Correlation and Analysis for SH-2F 101 Rotor

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The SH-2F helicopter flight test data correlation has been successfully performed using a modified version of the rotorcraft flight simulation computer program C81. This modified program has the capability for either the conventional rotor control option or the servo flap control option. The analytical model of the servo flap in the analysis is treated as a control system, not a degree of freedom. The airfoil data tables are modified to have the capability to simulate the appropriate servo flap aerodynamic coefficients C_ℓ, C_d, and C_M as a function of servo flap deflection. The blade index angle and servo flap control feedback coefficients are included to model the blade having various combinations of servo flap design variables. The existing SH-2F fuselage characteristics and the 101 Rotor system are utilized to perform the correlation with the flight test data to verify the analysis. Results obtained from the analysis, when compared with the flight test data, such as servo flap control position, fuselage attitude, main rotor torque, and bending moment distribution, correlate very well. From both the analysis and test data results, it is shown that the modified computer program could be a viable tool for future design of the advanced servo flap controlled main rotor helicopter.

Nomenclature

C_d = two-dimensional airfoil drag coefficient
C_ℓ = two-dimensional airfoil lift coefficient
C_M = two-dimensional airfoil pitching moment coefficient about 1/4 chord; nose up is positive
$K_{\delta\beta}$ = flapping to servo flap feedback coefficient
$K_{\delta\zeta}$ = lap to servo flap feedback coefficient
$K_{\delta\theta}$ = feathering to servo flap feedback coefficient
v' = in-plane bending slope
w' = out-of-plane bending slope
δ_{input} = net servo flap control input, deg
δ_0 = collective servo flap control input, deg
δ_{1c} = lateral servo flap control input, deg
δ_{1s} = longitudinal servo flap control input, deg
δ_3 = pitch flap coupling, positive pitch flap coupling represents decreasing the blade pitch for an increase in flapping, deg
θ = blade feathering displacement measured leading edge up from the shaft plane, deg
Ψ = blade azimuth position, deg

Introduction

THE SH-2F helicopter began operation with the Navy service in 1973 as a ship-based, multirole helicopter. The present primary mission of this aircraft is anti-submarine warfare (ASW) and anti-ship surveillance and targeting (ASST), and the secondary mission is search and rescue (SAR).

In order to enhance the future combat mission capability, the present ongoing improvement and development programs on this aircraft include the installation of twin GE-T700 engines, the installation of composite main rotor blades, the enhancement of the avionics systems, and the upgrade of the tail rotor system. The total gross weight after these improvements will be 13,500 lb, and this aircraft will remain in Navy service until the year 2010.

The original 101 main rotor design computer programs, which included a frequency and mode shape program (XFREQ) and a six-degree-of-freedom aeroelastic rotor program (6F),[1] were utilized to analyze the blade airloads, pilot control positions, fuselage vibration, and blade bending moments. These two programs are relatively unfamiliar to other helicopter manufacturers because the 101 Rotor uses the servo flap as the primary control system located at 75% radius on the trailing edge of each blade.[1–6]

Recently, the concept of using the servo flap as a primary system to control helicopter flight has drawn interest in the helicopter industry because this type of control system is a viable candidate for individual blade control with higher harmonic inputs. Therefore, the rotorcraft flight simulation computer program C81, originally developed by the Army Applied Technology Laboratory and Bell Helicopter Textron, was adapted at Kaman Aerospace Corporation to model the servo flap controlled main rotor.[7,8] This modified computer code has the capability for either the conventional rotor control analysis or the servo flap rotor control analysis.[9,10]

In order to verify the analysis, Kaman developed the 101 Rotor system and the SH-2F helicopter fuselage characteristics are utilized to conduct the test data correlation. From both the analysis and test results, the modified C81 computer program could be used for future design of the advanced servo flap controlled main rotor.

