Performance and Vibration Analyses of Lift-offset Helicopters using a Rigid Coaxial Rotor

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ABSTRACT

The performance, vibration, and load analyses of the XH-59A compound helicopter are validated to establish the analysis techniques for lift-offset compound helicopters using a rigid coaxial rotor. For the performance analysis, this study uses two different analysis codes such as CAMRAD II (Comprehensive Analytical method of Rotorcraft Aerodynamics and Dynamics II) and NDARC (NASA Design and Analysis of Rotorcraft), and for the vibration and load analyses, CAMRAD II is used. Performance analyses using CAMRAD II and NDARC are compared to each other well, and they are also correlated nicely with the flight test results. The 3/rev hub vibratory loads and blade loads of the XH-59A helicopter with auxiliary propulsions are analyzed using CAMRAD II in forward flight and validated reasonably well to the flight test results. Since the present analysis results are in moderate or good agreement with the flight test data, the techniques for performance, vibration, and structural load analyses for lift-offset compound helicopters are established appropriately. Furthermore, the blade section lifts are investigated for the XH-59A with auxiliary propulsions in forward flight to examine the unique characteristics of the ABC™ (Advancing Blade Concept™) rotor.

1. INTRODUCTION

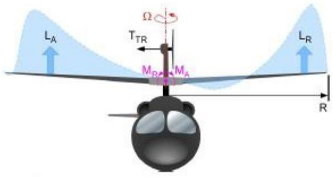
Conventional helicopters have the unique capabilities such as vertical take-off/landing (VTOL) and hovering. However, their maximum flight speed (usually 150-170 knots) is much slower than the fixed-wing aircraft. Thus, the development and research of compound helicopters that can flight in high-speed while maintaining VTOL and hovering capabilities have been conducted recently to solve this drawback of conventional helicopters.

Wings and auxiliary propulsions as well as rotors are used for the compound helicopters. Particularly, the XH-59A (Figure 1), X2 technical demonstrators, and S-97 Raider developed by Sikorsky (now Lockheed Martin) are the lift-offset compound helicopters using the ABC™ (Advancing Blade Concept™, [1]). The ABC™ uses a counter-rotating rigid coaxial rotor in order to enable high-speed forward flight of helicopters. The ABC™ is named since it generates the most lift on the advancing blades (Figure 2, [2]). Alternately, the ABC™ is represented as the lift-offset (LOS), which is calculated by dividing the rolling moment of each rotor by its thrust. Compound helicopters using the ABC™ have the unique advantages as follows. Since the rolling moments for the upper and lower rotors are the same in magnitudes but are opposite directions, the performance loss of the rotor because of the trim for rolling moment can be reduced. In addition, the dynamic stall on the retreating side of the rotor can be avoid. Furthermore, the lift-to-drag ratio of the ABC™

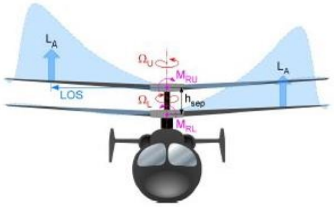
(a) Pure helicopter configuration

(b) Compound helicopter configuration

Figure 1. XH-59A technical demonstrator.



(a) Single main rotor



(b) Rigid coaxial rotor with ABC™

Figure 2. Lift and moment characteristics.

helicopter can be improved, as compared to that of conventional helicopters. Thus, the rotor speed can be reduced; therefore, high-speed forward flight is possible [2]. However, a significant disadvantage of the lift-offset helicopter is a serious vibration during high-speed flight. In case of the XH-59A helicopter, severe 3/rev cockpit vibration during high-speed forward flight was observed in its flight test because of the use of the rigid coaxial rotor and the absence of a vibration control system [3]. Thus, both performance and vibration predictions are important when compound rotorcrafts using the ABC™ rotor are developed. However, few works using analysis codes have been conducted for the predictions of performance and vibration, in spite of the development of lift-offset compound helicopters such as the XH-59A, X2 technical demonstrators, and S-97 Raider.

The performance analyses [4, 5] of an XH-59A lift-offset helicopter were conducted using NDARC (NASA Design and Analysis of Rotorcraft, [4]) and CAMRAD II (Comprehensive Analytical Method of Rotorcraft Aerodynamics and Dynamics II, [6]). In Ref. [5], the free wake model was used only for the performance analyses in the hover condition; however, the prescribed wake model, which is relatively simpler than the free wake model was used for the performance analyses in the forward flight condition. Moreover, the vibration of the XH-59A helicopter was not studied in that work [5]. Recently, RCAS (Rotorcraft Comprehensive Analysis System, [7]) was used in the work for performance, loads, and vibration of the XH-59A helicopter in high-speed forward flight [8]. But, most of results in this study [8] were obtained using a finite-state dynamic inflow model, which is much simpler than the free wake model; therefore the validation for the 3/rev hub pitch moment was not good. Also, the analysis of the hover performance was not conducted.

