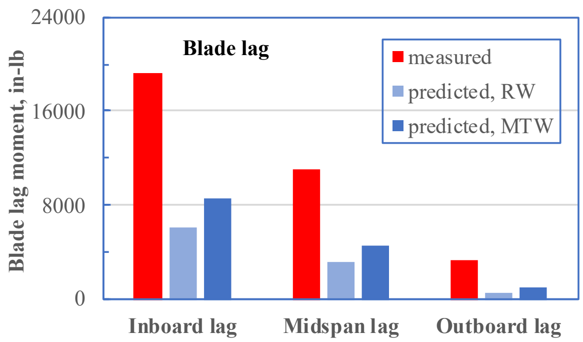


(a) Blade moments

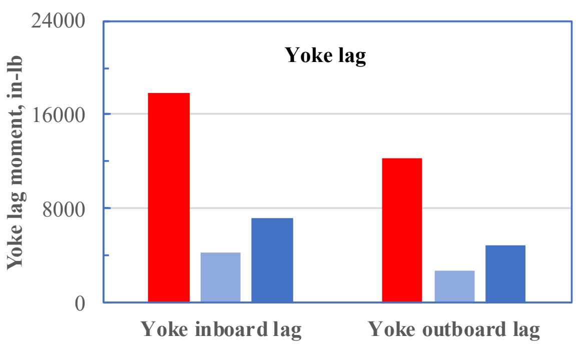


(b) Yoke moments

Figure 40. Measured and predicted blade and yoke hpp flap moments, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.



(a) Blade moments



(b) Yoke moments

Figure 41. Measured and predicted blade and yoke hpp lag moments, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.

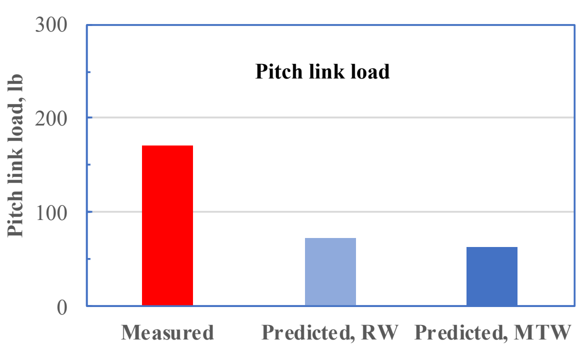


Figure 42. Measured and predicted hpp pitch link load, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.

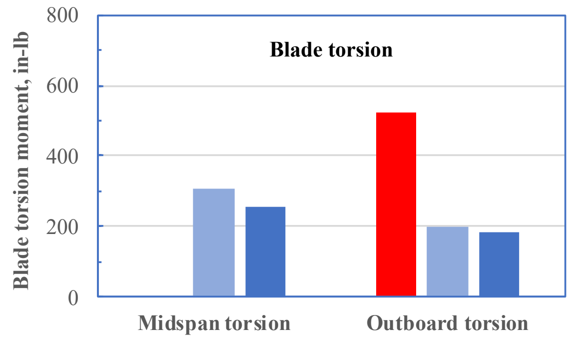
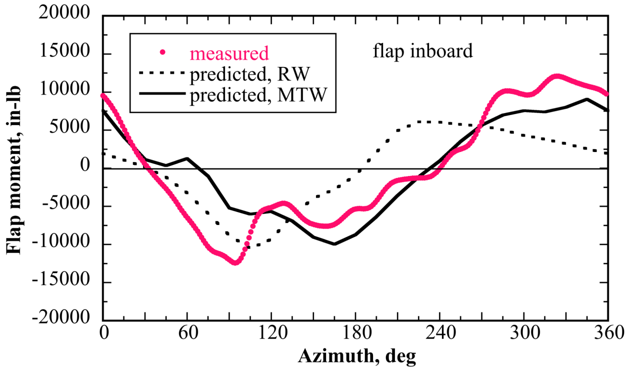


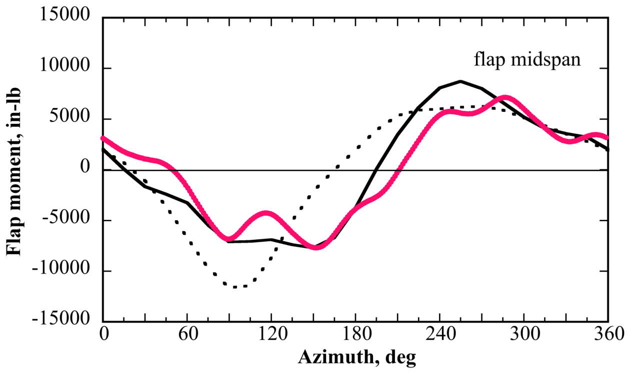
Figure 43. Measured and predicted hpp torsion moments, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.

75-deg time-history correlation. Figures 44-47 show the time-history correlations for the blade and yoke bending moments. Figure 48 shows the pitch link load correlation and Figure 49 shows the blade torsion moments. These are consistent with Figures 40-43.

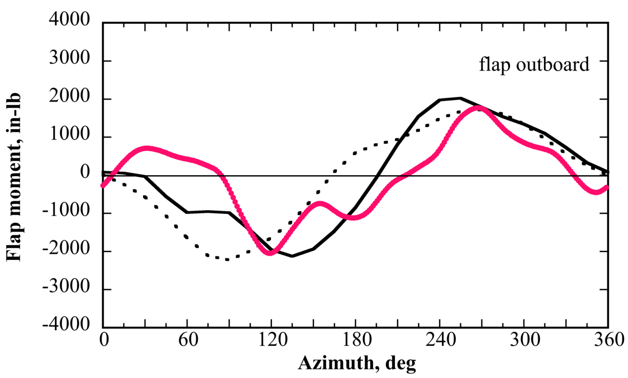
Specific observations are as follows. The blade and yoke flap moment correlations are reasonable to good, with the phase and magnitude being captured better by the MTW model (Figures 44 and 46). As an example of the differing predictions resulting from the RW and MTW models, it can be seen from Figure 46a that the predicted RW and MTW peaks for the yoke flap inboard moment differ by almost 60-deg (195-deg vs. 255-deg, respectively). The blade and yoke lag moments are underpredicted with the MTW model improving the phase correlation (Figures 45 and 47). Similar to the 45-deg and 60-deg correlations (Figures 21, 23, 33, 35), the current analysis, which assumes identical blades, does not capture the 2P lag moment (Figures 45 and 47). This is discussed later under torque correlation. The analysis picks up some of the higher frequency content in the pitch link load time-history, with the magnitude underpredicted (Figure 48). The torsion moment correlation is poor and needs further study (the excursion between 90-deg and 180-deg azimuth is not captured at all, Figure 49b).