101 Rotor System

The 101 Rotor is a four-bladed design which has a radius of 264 in. (Fig. 1). The blade chord is 22.066 in. in the nonservo flap region and 30.09 in. in the servo flap region. The airfoils used on the main rotor and servo flap are the modified 23012 airfoil and the 63_3-018 airfoil, respectively. The rotor nominal operating speed is 298 rpm. Both blade flapping and lagging hinge offsets are coincident at station 8.25 in. The inboard and outboard stations of the pitch barrel are located at stations 17.5 and 42, respectively. The blade weight is 288 lb including the weight of the rotor retention and servo flap; the flapping inertia about the flapping hinge is 1148 slug-ft^2, and the static mass moment about the flapping hinge is 76 slug-ft. The rotor shaft was designed to have 6 deg forward tilt and 4 deg lateral tilt in order to maintain the fuselage in a level position in hover.

Presented as Paper 87-0922 at the AIAA Dynamics Specialists Conference, Monterey, CA, April 9–10, 1987; received June 9, 1987; revision received Nov. 7, 1987.

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The servo flap has an 8.5 in. chord and is 42 in. in length. The center line of the servo flap is located at the main rotor station 195. The chordwise aerodynamic center offset of the servo flap section is 2% aft of the feathering axis, which is 18.66 in. ahead of the servo flap deflection axis. The total weight of the servo flap is 6 lb and the effective blade chordwise c.g. offset is 0.44 in. aft of the feathering axis. The blade feathering spring rate is 562 ft-lb/rad and the feathering frequency at the nominal speed is 7 Hz in a vacuum. Each blade is designed to have a lag damper of 3000 ft-lb/rad/s to prevent ground resonance during ground operation.

Retention Wind-up Angle

Kaman's 101 Rotor with servo flap control has been designed using a tension/torsion strap to provide the soft feathering restraint. Aerodynamic action of the servo flap rotates the blade and the outer portions of the blade retention assemblies with respect to the feathering axis. The inner portions of the blade retention assemblies, however, do not rotate about the feathering axis.

The retention strap wind-up angle is an important design parameter that will affect the lift on the servo flap, as shown in Fig. 2. For a blade with zero retention strap wind-up angle designed at the root end of the main rotor, the trailing edge of the servo flap will deflect up in order to achieve the proper feathering angle to maintain sufficient lift on the blade. This upward trailing edge deflection will produce a download on the servo flap that, in turn, will produce a nose-up pitching moment with respect to the blade feathering axis to increase the blade angle of attack.

For the 101 Rotor retention strap design, there is a pretwisted nose-up angle of 27 deg measured at 75% radius. The servo flap does not produce any pitching moments on the retention strap at this nose-up angle. This 27 deg nose-up angle setting is higher than the normal trimmed flight blade angle of attack requirement; therefore, the servo flap generates a nose-down pitching moment, with respect to the main rotor feathering axis, to reduce the blade angle of attack so that the SH-2F helicopter can be trimmed at the desired blade angle of attack. At this flight condition, the servo flap of the 101 Rotor requires an upload on the servo flap in order to generate a nose-down pitching moment on the main rotor. This upload will partially unload the main rotor lift requirements and improve the rotor performance in hover and forward flight.

Blade Coupling Effects

The 101 Rotor produces a destabilized pitch-flap coupling effect (δ_3) that is introduced by the combined effects of servo flap-feathering and servo flap-flapping coupling during operation. When the main rotor is flapping up under certain aerodynamic loading in a flight, the servo flap control linkage moves along with the rotor. This mechanical linkage movement increases the servo flap trailing edge upward deflection with respect to the main rotor. Therefore, the upward servo flap deflection will increase the blade pitch angle with respect to the feathering axis to generate the pitch-flap coupling. This destabilizing effect is equivalent to 23 deg of pitch-flap coupling.

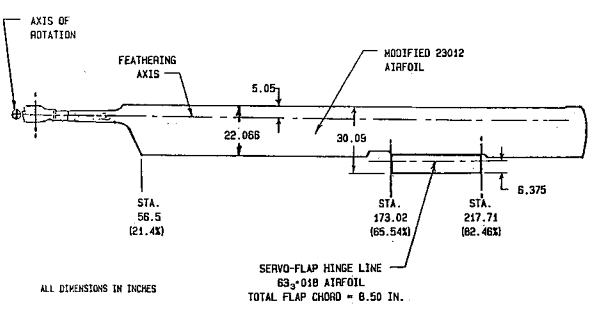

Fig. 1 SH-2F/101 Rotor blade configuration.

