Rotorcraft Aeromechanical Stability—Methodology Assessment: Phase 2 Workshop

William G. Bousman

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Rotorcraft Aeromechanical Stability--Methodology Assessment: Phase 2 Workshop

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March 1990
ROTORCRAFT AEROMECHANICAL STABILITY - METHODOLOGY ASSESSMENT PHASE 2 WORKSHOP

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Ames Research Center
and
Aeroflightdynamics Directorate
U.S. Army Research and Technology Activity (AVSCOM)

Introduction

A workshop was held at Ames Research Center August 2-3, 1988 to discuss the results of the Methodology Assessment Phase 2 Continuation. This workshop was a follow-on to the original Methodology Assessment reported in Ref. 1. The present volume contains the predictions that were obtained under the continuation efforts.

The original Integrated Technology Rotor (ITR) Methodology Assessment was a Government-funded study to assess the capability of industry analyses to predict the aeroelastic and aeromechanical stability of rotorcraft. Six different sets of experimental data were used as a baseline ranging from a hingeless rotor model in hover to data on a full-scale bearingless rotor in forward flight as shown in Table 1. For each data set, A through F, several cases or configuration variations were identified to enable comparisons for a range of rotor aeroelastic effects. Analyses from Bell Helicopter Textron, Boeing Helicopters, McDonnell Douglas Helicopter Company, and Sikorsky Aircraft were compared with the data. The first workshop to discuss these results was held in June 1983 at Ames Research Center and was reported in Ref. 1.

Following the original assessment, two data sets were selected for a significantly more detailed comparison in an effort referred to as the Phase 1 Continuation. The first set selected (Data Set A, Case 6) was for the torsionally-soft hingeless rotor model in hover with a soft pitch flexure and negative droop. This particular case had shown the greatest discrepancies in the Methodology Assessment results. The second case (Data Set C, Case 3) was from an aeromechanical rotor-body stability model test where there was extensive data available on modes other than the lead-lag regressing mode. Whereas in the original Methodology Assessment the basis of comparison was the damping of the least stable mode, in the Phase 1 Continuation the damping and frequency of all the rotor modes in the frequency range of the least stable mode were examined.

A Phase 2 Continuation effort followed the Phase 1 work. Additional computations were made with the torsionally-soft hingeless rotor model of Data Set A. The acquisition of frequency data in a vacuum test of this model rotor (Ref. 2) prompted inclusion of new calculations to compare with these data as well. A simplified hypothetical version of the torsionally-soft rotor model was also specified that retained the aeroelastic coupling effects that had caused difficulties in the torsionally-soft rotor comparisons but eliminated the unimportant blade root hardware that complicated the assessments. Finally, two new matched-stiffness configurations were added for the aeromechanical stability test (Data Set C) that had not been examined previously.
Table 1. — Experimental Data Sets

<table>
<thead>
<tr>
<th>DATA SET</th>
<th>ROTOR TYPE</th>
<th>FUSELAGE COUPLING</th>
<th>FLIGHT CONDITION</th>
<th>SCALE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hingeless</td>
<td>Isolated</td>
<td>Hover</td>
<td>Model</td>
<td>Aeroflightdynamics</td>
</tr>
<tr>
<td>B</td>
<td>Hingeless</td>
<td>Rotor-Body</td>
<td>Hover</td>
<td>Model</td>
<td>Aeroflightdynamics</td>
</tr>
<tr>
<td>C</td>
<td>Hingeless</td>
<td>Rotor-Body</td>
<td>Hover</td>
<td>Model</td>
<td>Aeroflightdynamics</td>
</tr>
<tr>
<td>D</td>
<td>Bearingless</td>
<td>Isolated</td>
<td>Hover</td>
<td>Model</td>
<td>Aeroflightdynamics</td>
</tr>
<tr>
<td>E</td>
<td>Bearingless</td>
<td>Rotor-Body</td>
<td>Hover/Fwd Flt</td>
<td>Model</td>
<td>Boeing Helicopters</td>
</tr>
<tr>
<td>F</td>
<td>Bearingless</td>
<td>Rotor-Body</td>
<td>Hover/Fwd Flt</td>
<td>Full</td>
<td>Boeing Helicopters</td>
</tr>
</tbody>
</table>

The purpose of this report was to collect and publish the results of the Phase 1 and Phase 2 Methodology Assessment Continuation efforts for use by future investigators. Discussion of these results is not provided in this document; conclusions about the relative merits of the various prediction codes, the quality of the predicted results, or explanation of the sources of differences between predicted and measured data are left to the reader. A full description of the experimental data sets, the experiments themselves, and the prediction codes can be found in Ref. 1. Although the analysis results presented in the figures contained herein should be self-explanatory, additional discussion of some details may be found in Ref. 1. This report is intended to be a companion to that report.