(a) Inboard

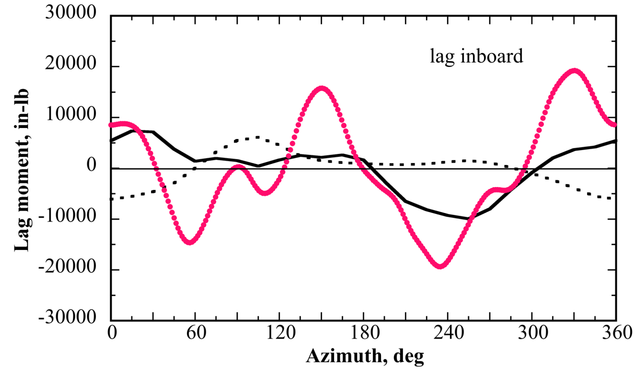


(b) Midspan

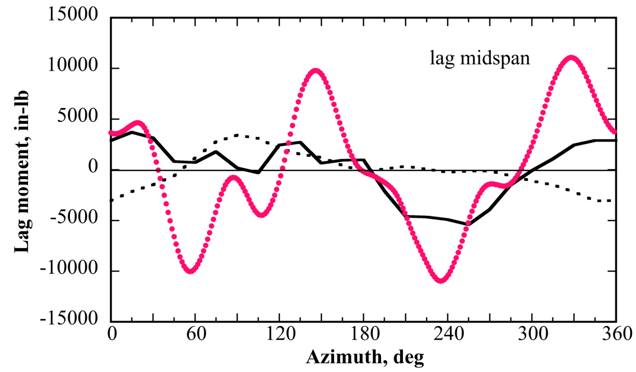


(c) Outboard

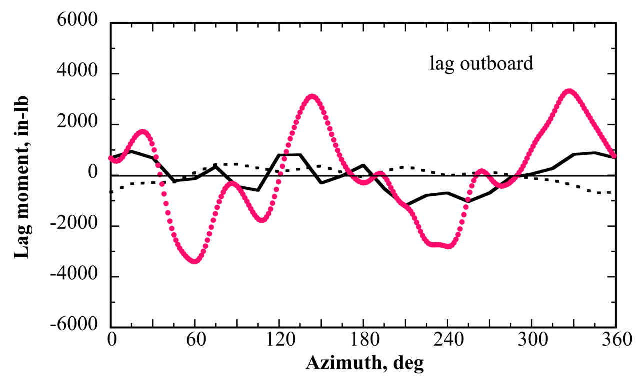
Figure 44. Blade flap moment time histories, helicopter mode, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081



(a) Inboard

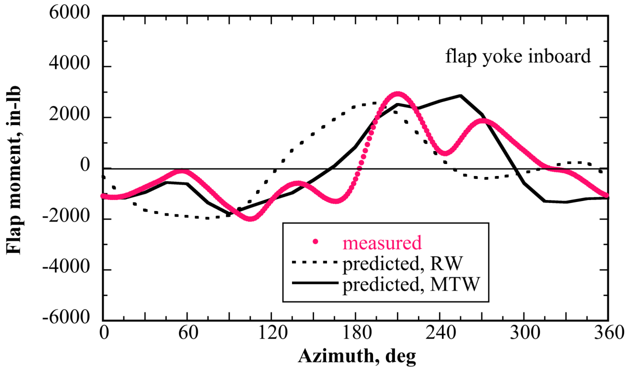


(b) Midspan

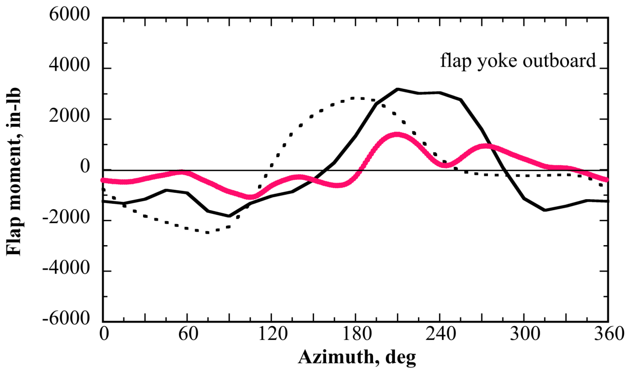


(c) Outboard

Figure 45. Blade lag moment time histories, helicopter mode, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.

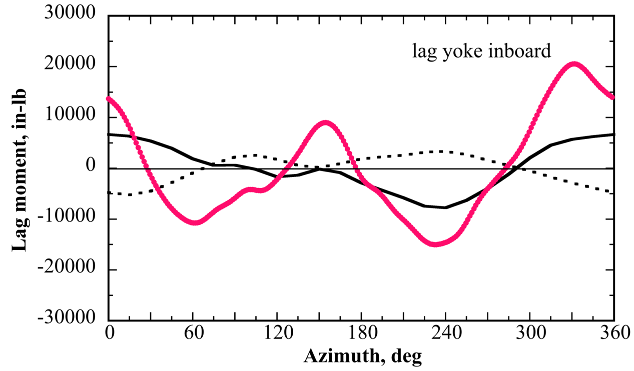


(a) Yoke inboard

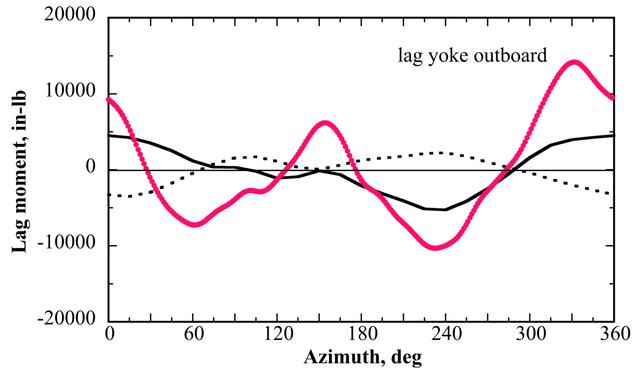


(b) Yoke outboard

Figure 46. Yoke flap moment time histories, helicopter mode, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.



(a) Yoke inboard



(b) Yoke outboard (lag)

Figure 47. Yoke lag moment time histories, helicopter mode, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.

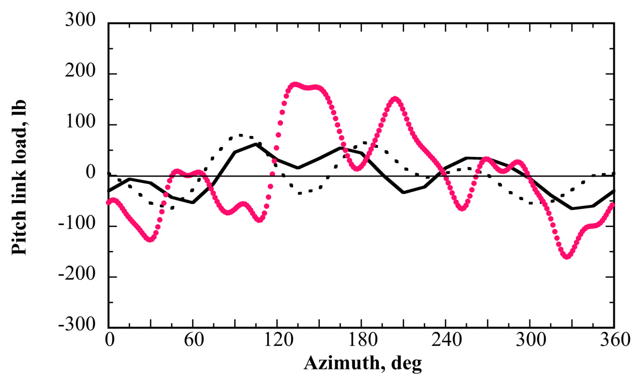
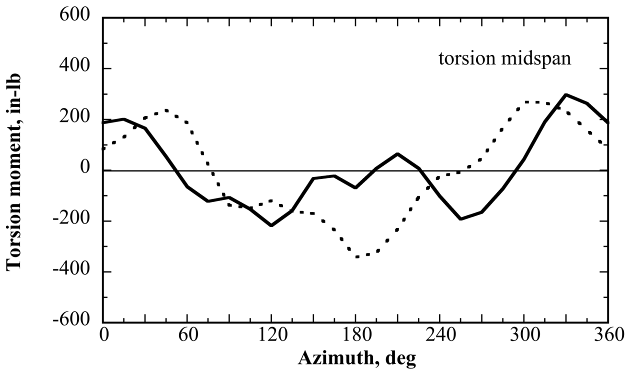
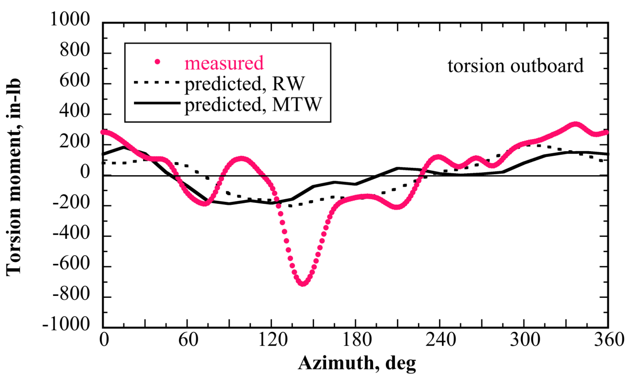


Figure 48. Pitch link load time history, helicopter mode, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.