Control System

The 101 Rotor control rod assembly provides the connection between the retention and rotor blade controls. The control linkage is divided into two categories, one for primary control input and the other for feedback control input.

As the main rotor blade responds to primary control inputs, it causes the blade retention assembly to rotate about its longitudinal axis. This rotational movement is picked up by the feedback crank and transmitted to the feedback idler. The idler then changes the moment arm of the retention control level. This action washes out a portion of the primary control input, thus preventing the blade flap from overcontrolling the blade (Fig. 3).

Since the blade control feedback washes out the pilot's input, the input and output of the servo flap control positions are different for the 101 Rotor. Therefore, the servo flap angular position with respect to the trailing edge of the main rotor are recorded during each trim time point. The feedback ratio of the 101 Rotor for servo flap angle vs blade feathering angle is 0.41.

Pilot Controls

The total stick travel for collective control of the SH-2F helicopter is 11.5 in., which is equivalent to 15.75 deg servo flap angular motion. At the 0% full down collective control position, the servo flap trailing edge is down at 6.38 deg

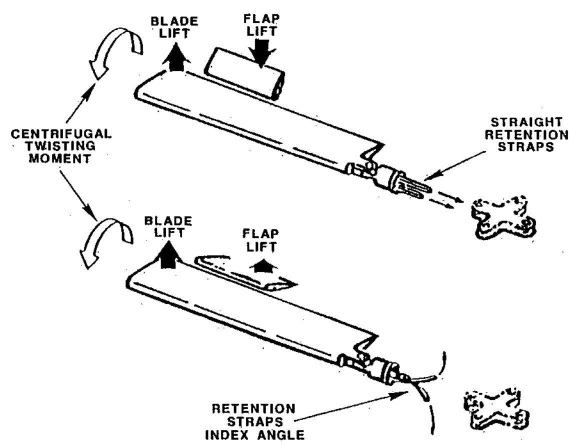

Fig. 2 Effect of retention strap windup on servo flap lift.

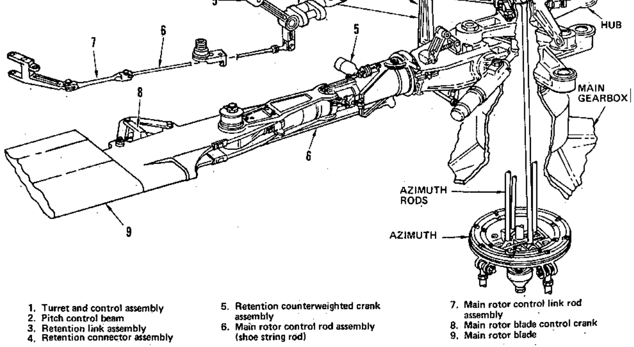

Fig. 3 SH-2F main rotor control rod assembly and retention assembly control linkage.

position. For the 100% full up collective control position, the servo flap trailing edge is up at -9.37 deg position.

The total longitudinal stick travel for longitudinal cyclic control of the SH-2F helicopter is 14 in., which is equivalent to 24 deg servo flap angular motion. For the most forward stick position, the 100% longitudinal cyclic servo flap control position is at 17.66 deg. For the most aft stick position, the 0% longitudinal cyclic servo flap control position is at -6.34 deg.

The total lateral stick travel for lateral cyclic servo flap control is 11.2 in., which is equivalent to 10.64 deg servo flap angular motion. At the 0% lateral cyclic control, the servo flap is at -5.32 deg, and for the 100% lateral cyclic control, the servo flap is at 5.32 deg.

The total pedal travel for tail rotor control is 6 in., the lower limit on tail rotor pitch is -7.5 deg at the full right control, and the upper limit on tail rotor pitch is 26 deg at the full left control.

C81 Modifications

The 6F aeroelastic rotor program uses the uncoupled frequencies and mode shapes approach to analyze the servo flap controlled aeroelastic rotor. The blade coupling effects are introduced from the equations of motion. The servo flap is treated as a degree of freedom in the governing equations in the analysis. Since the servo flap has a frequency higher than 75 Hz, it is justifiable to treat the servo flap as a control system instead of a degree of freedom. Therefore, significant efforts have been saved during the modification of the C81 analysis to include the servo flap.