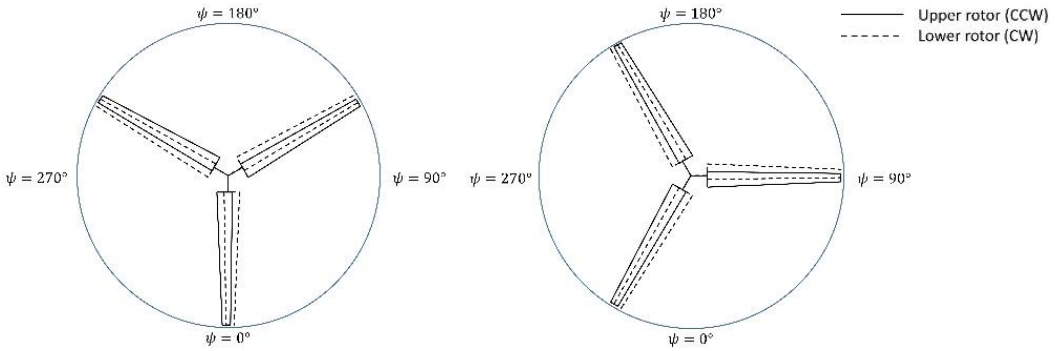
The goal of this research is to validate the predictions of performance, vibration, and load of the ABC™ helicopter, XH-59A, in both the hover and forward flight conditions. As prediction tools, two different codes are used. For the performance analyses, CAMRAD II using a general free wake model and NDARC are used. Unlike the previous research [4] using NDARC, the performance analyses using NDARC in this paper are conducted for the aircraft model obtained from the conceptual design [9]. For the vibration and loads analyses, CAMRAD II is used. Most of the present prediction results are compared to flight test results as well as to each other. Through the present study, techniques for analyses of performance and vibration for the ABC™ helicopter are established appropriately. Finally, the blade section lifts of the XH-59A helicopter rotor are studied although these predictions are not correlated with the flight test results.

2. VALIDATION MODEL

In this study, the XH-59A helicopter is considered as a model for the performance, vibration, and load analyses of the lift-offset compound helicopter. The XH-59A helicopter is an ABC™ technology demonstrator for high-speed flight while maintaining hovering and VTOL capabilities of conventional helicopters. The XH-59A helicopter was developed initially as a pure helicopter configuration (Figure 1(a), [2]) in 1964. After its successful flight tests in pure helicopter mode in 1973, and two auxiliary propulsions were added to the aircraft for transformation into a compound helicopter (Figure 1(b), [10]). The XH-59A in compound helicopter configuration reached a maximum level flight speed of 240 knots [3]. The general properties of XH-59A helicopter are summarized in Table 1 [3, 11, 12].

Table 1. Properties of XH-59A helicopter

Hub type	Hingeless rotor
Radius, R [ft]	18
Number of rotors	2
Number of blades	3
Total solidity, σ	0.127
Tip speed [ft/sec]	
Pure helicopter	650
Compound helicopter	450
Maximum speed [knots]	
Pure helicopter	160
Compound helicopter	240
Horizontal tail	
Area [ft^2]	60
Span [ft]	15.50
Tail length [ft]	20.30
Vertical tail	
Area [ft^2]	30
Span [ft]	12
Tail length [ft]	20.30
Fuselage	
Length [ft]	40.5
Rotor separation [ft]	2.5
Power plants	
Lift	PT6T-3 turboshaft engine
Thrust	J60-P-3A turbojet engine



(a) Cross-over angle of 0° (b) Cross-over angle of 90°

Figure 3. Definition of cross-over angle for a coaxial rotor.

Although the XH-59 helicopter in compound configuration solved the low-speed problem of conventional helicopters, it had serious problems such as severe vibration and technical limitation associated with the reduction of rotor speed [2]. The XH-59A compound helicopter not only uses very stiff rigid blades but also has no vibration control system. As a result, the XH-59A helicopter experienced severe vibration problems especially in high-speed flight conditions. The cross-over angle is defined as the azimuth angle where the upper and lower blades of a coaxial rotor cross over each other, as given in Figure 3 [13]. It is interesting that the vibration characteristics of the XH-59A in compound helicopter configuration were definitely different for the different cross-over angles of 90° and 0° [11]. For an example, the 3/rev hub pitch moment is more dominant as compared to the 3/rev hub roll moment for a cross-over angle of 0°. However, the characteristics of the 3/rev hub loads are opposite for a cross-over angle of 90°. The 3/rev pitch or roll moment has a strong effect on the vibration of the XH-59A helicopter [11]. In addition, the 2/rev component of loads on the rotating blade is the main source for the 3/rev hub vibratory loads of the XH-59A helicopter [13, 14].

In this work, the flight test data [5, 11, 15] are used for the correlation between the present analyses and the measured data.

3. ANALYSIS METHODS

3.1 NDARC

For the performance analyses of the XH-59A helicopter, this study uses the NDARC, which is a rotorcraft design and analysis tool, developed by NASA. NDARC can conduct rapidly the conceptual design and performance analysis for various rotorcrafts as well as conventional helicopters. However, it is difficult to establish the modeling and analysis techniques using NDARC because a number of input values are required for design and analysis using NDARC [16]. The tasks and functions of the NDARC are briefly represented in Figure 4 [4].