(a) Midspan (torsion)



(b) Outboard (torsion)

Figure 49. Torsion moment time histories, helicopter mode, 75-deg yaw, Ω=573, V=70 knots, μ=0.15, C_T/σ =0.081.

The 75-deg (Case IV) helicopter correlation is summarized as follows. The mean and hpp correlations (Figures 38-43) and the loads time-history correlations (Figures 44-49) show that:

- The MTW multiple-trailer wake model improves the correlation slightly. At 75-deg yaw (μ=0.15, C_T/σ =0.081), the wake is close enough to the rotor disk for the MTW model to be preferable (instead of the simpler RW model).
- The trim control angles are predicted reasonably well.
- The flap moment predictions are reasonable to good.
- The lag moments are underpredicted. The 2P lag moment is not picked up by the analysis (addressed later in detail in the torque correlation section).
- The pitch link load is underpredicted.
- The torsion moment correlation is poor and needs further study.

The limitations of the present analytical model have been noted earlier in the last paragraph of the 30-deg (Case I) correlation, further expanded in the last paragraph of the 45-deg correlation (Case II) and also noted in the last paragraph of the 60-deg (Case III) correlation, and are not repeated here. The 2P component is discussed later under torque correlation.

Case V. Helicopter Mode, 90-deg yaw

The operating condition for this case is: 90-deg yaw, Ω=567 rpm, V=57 knots, μ=0.13, and C_T/σ=0.080.

90-deg mean and hpp correlation. The correlation for the mean quantities is shown in Figures 50-51 and the hpp correlation is shown in Figures 52-55. The torque is shown in Figure 50 and the trim controls are shown in Figure 51. The hpp blade (and yoke) flap and lag moment correlations are shown in Figures 52-53, respectively. The hpp pitch link load correlation is shown in Figure 54 and the hpp blade torsion moment correlation is shown in Figure 55.

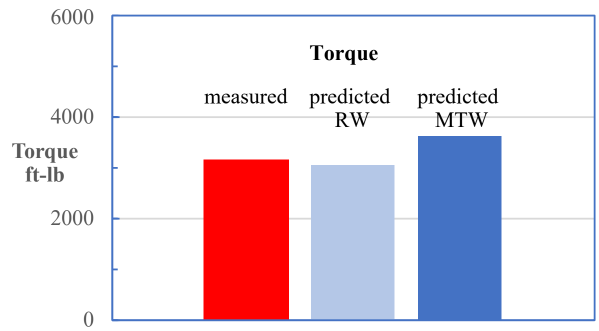
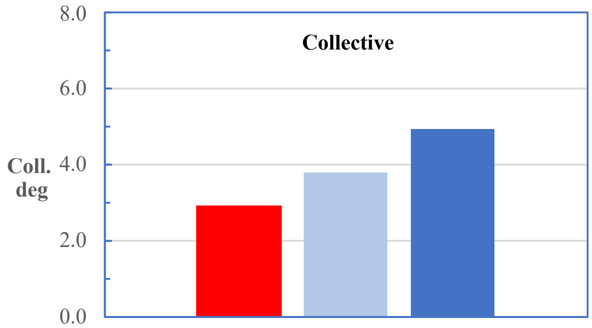
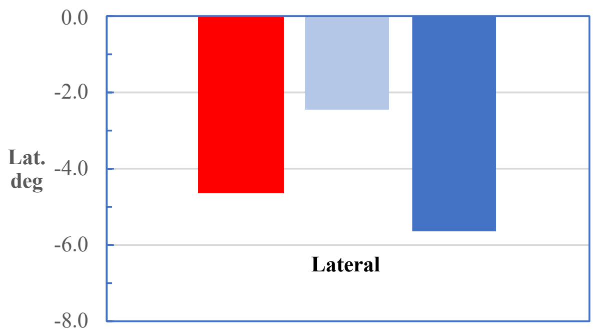


Figure 50. Measured and predicted torque, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.

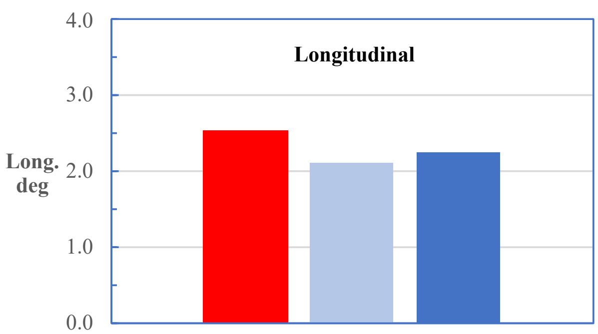
Specific observations are as follows. The torque is slightly underpredicted by the RW model but overpredicted by the MTW model (Figure 50). The trim control angles are not predicted well (Figure 51). The blade flap moment correlation is reasonable, and the yoke flap moment is not predicted well (Figure 52). The lag moment is underpredicted, with MTW improving the correlation slightly (Figure 53). The pitch link load and torsion moment are underpredicted (Figures 54-55, respectively).



(a) Collective

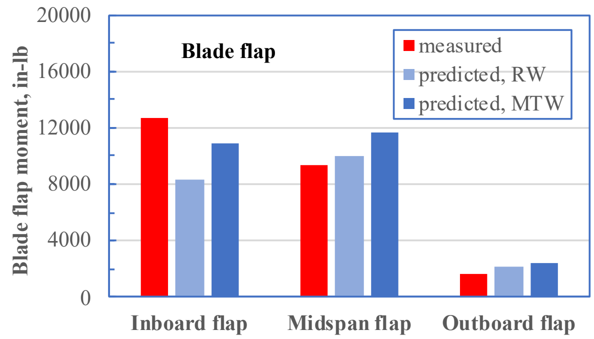


(b) Lateral cyclic

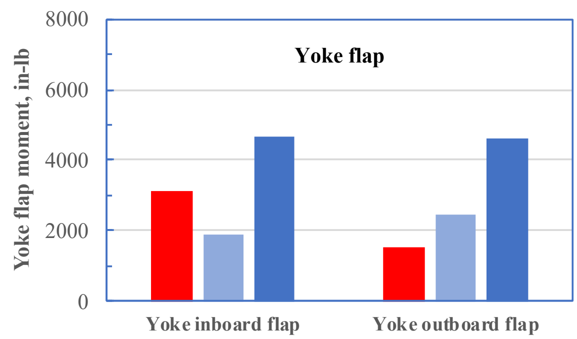


(c) Longitudinal cyclic

Figure 51. Measured and predicted control angles, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.