The C81 computer program change requirements to switch from a pitch horn controlled rotor to a servo flap controlled rotor are outlined as follows:

1) Modify the rotor control system option to have either the servo flap control option or the pitch horn control option.

2) Modify the airfoil data tables to have the capability to look up the appropriate aerodynamic coefficients, C_ℓ, C_d, and C_M, as a function of the servo flap deflections, local Mach number, and local blade angle of attack.

3) Input the blade retention wind-up angle and servo flap feedback coefficients to model the blade having various combinations of servo flap design variables.

4) Include pitching moment effects at the blade root section due to the retention feathering spring.

5) Output the servo flap angular position with respect to the trailing edge of the main rotor during each trim point.

Mode Shapes

The C81 computer program uses the coupled mode shapes and frequencies generated by a Myklestad analysis as the input to the analysis. Blade properties are modified in the input data to reflect the servo flap effects at the servo flap region. Blade chordwise c.g. and ac offsets with respect to the feathering axis are moved aft in the servo flap region as the servo flap properties are taken into consideration. These aft movements of the blade characteristics in the servo flap region require a forward balance of the blade properties in the nonservo flap region to offset the possible adverse unstable effects. The destabilizing δ_3 coupling effect is modeled by control linkage geometry in the Myklestad coupled mode shape program which can be obtained from the feathering component in the first out-of-plane mode. Up to nine elastic modes are required to include the second torsional mode in C81 for the 101 Rotor system. Only the first seven independent modes from Myklestad are necessary to generate enough accuracy for modeling the rotor. The eighth and ninth modes have very little effect on the trimmed results.

Airfoil Tables

The original C81 program is designed for pitch horn rotor analysis that has the capability to handle up to 10 main rotor airfoil data tables to look up the appropriate aerodynamic coefficients. These aerodynamic coefficients are functions of blade local angle of attack and Mach number. In the servo flap controlled rotor simulation, the C81 program has been modified to use the airfoil data tables, which have the capability to include the effects due to servo flap deflections. The

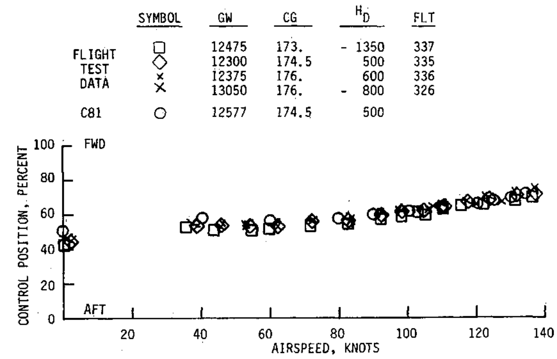

Fig. 5 SH-2F longitudinal cyclic control positions.

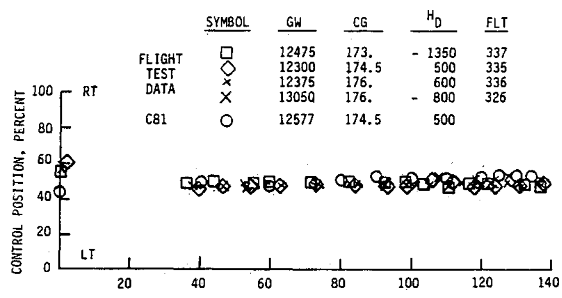

Fig. 6 SH-2F lateral cyclic control positions.

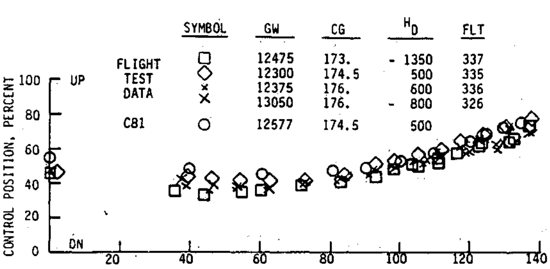

Fig. 4 SH-2F collective control positions.