The report is organized into four sections presenting the results for the predictions of the four data sets addressed in the Phase 1 and Phase 2 Continuations.

Torsionally-Soft Hingeless Rotor Model

The damping predictions shown in the original Methodology Assessment for the torsionally-soft rotor model (Data Set A) were obtained for six different cases or configurations. For the Phase 1 and 2 Continuations, more detailed predictions were made for Cases 2 and 6, and these predictions included the damping and frequency of the flap, lead-lag, and torsion modes as well as the blade equilibrium flap, lead-lag, and torsional deflections. The additional parameters calculated in the continuation were intended to help understand the variations in the original lead-lag damping results. The two cases studied, both with the soft pitch-flexure configuration, were Case 2 without precone or droop and Case 6 with -5° droop and no precone. The Case 6 configuration has the largest aeroelastic coupling and showed the widest variations in predicted lead-lag damping. The calculations shown here are outlined in Table 2. The task numbers shown in Table 2 refer to the tasks listed in the continuation statement of work. The calculations are shown on the pages indicated in the table. A symbol is shown on the torsionally-soft rotor plots that represents the case plotted. The middle section of the symbol represents the root configuration and is open for cases with a soft pitch-flexure (Cases 2 and 6). The right hand section of the symbol represents the blade and is horizontal for Case 2 (no precone or droop) and is canted upwards for Case 6 (-5° droop).
Table 2. - Torsionally-Soft Rotor Hover Test (Data Set A)

<table>
<thead>
<tr>
<th>CASE</th>
<th>PITCH FLEXURE</th>
<th>PRECONE $\beta_{pe}$, deg</th>
<th>DROOP $\beta_d$, deg</th>
<th>PHASE 2</th>
<th>PAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>stiff</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>soft</td>
<td>0.0</td>
<td>0.0</td>
<td>Tasks 86d, 86e</td>
<td>10-107</td>
</tr>
<tr>
<td>3</td>
<td>stiff</td>
<td>5.0</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>soft</td>
<td>5.0</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>stiff</td>
<td>0.0</td>
<td>-5.0</td>
<td>Tasks 86f, 86g</td>
<td>108-205</td>
</tr>
<tr>
<td>6</td>
<td>soft</td>
<td>0.0</td>
<td>-5.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The same model properties were used for the Phase 2 calculations as were used in the original Methodology Assessment (Ref. 1) except the analysts were instructed to adjust the chordwise structural properties so that the predicted nonrotating lead-lag frequency matched the measured Case 2 value. The chordwise properties were then fixed for the rest of the torsionally-soft rotor cases. For the Case 2 configuration without precone or droop, the Phase 2 comparisons of theory and experiment for Task 86d are shown on pages 10 to 44. Nonlinear aerodynamic section properties were used for these calculations, that is,

$$c_\ell = 6\alpha - (\text{sgn}\alpha) 10\alpha^2$$

$$c_d = 0.01 + 11.1|\alpha|^3$$

The same comparisons were made in Task 86e except that linear aerodynamic section properties were used

$$c_\ell = 2\pi\alpha$$

$$c_d = 0.008$$

The pitching moment was assumed to be zero and the section properties were assumed independent of Mach number for both tasks. The Task 86e calculations are shown on pages 45 to 107. Included in these calculations are comparisons of the linear and nonlinear predictions for each analyst.

Calculations made with nonlinear section properties for Case 6 (Task 86f) are given on pages 108 to 142. The predictions made with linear aerodynamic section properties (Task 86g) are on pages 143 to 205. Again, these latter calculations include comparisons of the linear and nonlinear predictions for each analyst.
Torsionally-Soft Hingeless Rotor Model in Vacuum

Calculations of flap, lead-lag, and torsion frequencies in vacuum were made during the Phase 2 continuation and these are compared here to experimental measurements that have been obtained on the torsionally-soft rotor model (Ref. 2). These results provide an opportunity to compare basic rotor structural and inertial analyses without the additional uncertainties of aerodynamic modeling. The calculations are shown for the cases outlined in Table 3. The comparisons for Case 2 (Task 86b) are on pages 206 to 215. The Case 6 comparisons (Task 86c) are on pages 216 to 225.