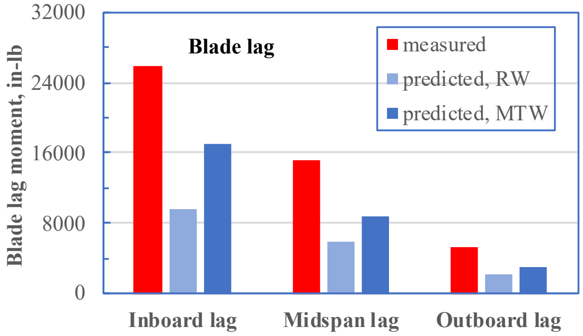


(a) Blade moments

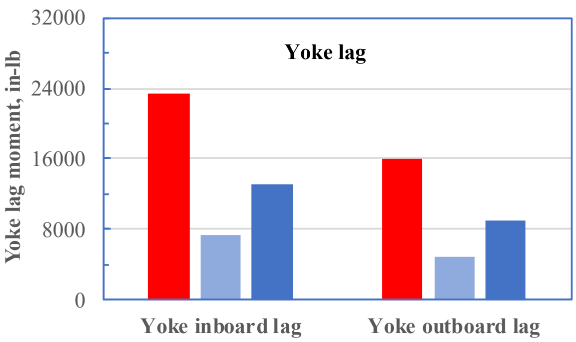


(b) Yoke moments

Figure 52. Measured and predicted blade and yoke hpp flap moments, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.



(a) Blade moments



(b) Yoke moments

Figure 53. Measured and predicted blade and yoke hpp lag moments, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.

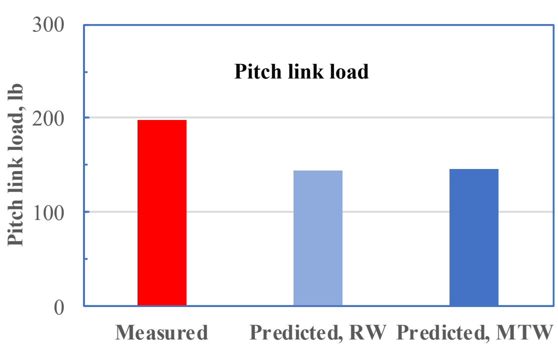


Figure 54. Measured and predicted hpp pitch link load, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.

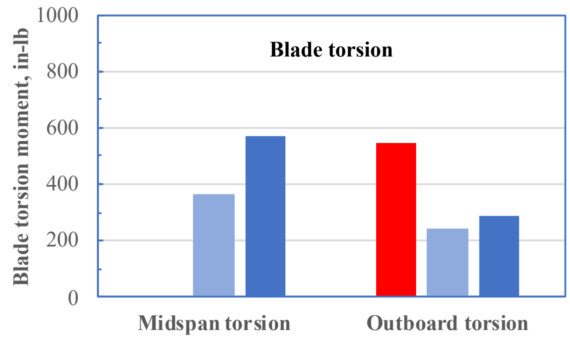
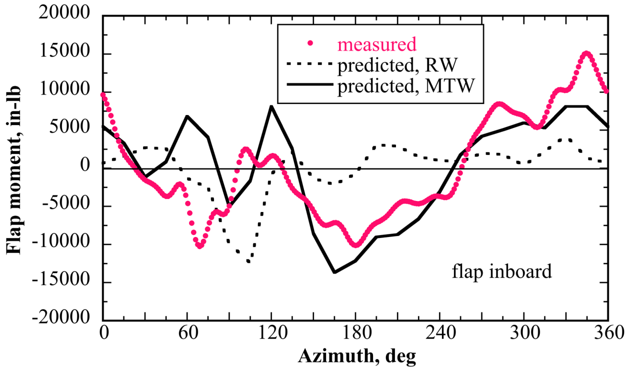


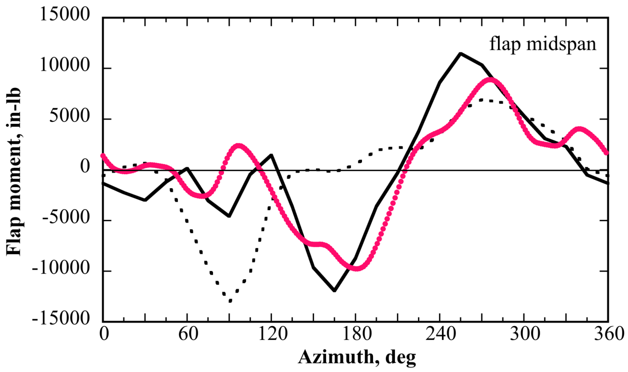
Figure 55. Measured and predicted hpp torsion moments, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.

90-deg time-history correlation. Figures 56-59 show the time-history correlations for the blade and yoke bending moments. Figure 60 shows the pitch link load correlation and Figure 61 shows the blade torsion moments. These are consistent with Figures 52-55.

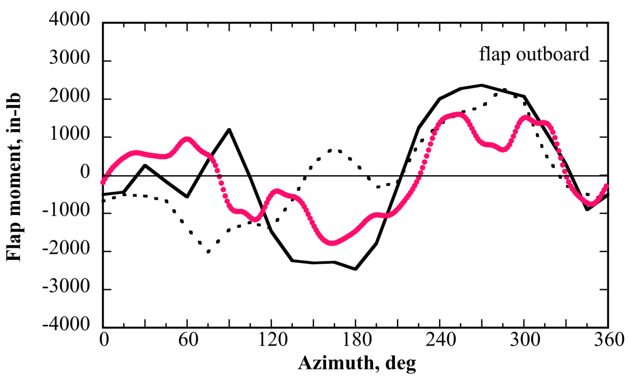
Specific observations are as follows. The blade and inboard yoke flap moment correlations are reasonable to good, with the phase and magnitude being captured better by the MTW model (Figures 56 and 58). The blade and yoke lag moments are underpredicted with the MTW model improving the phase correlation (Figures 57 and 59). Unlike the 45-deg, 60-deg, and 75-deg conditions (Figures 21, 23, 33, 35, 45, 47) where the test 2P lag component was strong and not picked up by the analysis, the analysis does a bit better at the current 90-deg condition in predicting the lag moments (Figures 57 and 59). This is discussed later under torque correlation. The analysis picks up some of the higher frequency content in the pitch link load time-history, with the magnitude underpredicted (Figure 60). The torsion moment correlation is poor (Figure 61). The MTW predictions are clearly better than the RW predictions.



(a) Inboard

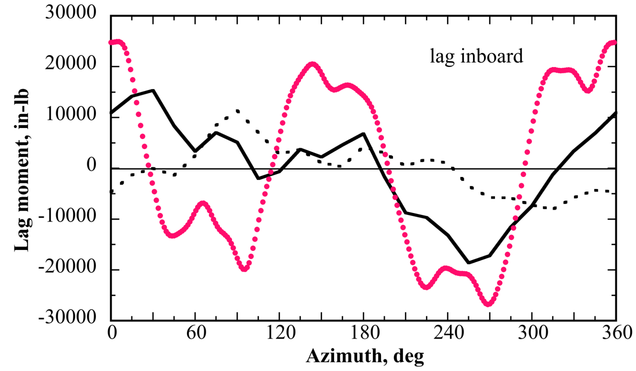


(b) Midspan

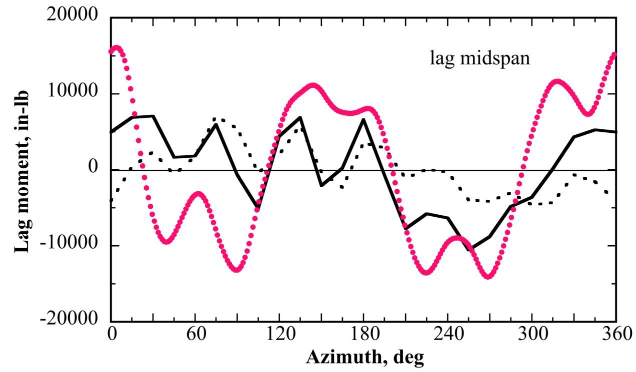


(c) Outboard

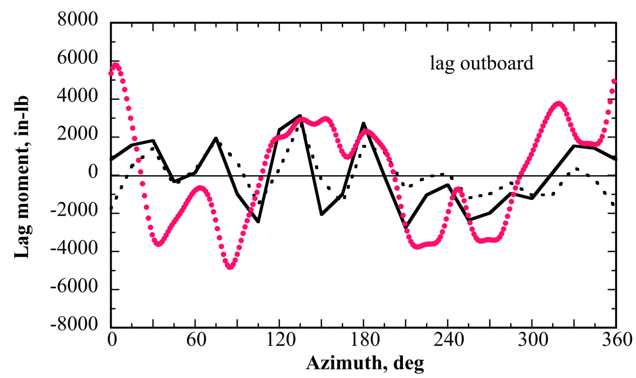
Figure 56. Blade flap moment time histories, helicopter mode, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.