In this study using NDARC, performance analyses of the XH-59A in pure and compound helicopter configurations are conducted. The XH-59A aircraft model for analyses is obtained from the previous work [9]. In addition, the lift-offset value is assumed as 0.25, which is the recommended value in the reference [5].

In the NDARC, the rotor power of each of the upper and lower rotors is calculated as the sum of the induced power (P_i), profile power (P_o), and parasite power (P_p), as shown in Eq. (1). In addition, various parameters such as induced power factor, and

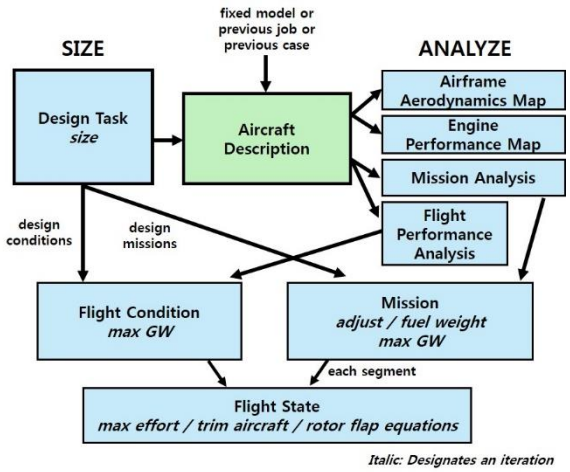


Figure 4. Outline of NDARC tasks.

mean drag coefficient are used to calculate the performance of the rotor. These performance parameters in this study are obtained from Ref. [4] and modified appropriately. The lift-to-drag ratio of aircraft (L/D), and effective lift-to-drag ratio of the rotor (L/D_e) can be calculated from the Eqs. (2) and (3), respectively. Rotor power of the coaxial rotor (P_{coaxial}) is the sum of the upper and lower rotor powers.

$$P = P_i + P_o + P_p \tag{1}$$

$$\frac{L}{D} = \frac{WV}{P_{\text{coaxial}}} \tag{2}$$

$$\frac{L}{D_e} = \frac{L}{(\frac{P_{\text{coaxial}}}{V} + X)} \tag{3}$$

3.2 CAMRAD II

CAMRAD II [6] is a comprehensive analysis code for performance, loads, and aeroelasticity stability of rotorcrafts. CAMRAD II has been used widely for the comprehensive analyses of rotorcrafts because it can be used for not only conventional helicopters but also rotorcrafts with various configurations. CAMRAD II has nonlinear finite elements, multibody dynamics, and rotor unsteady aerodynamics based on the lifting-line theory along with various inflow models and sophisticated wake models [17]. However, it is not easy to construct an analysis model using CAMRAD II since many input and empirical parameters are required.

This study conducts the performance, vibration, and load analyses using CAMRAD II for the XH-59A helicopter. To compare with the present authors' performance analysis results [9] using NDARC, the value of lift-offset (LOS) is assumed as 0.25 in the present CAMRAD II analysis. As represented in Figure 5, the XH-59A helicopter model with a cross-over angle of 0° is used for the present analyses.

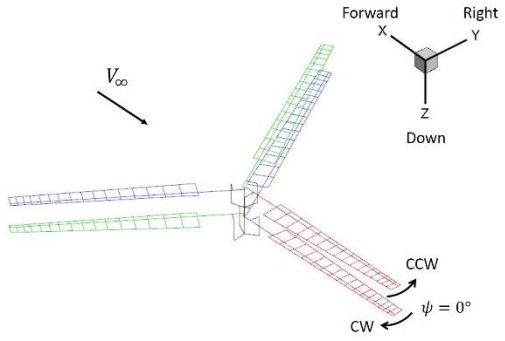
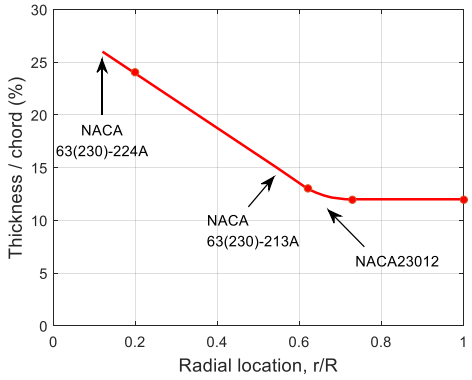


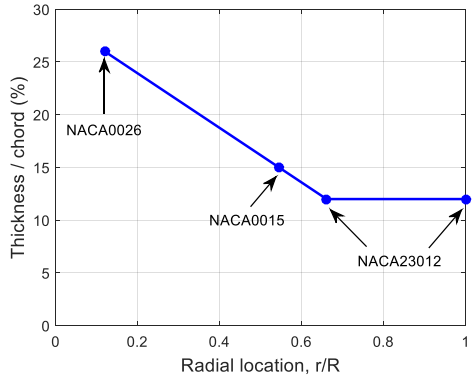
Figure 5. CAMRAD II model of XH-59A rotor.