Table 3. – Torsionally-Soft Rotor Vacuum Test

<table>
<thead>
<tr>
<th>CASE</th>
<th>PITCH FLEXURE</th>
<th>PRECONE $\beta_p$, deg</th>
<th>DROOP $\beta_d$, deg</th>
<th>PHASE 2</th>
<th>PAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>soft</td>
<td>0.0</td>
<td>0.0</td>
<td>Task 86b</td>
<td>206-215</td>
</tr>
<tr>
<td>6</td>
<td>soft</td>
<td>0.0</td>
<td>-5.0</td>
<td>Task 86c</td>
<td>216-225</td>
</tr>
</tbody>
</table>

Hypothetical Torsionally-Soft Hingeless Rotor

Although the torsionally-soft hingeless rotor model represents an almost ideal configuration intended for research purposes, several physical details such as the pitch flexure and blade root retention hardware require some care to properly represent in prediction codes. To remove these complications and provide a more unambiguous basis for analysis comparisons, a hypothetical rotor model was specified for the Phase 2 calculations. This rotor shows a number of simplifications from the actual torsionally-soft rotor model. A sketch of the hypothetical model is shown in Fig. 1 to illustrate the coordinate system that defines the blade pitch and precone angles. The blade of the hypothetical rotor model is defined in a coordinate system $\mathbf{b}_j^p$, where the blade axis system is defined relative to the coordinate system by

$$\mathbf{b}_i^p = [C_{ij}] \mathbf{b}_j^p$$

$$[C_{ij}] = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \beta & 0 & -\sin \beta \\ 0 & 1 & 0 \\ \sin \beta & 0 & \cos \beta \end{bmatrix}$$
Figure 1. – Schematic of hypothetical rotor model.

Table 4. – Hypothetical Rotor Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius, in</td>
<td>36.0</td>
</tr>
<tr>
<td>Chord, in</td>
<td>3.5</td>
</tr>
<tr>
<td>Blade mass, lb-in</td>
<td>0.0167</td>
</tr>
<tr>
<td>Blade inertia about elastic axis, lb-in^2/in</td>
<td>0.0167</td>
</tr>
<tr>
<td>Flap stiffness, lb-in^2</td>
<td>6000.</td>
</tr>
<tr>
<td>Chord stiffness, lb-in^2</td>
<td>100000.</td>
</tr>
<tr>
<td>Torsional stiffness, lb-in^2</td>
<td>1800.</td>
</tr>
<tr>
<td>Lift curve slope</td>
<td>6.28</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.01</td>
</tr>
<tr>
<td>Structural damping</td>
<td>0.0</td>
</tr>
</tbody>
</table>

where $\theta$ is the blade pitch angle and $\beta$ is the precone angle. The blade properties are given in Table 4. The blade c.g., and the elastic and tensile axes are at the 25% chord.

Two cases were calculated for the hypothetical rotor as shown in Table 5. The calculations are shown on pages 226-231 for the case without precone (Task 86h) and on pages 232-237 for the case with $5^\circ$ precone (Task 86i). As in the case of the torsionally-soft rotor calculations a symbol is used on the plots to represent the case being examined. As the hypothetical rotor does not have a pitch flexure there is no middle section to the symbol. The right hand section is either horizontal for zero precone cases or canted up for cases with precone.
Table 5. – Hypothetical Rotor

<table>
<thead>
<tr>
<th>PRECONES</th>
<th>PHASE 2</th>
<th>PAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{pe}$, deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>Task 86h</td>
<td>226-231</td>
</tr>
<tr>
<td>5.0</td>
<td>Task 86i</td>
<td>232-237</td>
</tr>
</tbody>
</table>

Hingeless Rotor Body Model

Calculations of modal frequency and damping have been compared to the coupled rotor-body experimental model data of Ref. 3 in the Phase 1 and 2 Continuations. Calculations have been made for Case 3 of the original Methodology Assessment as well for configurations not previously examined. The calculation cases are outlined in Table 6. Tabulated parameters in Table 6 include the pitch-lag coupling, $\theta_{\zeta}$, and the elastic coupling, $R$.