(a) Inboard

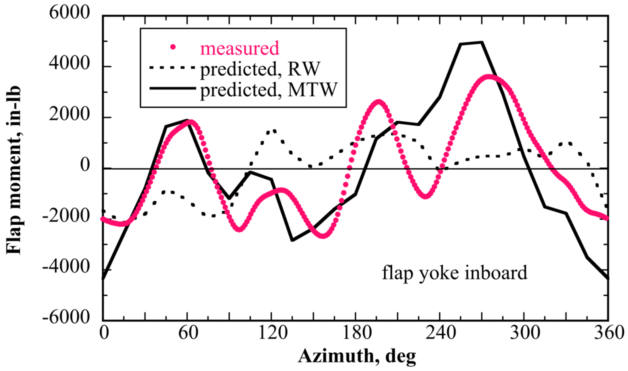


(b) Midspan

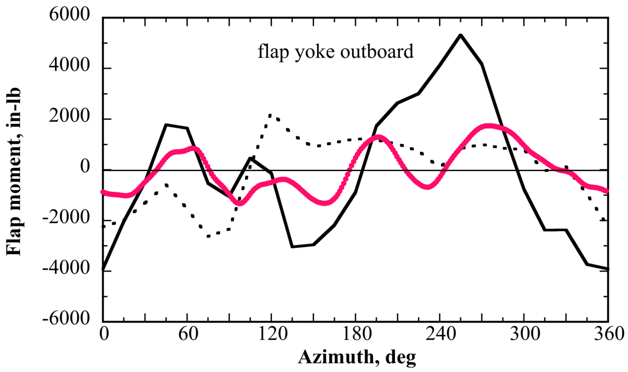


(c) Outboard

Figure 57. Blade lag moment time histories, helicopter mode, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.

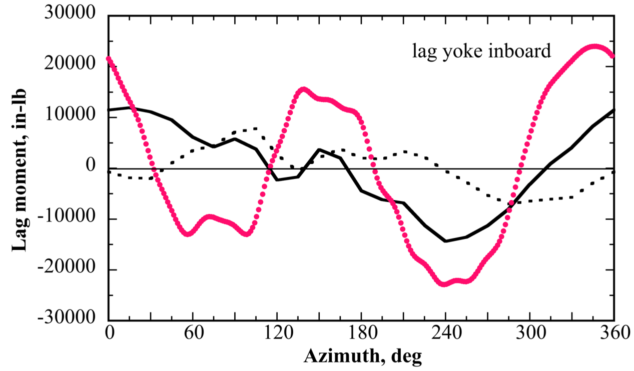


(a) Yoke inboard

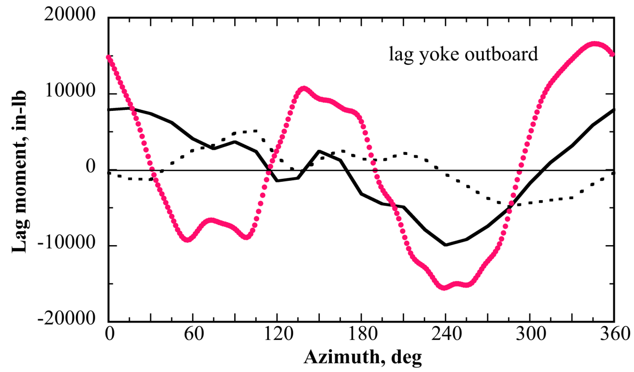


(b) Yoke outboard

Figure 58. Yoke flap moment time histories, helicopter mode, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.



(a) Yoke inboard



(b) Yoke outboard (lag)

Figure 59. Yoke lag moment time histories, helicopter mode, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.

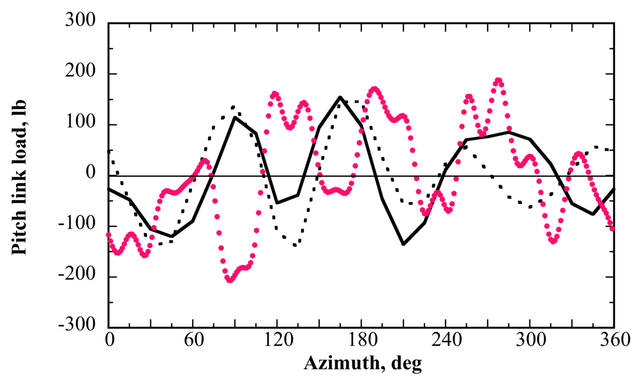
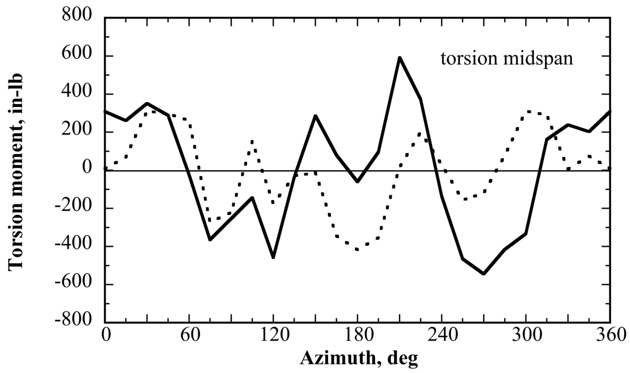
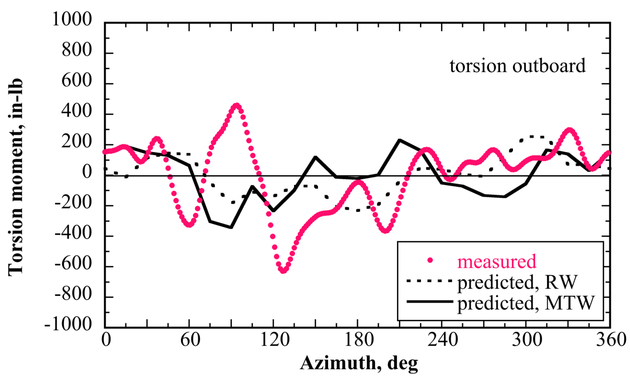


Figure 60. Pitch link load time history, helicopter mode, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.



(b) Midspan (torsion)



(c) Outboard (torsion)

Figure 61. Torsion moment time histories, helicopter mode, 90-deg yaw, Ω=567, V=57 knots, μ=0.13, C_T/σ =0.080.