Since the C81 tables for the actual airfoils of the XH-59A rotor blade are not available in public domain, this study uses the C81 tables for the airfoils similar to the actual airfoils of the XH-59A rotor blade, as shown in Figure 6. This method was used successfully in the previous works [5, 8]. However, the C81 airfoil tables used in this study cannot accurately represent the aerodynamics characteristics of the XH-59A rotor blade, for an example, Reynolds number. Therefore, the drag coefficients are adjusted in order to obtain better performance analysis results, similar to the method used in Ref. [5].

Each blade is modeled as 16 aerodynamic panels, and the general free wake model is used for forward flight condition as well as for hover condition. The initial size of the vortex core of the free wake model is modeled as 50% of the chord length at the tip [5]. In addition, each blade is modeled as 7 nonlinear finite beam elements. The cross-sectional properties of the XH-59A rotor blade in Ref. [18] are used appropriately for the present blade modeling. In addition, the pitch hinge of the XH-59A rotor is



(a) Actual airfoils



(b) Present airfoil model

Figure 6. Blade thickness and airfoil distribution.

modeled to be located at 5%R, and the rotor control system such as pitch links, pitch horns, and swashplates is modeled sophisticatedly.

The aerodynamic coefficients of the XH-59A fuselage are obtained from Ref. [15]. The trim analysis at the forward flight condition is performed such that the 6 components of loads acting on the aircraft are zero. The mean collective pitch angle, and lateral and longitudinal cyclic pitch angles of each rotor are used as trim variables for lift-offset helicopter. The control phase angle to control the lift-offset rotor is represented as the combination of the lateral and longitudinal cyclic pitches [5]. Alternatively, the trim analysis can be conducted using 6 rotor controls of the upper and lower rotors when the pitch angle of the aircraft is fixed as 0°, which gives the best performance for the lift-offset helicopter [11]. In this approach, trim targets are considered as the vertical force, the torque offset of the upper and lower rotors, and the rolling and pitching moments of the upper and lower rotors. The lift-offset can be considered as the differential rolling moment.

To validate the structural dynamics of the present CAMRAD II model, a fan plot analysis for an XH-59A rotor blade is performed [19] and the results are shown in Figure 7. The predicted non-rotating frequencies by CAMRAD II are correlated well with the measured values [15]. In addition, the present frequencies in lower modes are also compared well with the previous predictions [11, 15]. However, for the first torsional frequency (T1) at nonrotating condition, the present result is better than the previous analyses [11, 15], as compared to the measured data. Therefore, it is considered that the present structural dynamics model using CAMRAD II for XH-59A is successfully validated.

In the performance analysis using CAMRAD II, the rotor power and lift-to-drag ratio are calculated using Eqs. (1) to (3), as given previously. For the vibration analysis of the XH-59A helicopter, the 3/rev hub moment (M_{3P}) is calculated using Eq. (4). In Eq. (4), subscripts *upper* and *lower* denote upper and lower rotors, respectively, c and s mean the cosine and sine components of the hub loads, respectively [8].

$$M_{3P} = \sqrt{[M_{3Pc}^{upper} + M_{3Pc}^{lower}]^2 + [M_{3Ps}^{upper} + M_{3Ps}^{lower}]^2} \quad (4)$$

4. RESULTS AND DISCUSSIONS

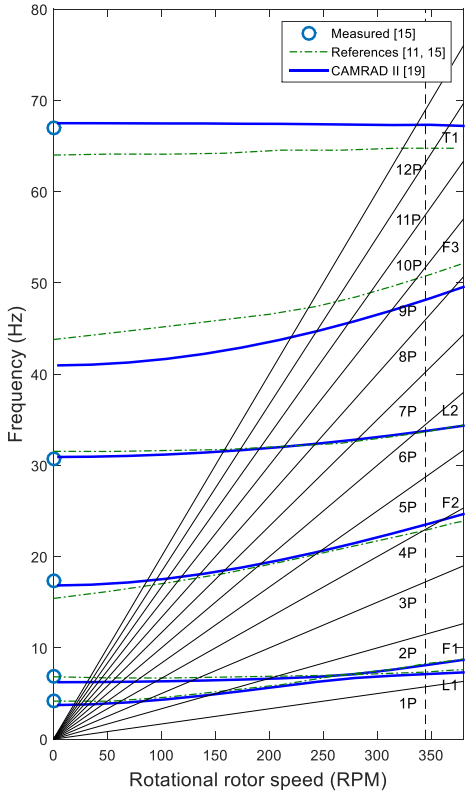


Figure 7. Validation of the fan plot analysis.

4.1 Performance analyses

In this section, the performance are studied for the XH-59A helicopter with and without auxiliary propulsions in hover and forward flight conditions. For the correlation, the analysis results using CAMRAD II and NDARC are compared to each other as well as flight test data [5]. Some of prediction results using CAMRAD II and NDARC in this section are obtained from the present authors' recent works [9, 19] for the comparison and validation.

Figure 8 shows the correlation results of the figure of merit for the XH-59A without the auxiliary propulsion in hover. As seen in the figure, two prediction results by CAMRAD II and NDARC are quite similar to each other, although they use different analytical models and analysis techniques. They are also compared well with the flight test data. In addition, the figure of merit of the XH-59A helicopter (between 0.75 and 0.8) is better than that of conventional helicopter (between 0.6 and 0.75, [20]) since the wake of the upper rotor is reduced before it reaches the lower rotor in case of a coaxial rotor system [5].