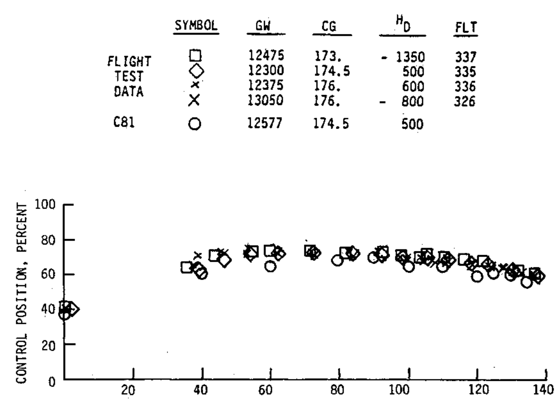

Fig. 7 SH-2F directional pedal control positions.

total number of airfoil data tables remains unchanged during the conversion. These aerodynamic coefficients in the new subroutines are not only functions of blade local Mach number and angle of attack, but also a function of servo flap deflections.

From previous experience, it is recommended that five sets of airfoil data tables with different servo flap angle settings be used in the servo flap region in order to have enough range to simulate the servo flap blade aerodynamic characteristics. The remaining five sets of airfoil tables could be used to represent the aerodynamics of the main rotor. Therefore, slightly more computer time is required to ascertain the aerodynamic coefficients C_ℓ, C_d, and C_M in the analysis during each trim time step.

Feedback Controls

The control system in the C81 analysis describes the behavior of articulated rotors with servo flap control input. The servo flap input is given by the following equation:

$$\delta_{\text{input}} = \delta_0 - \delta_{1s} \sin\psi - \delta_{1c} \cos\psi + K_{\delta\beta} w' + K_{\delta\theta} \theta + K_{\delta\zeta} v'$$

The various azimuthal coefficients correspond to: collective, δ_0; and cyclic, δ_{1s}, δ_{1c}; and the constants $K_{\delta\beta}$, $K_{\delta\theta}$, $K_{\delta\zeta}$ correspond to the mechanical feed-back couplings among the modes.

Pitching Moment Modification

The nose-up index angle on the retention strap is modeled to have the virtual work performed by the torsional spring at the blade root section during the conversion. This virtual work is incorporated on the right-hand side of the governing equations to ensure the correct blade pitching moment representation. Therefore, the effect of the blade wind-up angle has been included in the response outputs. From the analysis, results also show that the blade wind-up angle has power saving advantage as the nose-up index angle increases.

Results

The original 101 Rotor frequencies and damping used in the 6F program were computed from the linearized equations of motion and utilized to compare with Myklestad results in vacuum, shown in Table 1. The flapping, lagging, feathering, and bending frequencies, and damping obtained from the 6F coupled modes, show very little difference when compared to those of the uncoupled modes. The uncoupled twisting mode frequency input to the 6F program was obtained from a cantilever blade analysis. Significant differences are seen in the twisting mode frequencies and damping due to the coupling effects. Also, the frequencies obtained from Myklestad are about the same as compared to the 6F coupled frequencies. Only the percent critical damping used in the C81 program is different in the feathering equation in order to have proper representation in the time history results.

Both the SH-2F fuselage characteristics and the 101 Rotor are used to correlate with flight test data to verify the analysis. The primary ASW mission gross weight and c.g. location are used to simulate the test. For pilot's collective control position inputs vs airspeed, shown in Fig. 4, the analysis correlates very well with the test data as airspeed increases. The collective control position from the analysis predicts 8% higher than those measured data in hover and 6% higher in transition area. This is because the trim procedure used in the analysis holds Euler yaw angle constant to iterate pitch and roll angles in hover. A similar procedure, used in the analysis, holds the Euler roll angle constant at high speed to iterate on pitch and

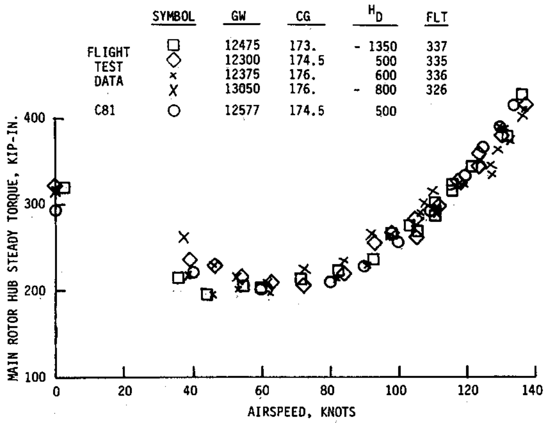

Fig. 8 SH-2F main rotor hub steady torque.