The 90-deg (Case V) helicopter correlation is summarized as follows. The mean and hpp correlations (Figures 50-55) and the loads time-history correlations (Figures 56-61) show that:

- The MTW multiple-trailer wake model improves the correlation. At the current 90-deg yaw small advance ratio condition (μ=0.13, C_T/σ =0.080), the wake is close to the rotor disk and the MTW model is preferable (instead of the simpler RW model).
- The trim control angles are not predicted well.
- The flap moment predictions are reasonable to good.
- The lag moments are underpredicted. Compared to the 45-deg, 60-deg, and 75-deg correlations, the 90-deg lag moment predictions are better. This is further addressed in the torque correlation section in the context of the 2P lag moment seen at 45-deg, 60-deg and 75-deg angles.
- The pitch link load is underpredicted.
- The torsion moment correlation is poor.

The limitations of the present analytical model have been noted earlier in the last paragraphs of all correlations presented up to this point (30-deg to 75-deg, Cases I-IV), and are not repeated here. The 2P lag moment is discussed in the following section on the correlation of the harmonics and time-histories of the rotor torque.

Torque Correlation, Cases I - V (Full Yaw Range, 30-deg to 90-deg)

At 45-deg, 60-deg, 75-deg, and 90-deg yaw conditions (Cases II-V) a strong 2P component is present in the measured blade and yoke lag moments. The current analysis does not predict this 2P lag moment. This inability to predict the 2P lag moment was further investigated by looking at the measured rotor torque. It was observed that the measured torque itself also has a significant 2P component. This led to the present torque correlation study which considers not just the mean torque but also the torque harmonics and time-histories. The associated midspan lag moment time-histories are also shown to shed more light on the 2P issue.

For clarity, the predicted torque and midspan lag moments shown in this section are based on a single wake model, either RW or MTW, not both as in the previous sections. Results until now (Cases I-V) have shown that the RW model is adequate for the 30-deg and 45-deg yaw conversion conditions. Thus, in this section, the predictions at 30-deg and 45-deg are based on the RW model and at 60-deg, 75-deg, and 90-deg the predictions are based on the MTW model.

Mean torque correlation summary. For completeness, the mean torque correlation for the full operating range of yaw angles covering conversion and helicopter conditions, 30-deg to 90-deg, is summarized in Figure 62; all of these results have been presented earlier (Cases I-V). The correlation is considered satisfactory in the context of the current emphasis on loads (no attempt was made in this study to fine tune the analytical model in order to improve the prediction of torque).

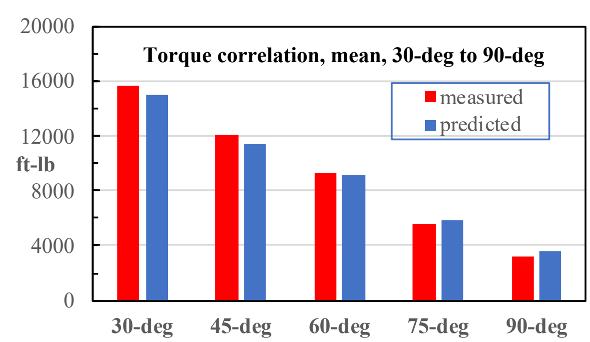


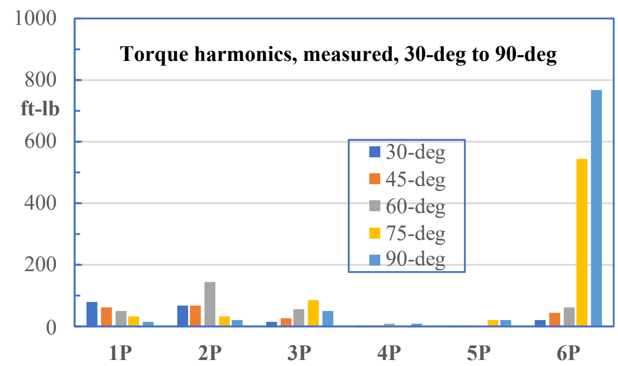
Figure 62. Measured and predicted mean torque, full yaw range (30-deg to 90-deg).

Torque harmonics correlation. Figures 63a-63b compare separately the measured and predicted harmonics of the rotor torque, respectively, for the full yaw range. The measured torque (Figure 63a) shows that in addition to the expected 3P and 6P components, the measured torque also has a 2P component whose largest value is at 60-deg yaw. In fact, in some cases, the test 2P component is larger than the test 3P component. There is also a 1P component in the test data. Further inspection of the test data showed that the conversion mode (30-deg to 60-deg) 1P torque is comparable to the cruise 0-deg yaw 1P torque (0-deg torque data is not shown here). This 1P component and some of the 2P component can be attributed to instrumentation on one of the blades, resulting in the blades being dissimilar. Currently, it is believed that the presence of the strong 2P component in the torque and lag moment is due to blade dissimilarity (and possibly due to nonuniformity in the flow field caused by the wind tunnel walls).

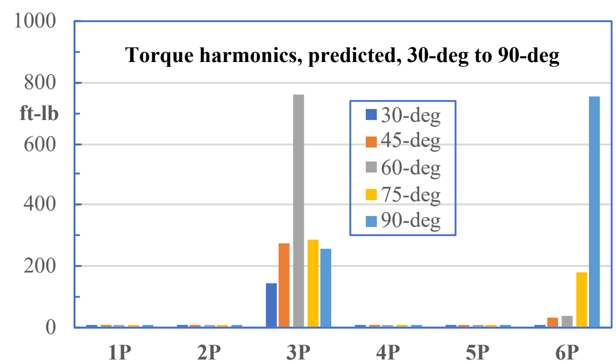
Since the analysis assumes identical blades, only the 3P and 6P torque show up in the predicted torque (Figure 63b). At 60-deg a very large predicted 3P torque is present. The 1P and 2P components are not captured by the current analytical model which assumes identical blades.

The measured and predicted 6P torques show a similar trend with yaw angle; the 6P torque increases as the rotor transitions from conversion to helicopter mode (30-deg to 90-deg, Figures 63a-63b). The largest 6P torque is at 90-deg, with the measured and predicted 6P torques having almost the same magnitude. Also, at 90-deg, the test 1P and 2P torques are relatively small compared to the 6P torque.

Figures 64a-64b show torque harmonics correlation at the two helicopter conditions, 75-deg and 90-deg yaw (the test data and predictions in these figures are the same as in Figures 63a-63b). The best correlation is at 90-deg (Figure 64b), with the measured and predicted 6P components having almost the same magnitude; for both helicopter conditions the 3P torque is overpredicted. The test 1P and 2P components are small compared to the 3P and 6P components. As can also be seen in the following section on time-history correlation, these two factors (similar 6P and small 1P/2P torques) make the 90-deg torque correlation to be the best (the midspan lag moment is also captured reasonably well at 90-deg).

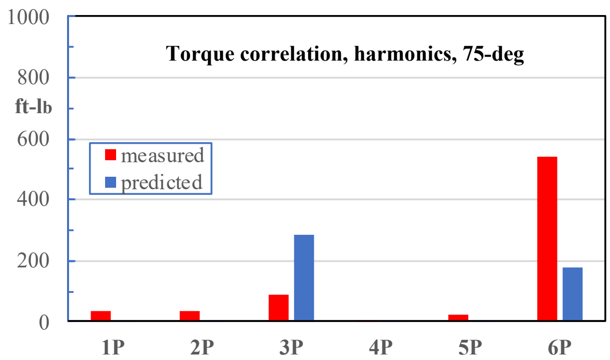


(a) Measured harmonics of torque

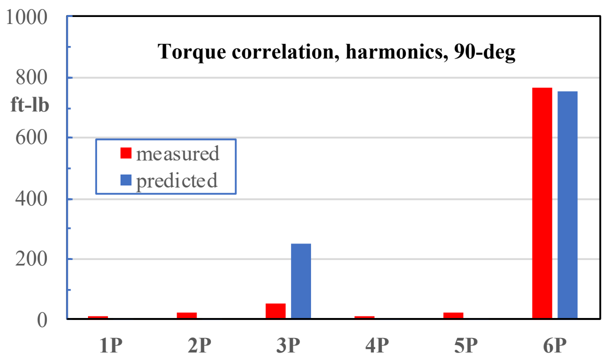


(b) Predicted harmonics of torque

Figure 63. Measured and predicted harmonics of torque, full yaw range (30-deg to 90-deg).