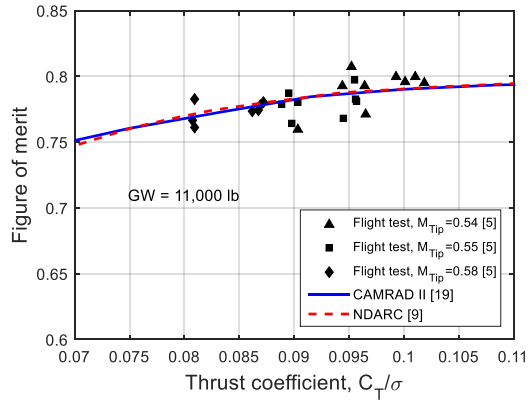


Figure 8. Figure of merit in hover.

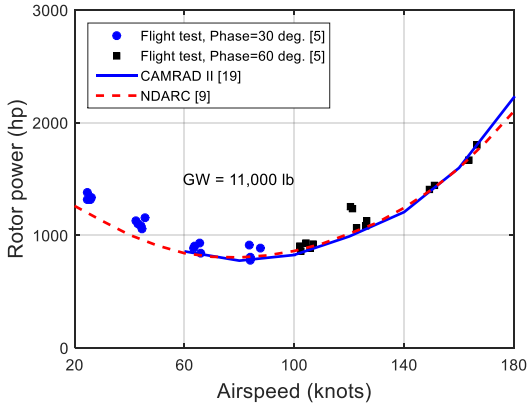


Figure 9. Validation of rotor power in pure helicopter mode.

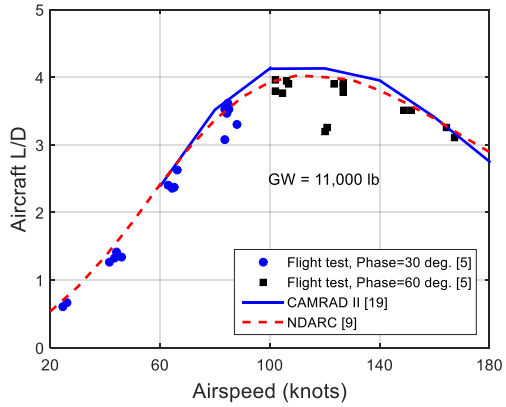


Figure 10. Validation of aircraft lift-to-drag ratio in pure helicopter mode.

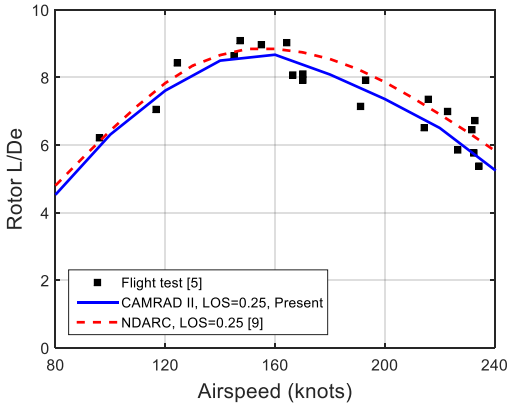


Figure 11. Validation of the rotor effective lift-to-drag ratio in compound helicopter mode.

Figures 9 and 10 show the results of performance analyses using CAMRAD II and NDARC for the XH-59A without auxiliary propulsions in forward flight. As given in the figures, the rotor power and the aircraft lift-to-drag ratio both are predicted well, as compared to the flight test data. In addition, CAMRAD II and NDARC predictions are quite similar to each other; although CAMRAD II over-predicts slightly the aircraft lift-to-drag ratio than the NDARC result at 80-160 knots in Figure 10 because the rotor power using CAMRAD II is estimated to be lower slightly than the result by NDARC, as shown in Figure 9.

The effective lift-to-drag ratios of the rotor for XH-59A using auxiliary propulsions are validated in Figure 11. Note that the flight test results include all the test data for the gross weight ranging from 11,000 to 13,000 lb, but CAMRAD II and NDARC results in this figure are for 13,000 and 11,000 lb, respectively. In addition, although the lift-offset value in the flight test varies with the flight speed, the lift-offset value is fixed as 0.25 for both CAMRAD II and NDARC analyses. As shown in Figure 11, the analysis results using CAMRAD II and NDARC are all within the upper and lower bounds of the flight test results. When the flight speed is above 160 knots, the NDARC result is slightly overpredicted, as compared to the prediction by CAMRAD II. Again, two predictions are quite similar to each other, although different analysis models and techniques are used.