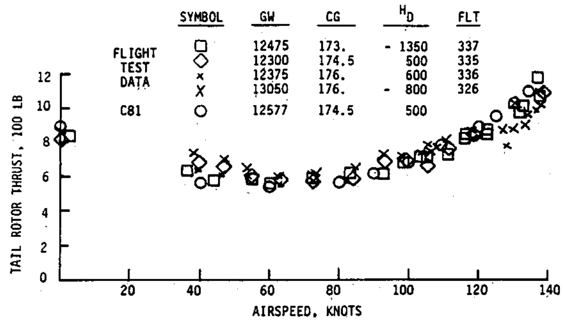

Fig. 9 SH-2F tail rotor thrust.

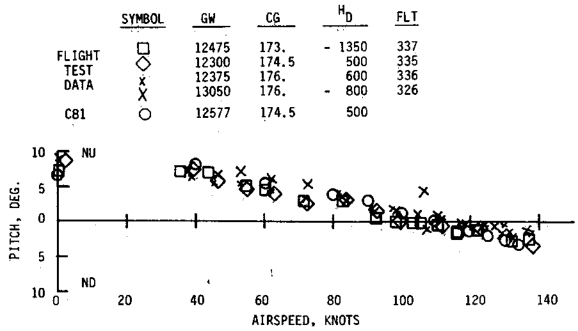

Fig. 10 SH-2F aircraft pitch attitude.

Table 1 Frequency and damping comparison in 6F and Myklestad

	6F (RHO = 0)				Myklestad	
	Uncoupled mode		Coupled mode		Coupled mode	
DOF	Freq. (per rev)	Damping (% critical)	Freq. (per rev)	Damping (% critical)	Freq. (per rev)	Damping (% critical)
Lagging	0.213	19.6	0.209	19.98	0.206	20.0
Flapping	1.023	2.0	1.022	2.0	1.021	2.0
Feathering	1.354	1.15	1.254	1.30	1.48	5.7
Bending	3.125	4.68	3.18	4.785	3.397	2.2
Twisting	3.946	5.17	13.41	20.17	13.93	4.1
Servo flap	14.72	5.12	15.27	5.2	– –	– –

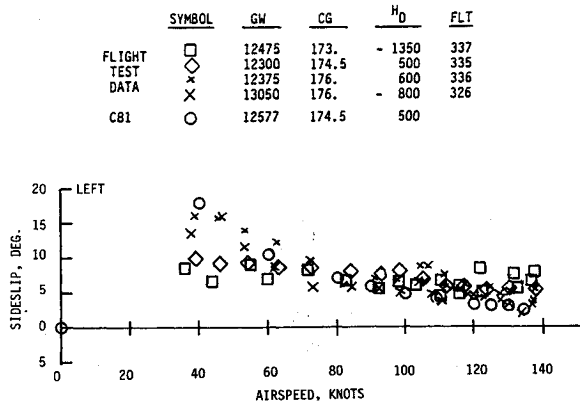

Fig. 11 SH-2F aircraft sideslip.

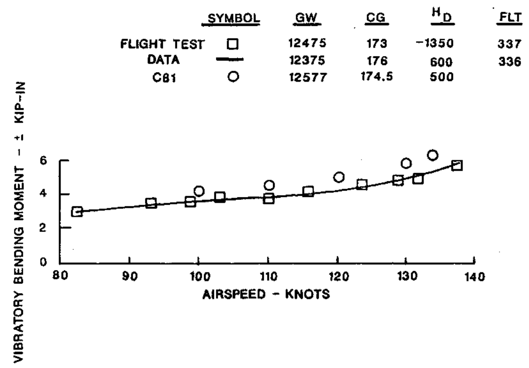

Fig. 12 SH-2F main rotor blade flatwise bending at station 98.