(a) 75-deg, helicopter

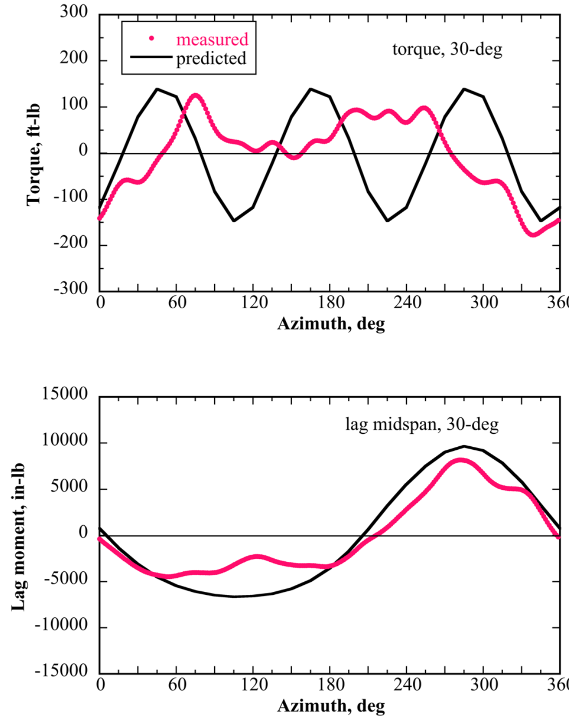


(b) 90-deg, helicopter

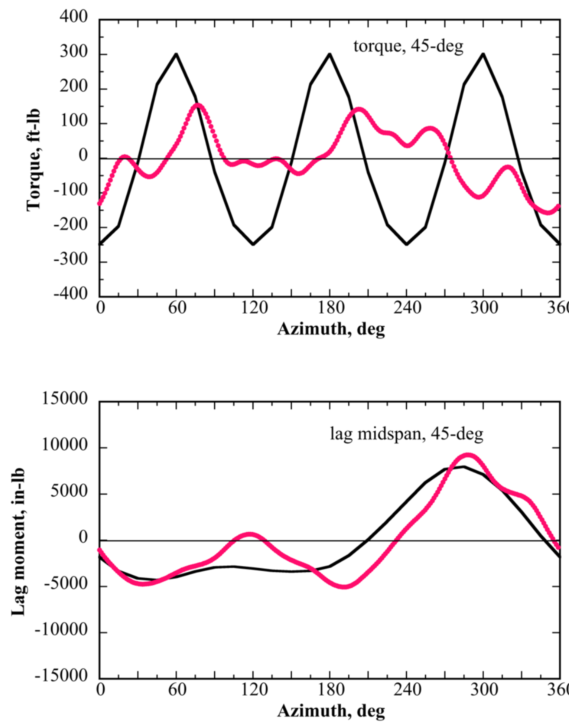
Figure 64. Correlation of torque harmonics, helicopter mode, 75-deg and 90-deg yaw.

Torque time-history correlation. Figures 65a-65c show the conversion mode time-history correlations for the torque and midspan lag moment (30-deg, 45-deg, and 60-deg). Figures 66a-66b show the corresponding helicopter mode time-history correlations (75-deg and 90-deg). The midspan lag moments shown in this section are the same as those presented earlier in the correlations for Cases I-V.

Figures 65a-65c show that the conversion torque is poorly predicted. As can be seen from Figures 63a-63b, the test torque has significant 1P and 2P components which the analysis in its present form (identical blades assumed) just cannot capture – hence the poor correlation. At 60-deg, the test torque and midspan lag moment have the largest 2P components (Figures 63a and 65c). Figures 66a-66b show that not only the helicopter mode torque is predicted discernibly better than the conversion torque, but that the lag moment prediction has also improved, especially for the 90-deg condition (Figure 66b) where the torque correlation is the best (due to similar measured and predicted 6P magnitudes and relatively small test 1P and 2P magnitudes); the midspan lag moment is also predicted reasonably well (though underpredicted, Figure 66b).

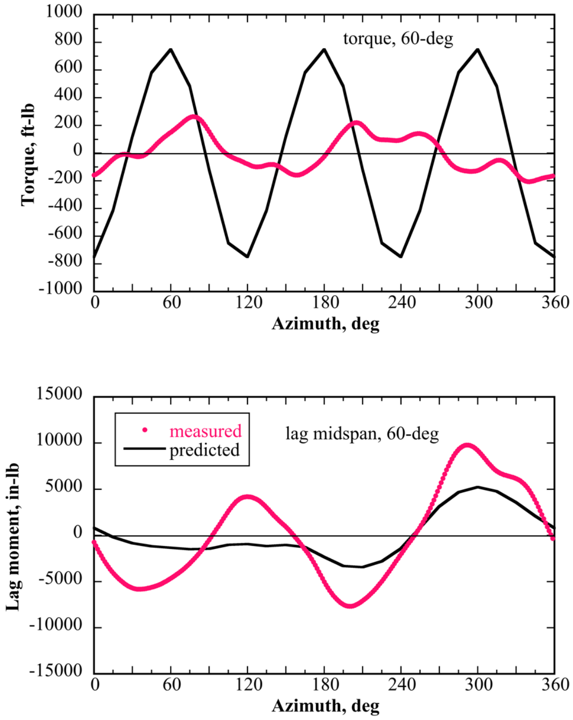


(a) 30-deg conversion, torque and midspan lag moment (see Figure 9b).



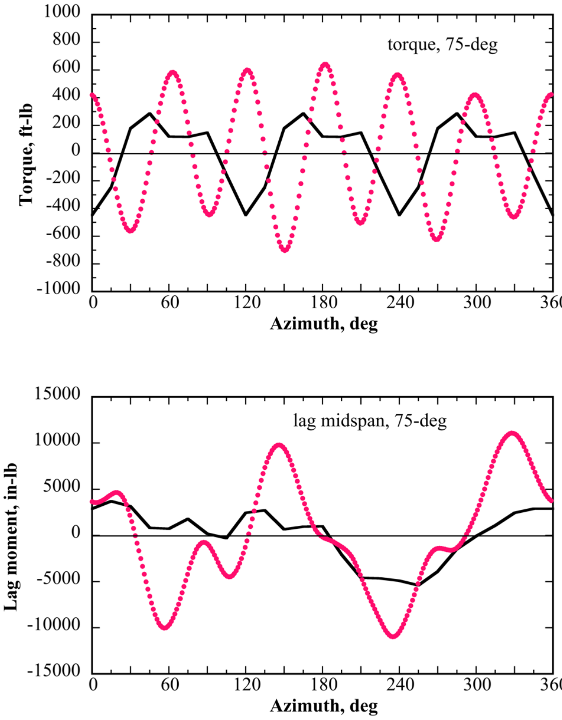
(b) 45-deg conversion, torque and midspan lag moment (see Figure 21b).

Figures 65a-b. Torque and midspan lag moment time-histories, conversion mode, 30-deg and 45-deg yaw.