4.2 Vibration and load analyses

In this section, the 3/rev hub vibrations and blade loads of the XH-59A compound helicopter in forward flight are analyzed using CAMRAD II and the results are validated to the flight test results. For the CAMRAD II analyses given in this section, the compound helicopter configuration using auxiliary

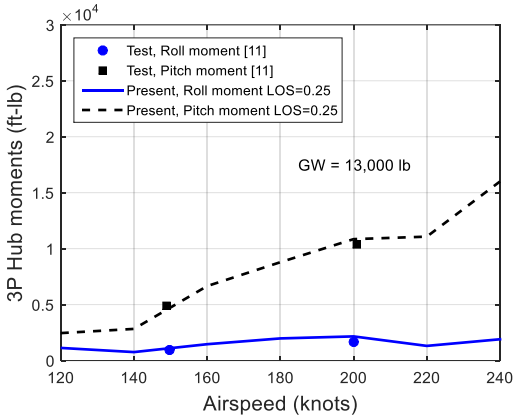


Figure 12. Validation of 3P hub moments.

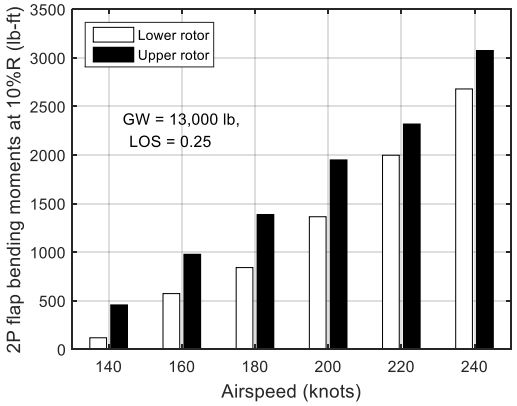
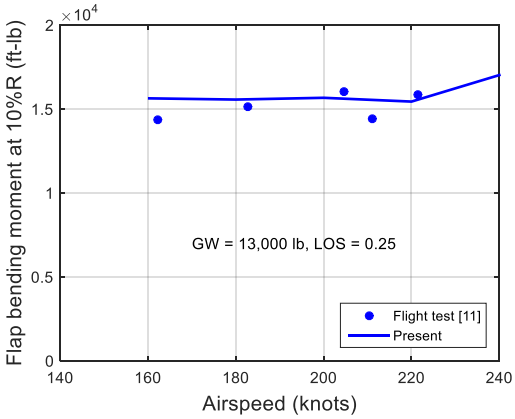
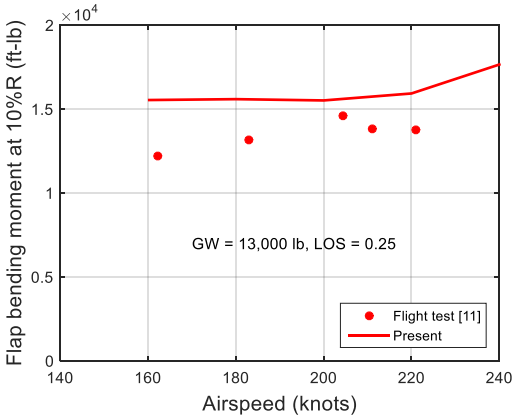


Figure 13. 2P flap bending moments at 10%R.



(a) Lower rotor



(b) Upper rotor

Figure 14. Validation of blade structural loads at 10%R (1/2 peak-to-peak values).

propulsions are considered and the lift-offset value is fixed as 0.25.

Figure 12 validates the 3/rev hub vibratory loads in forward flight. The CAMRAD II analysis and flight test [11] results both show that the 3/rev hub pitch moment is much higher than the 3/rev hub roll moment for the cross-over angle of 0°. In addition, the 3/rev hub moments increase as the flight speed increases in both the analysis and flight test. Although there are only two flight test data that can be compared, the present CAMRAD II predictions are correlated nicely with the measured data [11]. Therefore, the analysis method of the hub vibratory loads for the XH-59A compound helicopter is appropriately established.

Since the 2/rev load components of the rotating blade have a strong effect on the 3/rev hub vibratory loads for the XH-59A helicopter, the 2/rev flap bending moments of the upper and lower blades at 10%R are investigated in Figure 13. The present analysis results are not validated because there is no flight test data for these. As shown in Figure 13, the 2/rev flap bending moments of upper and lower rotors increase with the increase of the flight speed, which is a similar trend to the relation between the 3/rev hub loads and flight speed, as given previously in Figure 12.

Figures 14 shows the 1/2 peak-to-peak values of the flap bending moments of upper and lower blades at 10%R for the XH-59A helicopter in compound mode since the flap bending moment is dominant at the blade root. For the lower rotor blade, the present CAMRAD II shows a reasonable prediction as compared with the flight test, although the down-up behavior at 200-220 knots is not clearly predicted in this analysis. For the upper rotor blade, the CAMRAD II result is over-predicted, as compared to the flight test data. In addition, the measured 1/2 peak-to-peak value for the upper rotor blade is lower than that for the lower rotor blade in the flight test; however, the present predictions for upper and lower rotor blades are quite similar to each other.