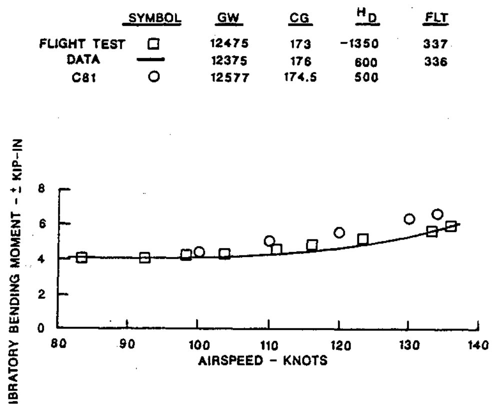

Fig. 13 SH-2F main rotor blade flatwise bending at station 158.

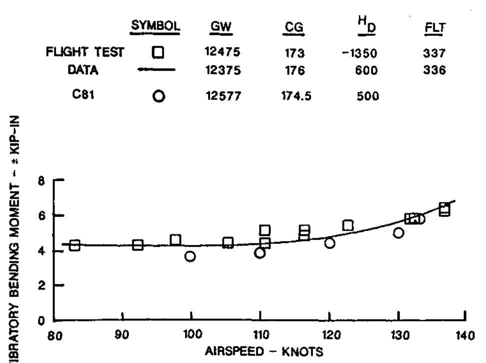

Fig. 14 SH-2F main rotor blade flatwise bending at station 192.

yaw angles. This is why the analysis contributes the different result in hover. From Fig. 5, similar results are obtained for the longitudinal cyclic control positions vs airspeed. Slight overpredictions are observed in hover and transition flight. For the lateral cyclic control position shown in Fig. 6, the analysis predicts excellent results as the helicopter airspeed is higher than 40 knots, and the analysis underpredicts the test data in hover. From Fig. 7, the analysis of directional pedal control position vs airspeed shows good correlation compared to the test data. The analysis has slightly underpredicted the test data. From Fig. 8, the analysis predicts the main rotor hub steady torque very well in the whole speed range. The main rotor torque predicts 6% lower in hover compared to the test data. This discrepancy can be improved if a wake model is used in the hover analysis.

The SH-2F helicopter vertical tail is designed to have 6.5 deg cambered toward the port side. As the helicopter forward speed increases, the thrust will be generated to the right-hand side of the fuselage. This thrust, generated by the vertical tail, could be used to unload the tail rotor thrust during the high-speed flight. Therefore, it is interesting to correlate the tail rotor thrust in the entire speed range. Results show that the analysis correlates the test data exceptionally well (see Fig. 9).

The range of fuselage pitch attitude and sideslip angle variations as functions of airspeed are also examined and correlated, as shown in Figs. 10 and 11. Good correlations between test data and analysis are achieved. In Fig. 11, the results show that the sideslip angle is predicted slightly higher at 40 knots airspeed compared to the test data.

The SH-2F helicopter has a very low vibration level. The 4/rev vertical hub shear at 134 knots airspeed obtained from the analysis is less than 480 lb, which is in agreement with the existing SH-2F helicopter vibration characteristics.

The bending moment distributions along the blade, at three blade stations (98, 158, and 192), are also computed and compared with the test data at speeds higher than 90 knots. Results show that these correlations agree well, as shown in Figs. 12–14. The main rotor blade flatwise bending moments at stations 98 and 158 are slightly overpredicted as airspeed increases. This slight overprediction could be a good conservative approach for future design analysis. Also, station 192, used in the correlation located at the midpoint of the servo flap region, has the unique characteristics that one cannot find in the conventional type of rotor. The vibratory bending moment at station 192 is slightly underpredicted. This could be because the aerodynamic coefficients used in the analysis for the servo flap model have not included the three-dimensional effects.

Conclusions

The rotorcraft flight simulation computer program has been successfully modified to have the capability of analyzing the servo flap controlled main rotor. The aerodynamic coefficients obtained from the airfoil tables have been modified to include the servo flap deflection effects. The analytical model in the analysis treats the servo flap as a control system only, not a degree of freedom. Very low 4/rev vertical hub shears and 3/rev hub moments are also obtained using the modified computer program to reflect the low vibration characteristics of the SH-2F helicopter. The correlation between the analysis and the test data is excellent. This program can be a viable tool for future advanced servo flap rotor analysis.

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