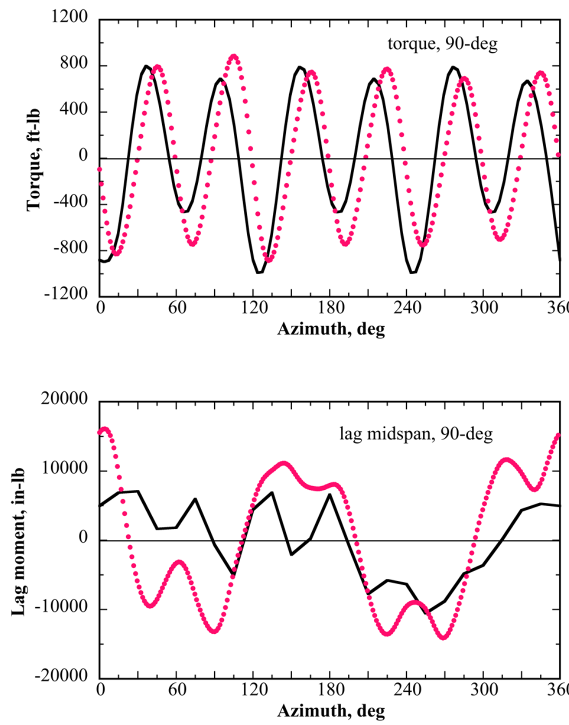


(c) 60-deg conversion, torque and midspan lag moment (see Figure 33b).

Figure 65c. Torque and midspan lag moment time-histories, conversion mode, 60-deg yaw.



(a) 75-deg helicopter, torque and midspan lag moment (see Figure 45b).



(b) 90-deg helicopter, torque and midspan lag moment (see Figure 57b).

Figure 66. Torque and midspan lag moment time-histories, helicopter mode, 75-deg and 90-deg yaw.

The torque correlation is summarized as follows. Figures 62-66 show that:

- For current purposes where the emphasis is on the prediction of loads, the mean torque prediction is considered to be reasonable over the full yaw range.
- In addition to the expected 3P and 6P components, the test torque contains 1P and 2P components. The presence the 1P and 2P components is currently attributed to dissimilar blades (and possibly due to nonuniformity in the flow field caused by the wind tunnel walls).
- The test lag moment also has a 2P component which is associated with the 2P torque.
- The analysis has been performed for an ideal, constant-speed gimbal and identical blades. With these assumptions, only 3P and 6P torques show up in the predictions. The 1P and 2P components are not captured by the current analytical model which assumes identical blades.
- At the 90-deg helicopter mode condition where the measured and predicted 6P torques have roughly the same magnitude and the test 2P (and 1P) torques are small compared to the 6P torque, best correlation for the torque is obtained (the midspan lag moment is also predicted reasonably well, though with underprediction).
- At conversion conditions, the oscillatory torque is poorly correlated.

MAJOR FINDINGS

This analytical study on proprotor loads and torque covered the full operating range of rotor yaw angles from the conversion (transition) mode to the helicopter mode. The major findings are as follows:

1. For rotor wake models, at the conversion 30-deg and 45-deg conditions, the rolled-up wake (RW) model is adequate. At 60-deg, either the RW or the multiple-trailer (MTW) model could be used. At the helicopter mode 75-deg and 90-deg conditions, it is better to use the MTW model.
2. For analysis limitations and development, the 1P and 2P (1 /rev and 2/rev) torque components observed in the test data could not be captured by the current analytical model which assumes identical blades. The associated, strong 2P lag moment also could not be predicted. To analytically bring in the 1P and 2P components, additional analysis with dissimilar blades is needed; this could include special aerodynamic modeling of the instrumented blade to account for surface irregularities caused by the strain gages.

CONCLUDING REMARKS

Full-scale proprotor loads and torque were correlated in this analytical study. The full operating range of tiltrotor conversion was covered: conversion 30-, 45-, and 60-deg TTR yaw, and helicopter 75- and 90-deg TTR yaw. The airplane (cruise) condition was not included. The comprehensive analysis CAMRAD II was used. The test data were obtained from a wind tunnel test of the Bell 699 proprotor installed on the Tiltrotor Test Rig (TTR) in the USAF National Full-Scale Aerodynamics Complex (NFAC) 40- by 80-Foot Wind Tunnel at NASA Ames Research Center.

The predictions included mean, ½ peak-to-peak (hpp) quantities, harmonics, and time-histories. Rotor blade flap and lag bending moments, torsion moments and yoke (flexbeam) bending moments were correlated. Mean rotor torque, torque harmonics, and time-histories were also correlated. Aerodynamically, the CAMRAD II rolled-up (RW) and multiple-trailer wake (MTW) models were used.

Specific conclusions are as follows:

1. On wake models, the RW model is adequate at the 30-deg and 45-deg yaw conversion conditions. At 60-deg, either model could be used. At the 75-deg and 90-deg helicopter conditions it is better to use the MTW model.
2. The trim control angles (collective and cyclics) were predicted reasonably well, except for the 90-deg control angles which were not predicted well.
3. Flap moment correlation: The basic 1P (1/rev) azimuthal shape (and phase) was roughly captured (30-deg to 60-deg). For the blade, the 30-deg and 45-deg flap moments were overpredicted. The blade 60-deg, 75-deg, and 90-deg predictions were reasonable to good. For the yoke, the 30-deg, 45-deg, and 60-deg flap moments were overpredicted. The yoke 75-deg and 90-deg predictions were reasonable to good.
4. Lag moment correlation: The basic 1P azimuthal shape (and phase) was roughly captured (30-deg and 45-deg). The 30-deg blade and yoke lag moments were overpredicted. At 45-deg the blade and yoke lag moments were reasonably predicted except that the 2P lag moment was not captured (this is addressed under torque correlation, below). At 60-deg, 75-deg, and 90-deg the lag moment was underpredicted. At 60-deg and 75-deg, the 2P lag moment was not picked up by the analysis. The 90-deg lag moment correlation is considered to be reasonable.
5. The pitch link load and torsion moment were uniformly underpredicted. In particular, the 75-deg and 90-deg torsion moment predictions were poor.
6. Torque correlation: The mean torque correlation was reasonable for the full yaw range. The conversion torque harmonics and time-histories were poorly correlated. The 90-deg torque time-history correlation was the best. At all conversion yaw angles, a significant 2P component was observed in the measured torque; at the helicopter mode 75-deg

and 90-deg angles the 2P torque was relatively small. This 2P torque was not predicted by the analysis (the associated 2P lag moment was also not predicted). Since the analysis was performed assuming identical blades, only 3P and 6P torque show up in the predictions (no 1P and 2P components). Currently, it is believed that the presence of the 2P component in the torque (and lag moment) is due to blade dissimilarity (and possibly due to nonuniformity in the flow field caused by the wind tunnel walls).

Analysis limitations. The analysis was performed for an ideal, constant-speed gimbal and identical blades. The current predictions used a comprehensive analysis, with no wind tunnel wall effects (a completely isolated proprotor was considered). Inclusion of wall effects and the use of higher order airloads from a CFD analysis should improve the correlation. A full CFD analysis of the TTR/699/40x80-test section configuration should improve the correlation. Dissimilar blade analysis should also improve the correlation.

Recommendations. Future proprotor testing should include a checkout to ensure that the 2P component is within specified tolerances. To analytically bring in the 1P and 2P components, additional analysis with dissimilar blades could be undertaken; this could include special aerodynamic modeling of the instrumented blade to account for surface irregularities caused by the strain gages.

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