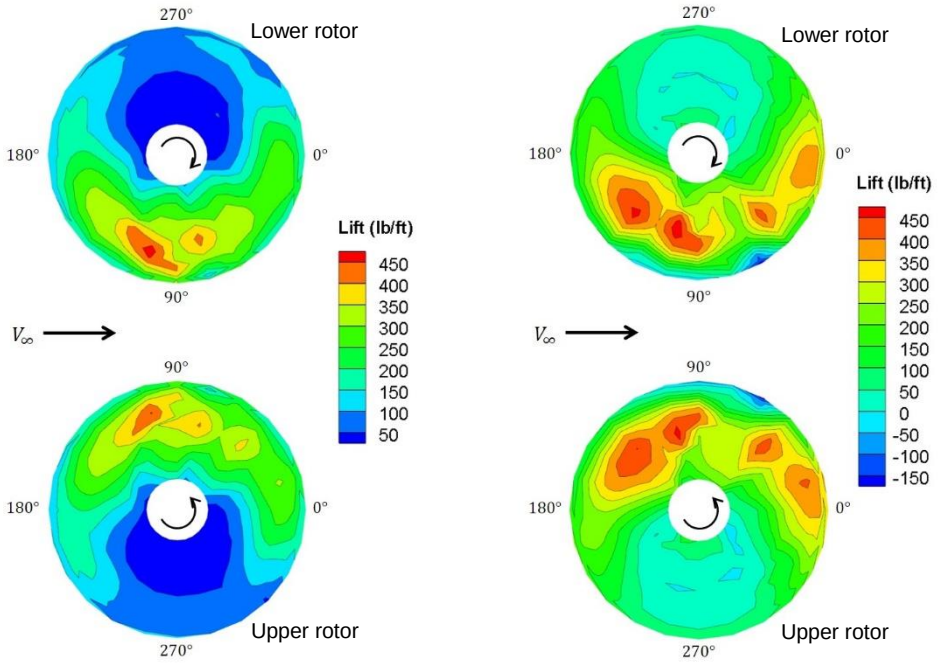


Figure 15. Lift distributions in compound helicopter mode (LOS=0.25).

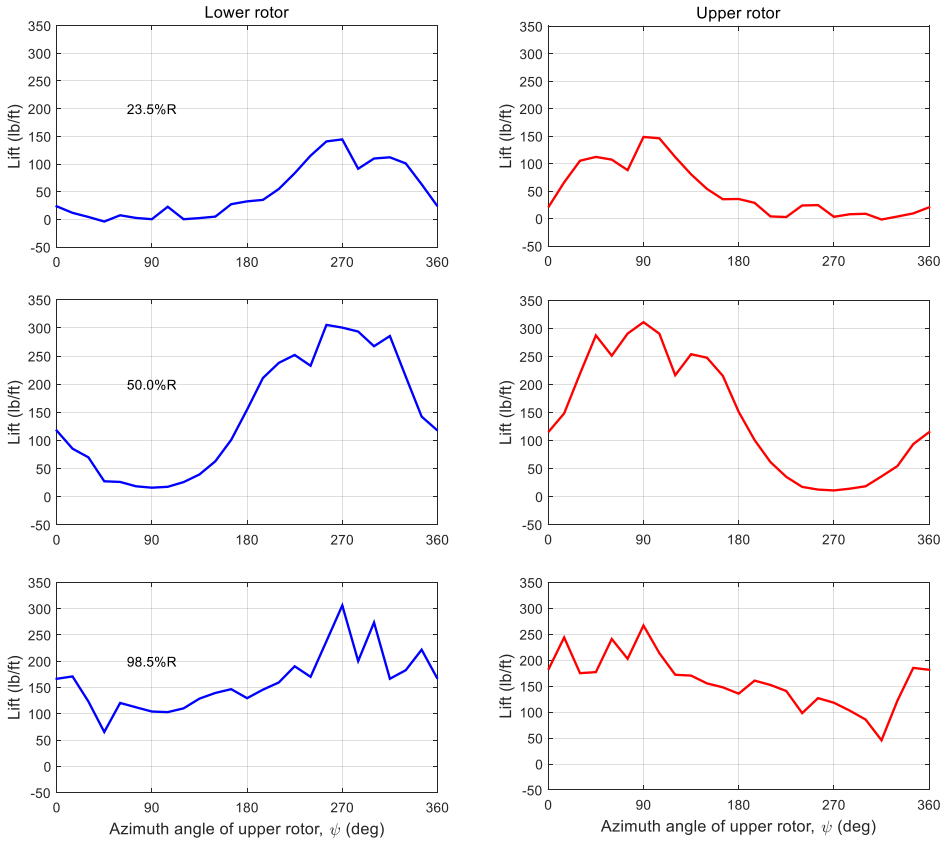


Figure 16. Blade section lifts at 140 knots in compound helicopter mode (LOS=0.25).

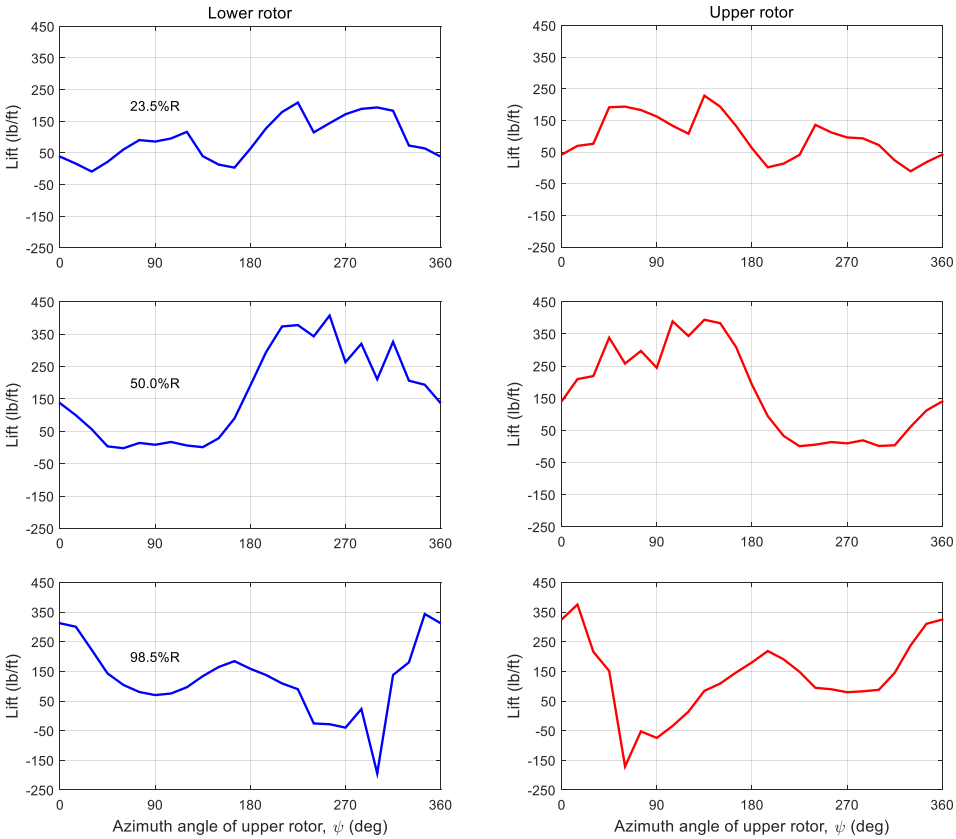


Figure 17. Blade section lifts at 240 knots in compound helicopter mode (LOS=0.25)

The reasons for this discrepancy between the analysis and test data are as follows. First, the trim condition used in this CAMRAD II analysis is different from the trim condition for the flight test [11]. Second, the lift-offset value is fixed as 0.25 in the present analysis while the lift-offset value in the flight test changes as the flight speed increases. Third, it is not easy to calculate the blade structural loads accurately using the rotorcraft comprehensive analysis.

Figure 15 shows the lift distributions for the XH-59A helicopter in compound mode at 140 and 240 knots. The flight speeds of 140 and 240 knots are for the best effective lift-to-drag ratio and maximum forward flight speed conditions, respectively. Because the flight test for the XH-59A helicopter did not measure the rotor airloads, the correlation between the measured data and the analysis results is not possible for the rotor airloads. As given in the figures, most lift is produced on the advancing side of each of the upper and lower rotors, which is an inherent characteristic of the ABC™ rotor. In addition, the lift distributions of the upper and lower rotors are almost similar to each other. Particularly, the negative tip loadings on the advancing side are observed clearly at 240 knots than the results at 140 knots.

Figures 16 and 17 predict the blade section lifts at 140 and 240 knots, respectively. In the present predictions, three blade stations (23.5, 50.0, and 98.5% R) of the upper and lower rotor blades are considered. It should be noted that the azimuth angles in these figures are defined based on the rotation direction of an upper rotor (counter-clockwise direction). As shown in these figures, the amplitude and variation of the section lifts of the upper and lower rotor blades are similar to each other at three blade locations at both 140 and 240 knots. The lift fluctuations are predicted at 98.5%R of both upper and lower rotor blades at 140 knots, while the fluctuations of section lifts are definitely observed at 50.0 and 98.5%R of upper and lower rotor blades at 240 knots. Particularly, the amplitude of fluctuations of the lower rotor blade is larger than that of the upper rotor blade because the wake of the upper rotor may affect the lower rotor. In addition, the section lifts at 98.5%R at 240 knots in Figure 17 clearly exhibits negative loading behaviors in the

first quadrants, however this is not shown in the prediction at 140 knots in Figure 16.

5. CONCLUSIONS

This work conducted the validation of the performance, vibration, and load analyses of the XH-59A compound helicopter using a rigid coaxial rotor. For the performance analyses in various flight conditions, two analysis codes, CAMRAD II and NDARC, were used. The prediction results by CAMRAD II and NDARC were quite similar to each other, and also they were correlated well with the flight test data.

For the hub vibratory loads and the blade loads in forward flight, CAMRAD II analyses using the lift-offset value of 0.25 was conducted for the XH-59A in compound helicopter mode. The predicted 3/rev hub loads were compared excellently with the flight test data. But, the validation of the 1/2 peak-to-peak values for the flap bending moments was moderate. In addition, the lifts of the XH-59A rotor in compound helicopter mode in forward flight were calculated in order to investigate a unique characteristic of the ABC^{TM} rotor, although they were not validated to the flight test results.

Through the present study, the analysis techniques of the performance, vibration, and load for the ABC^{TM} helicopter using a rigid coaxial rotor were established appropriately.

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