Table 6. – Aeromechanical Stability

<table>
<thead>
<tr>
<th>CONF.</th>
<th>FLAP &amp; LAG STIFFNESSES</th>
<th>$\theta_{\zeta}$</th>
<th>R</th>
<th>METHODOLOGY ASSESSMENT CASES</th>
<th>PHASE 1</th>
<th>PHASE 2</th>
<th>PAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Ref. 3)</td>
<td>$\omega_{\beta_0} &lt; \omega_{\zeta_0}$</td>
<td>0.0</td>
<td>0</td>
<td>1,2</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>$\omega_{\beta_0} &lt; \omega_{\zeta_0}$</td>
<td>-0.4</td>
<td>0</td>
<td>3</td>
<td>Task 84-2</td>
<td>–</td>
<td>238-244</td>
</tr>
<tr>
<td>3</td>
<td>$\omega_{\beta_0} &lt; \omega_{\zeta_0}$</td>
<td>-0.4</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>$\omega_{\beta_0} \approx \omega_{\zeta_0}$</td>
<td>0.0</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>$\omega_{\beta_0} \approx \omega_{\zeta_0}$</td>
<td>-0.4</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Task 86j, 86k 250-267</td>
</tr>
</tbody>
</table>

The Task 84-2 calculations were made for a blade pitch angle of 9° and are compared to the data on pages 238 to 249. These results include frequency and damping of several modes in addition to the least stable mode that was presented in the original Methodology Assessment. The Phase 2 Continuation addressed a model configuration having roughly equal flap and lead-lag flexure bending stiffness levels. This "matched stiffness" configuration revealed evidence of a dynamic inflow mode that was later confirmed by analysis (Ref. 4). The Task 86j and 86k calculations were addressed to this matched stiffness configuration and included dynamic inflow models where available. For Task 86j the flap and lead-lag flexure thicknesses were adjusted from the Methodology Assessment model parameters to yield nonrotating flap and lead-lag frequencies of 7.04 and 6.64 Hz respectively. For Task 86k the adjustments were made to provide values of 6.73 and 6.64 Hz for the nonrotating flap and lead-lag frequencies. The Task 86j calculations were run for a pitch angle of 9° and are shown on pages 250 to 258. The Task 86k calculations were run for zero pitch and are shown on pages 259 to 267.
References


APPENDIX

ROTOR CONFIGURATION ANALYSIS DATA
FLAP MODE DAMPING – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)

PITCH ANGLE, deg
0 4 8 12

FLAP MODE DAMPING, 1/sec
0 -10 -20 -30 -40 -50 -60
FLAP MODE FREQUENCY – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)

FLAP MODE FREQUENCY, Hz

PITCH ANGLE, deg
LEAD–LAG MODE DAMPING – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)
LEAD–LAG MODE FREQUENCY – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION:
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFIGHTDYNAMICS (GRASP)

LEAD–LAG MODE FREQUENCY, Hz

PITCH ANGLE, deg
TORSION MODE DAMPING – TASK 86d
NONLINEAR AERODYNAMIC COEefICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)

TORSION MODE DAMPING, 1/sec

-80
-70
-60
-50
-40
-30
-20
-10
0
10

PITCH ANGLE, deg

-12 -8 -4 0 4 8 12
TORSION MODE FREQUENCY – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (GRASP)

PITCH ANGLE, deg

TORSION MODE FREQUENCY, Hz
FLAP EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −4 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg

CALCULATION
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFLIGHTDYNAMICS (GRASP)
FLAP EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg
LEAD-LAG EQUILIBRIUM DEFLECTION - TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 66d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −8 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg
TORSION EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −12 deg

DEFLECTION, deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)

BLADE STATION, in
TORSION EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg

DEFLECTION, deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)

BLADE STATION, in
TORSION EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −4 deg
TORSION EQUILIBRIUM DEFLECTION - TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2  TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)
TORSION EQUILIBRIUM DEFLECTION - TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
TORISON EQUILIBRIUM DEFLECTION - TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)

DEFLECTION, deg

BLADE STATION, in
TORSION EQUILIBRIUM DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg
BLADE TIP DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION - TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg

FLAP DEFLECTION, in

LEAD-LAG DEFLECTION, in

CALCULATION

+ = UNDEFORMED
O = BELL HELICOPTER TEXTRON
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS HELICOPTER
■ = SIKORSKY AIRCRAFT
X = AEROFLIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg

CALCULATION
+ = UNDEFORMED
O = BELL HELICOPTER TEXTRON
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS HELICOPTER
■ = SIKORSKY AIRCRAFT
X = AEROFLIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg

CALCULATION

+ = UNDEFORMED
O = BELL HELICOPTER TEXITRON
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS HELICOPTER
■ = SIKORSKY AIRCRAFT
X = AEROFIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg
BLADE TIP DEFLECTION – TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
BLADE TIP DEFLECTION - TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg

CALCULATION
+ = UNDEFORMED
O = BELL HELICOPTER TEXTRON
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS HELICOPTER
■ = SIKORSKY AIRCRAFT
× = AEROFLIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION - TASK 86d
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

CALCULATION
÷ = UNDEFORMED
○ = BELL HELICOPTER TEXTRON
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS HELICOPTER
■ = SIKORSKY AIRCRAFT
× = AEROFIGHTDYNAMICS (GRASP)
FLAP MODE DAMPING – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (PFLT)

FLAP MODE DAMPING, 1/sec

PITCH ANGLE, deg
LEAD–LAG MODE DAMPING – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROSCRIPT DYNAMICS (PFLT)

LEAD–LAG MODE DAMPING, 1/sec

PITCH ANGLE, deg
LEAD–LAG MODE FREQUENCY – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION

BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (PFLT)

LEAD–LAG MODE FREQUENCY, Hz

PITCH ANGLE, deg
TORSION MODE FREQUENCY – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (PFL1)
FLAP MODE DAMPING
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

FLAP MODE DAMPING, 1/sec

PITCH ANGLE, deg
FLAP MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

FLAP MODE FREQUENCY, Hz

PITCH ANGLE, deg
LEAD–LAG MODE DAMPING
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

PITCH ANGLE, deg

LEAD–LAG MODE DAMPING, 1/sec
LEAD–LAG MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

PITCH ANGLE, deg

LEAD–LAG MODE FREQUENCY, Hz
TORSION MODE DAMPING
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

TORSION MODE DAMPING, 1/sec

PITCH ANGLE, deg
TORSION MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

TORSION MODE FREQUENCY, Hz

PITCH ANGLE, deg
LEAD–LAG MODE DAMPING
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

LEAD–LAG MODE DAMPING, 1/sec

PITCH ANGLE, deg
LEAD–LAG MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

LEAD–LAG MODE FREQUENCY, Hz

PITCH ANGLE, deg
TORSION MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

TORSION MODE FREQUENCY, Hz

PITCH ANGLE, deg
FLAP MODE DAMPING
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 2. NONLINEAR AERO
CASE 2. LINEAR AERO

FLAP MODE DAMPING, 1/sec

PITCH ANGLE, deg

0.0
-10.0
-20.0
-30.0
-40.0
-50.0

-12
-8
-4
0
4
8
12
FLAP MODE FREQUENCY
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

FLAP MODE FREQUENCY, Hz

PITCH ANGLE, deg
LEAD–LAG MODE DAMPING
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

LEAD–LAG MODE DAMPING, 1/sec

PITCH ANGLE, deg

-12 -8 -4 0 4 8 12
TORSION MODE DAMPING
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

TORSION MODE DAMPING, 1/sec

PITCH ANGLE, deg
TORSION MODE FREQUENCY
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

TORSION MODE FREQUENCY, Hz

PITCH ANGLE, deg
FLAP MODE DAMPING
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

FLAP MODE DAMPING, 1/sec

PITCH ANGLE, deg
FLAP MODE FREQUENCY
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO
LEAD–LAG MODE DAMPING
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

PITCH ANGLE, deg

LEAD–LAG MODE DAMPING, 1/sec
TORSION MODE DAMPING
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

TORSION MODE DAMPING, 1/sec

PITCH ANGLE, deg
TORSION MODE FREQUENCY
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
CASE 2, NONLINEAR AERO
CASE 2, LINEAR AERO

PITCH ANGLE, deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −12 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg
FLAP EQUILIBRUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg

BLADE STATION, in

[Diagram with labels and deflection values]
FLAP EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

DEFLECTION, in

0 5 10 15 20 25 30 35 40
BLADE STATION, in

CALCULATION

BELL

BOEING HELICOPTER

MCDONNELL DOUGLAS

SIKORSKY
LEAD-LAG EQUILIBRIUM DEFLECTION - TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg

DEFLECTION, in

CALCULATION

BELL
BOEING HELICOPTER
MCDONNELL DOUGLAS
SIKORSKY

BLADE STATION, in
LEAD–LAG EQUILIBRIUM DEFLECTION - TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 66e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg
TORSION EQUILIBRIUM DEFLECTION - TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg
TORSION EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg
TORSION EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg

DEFORMATION, deg

BLADE STATION, in

BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY
TORSION EQUILIBRIUM DEFLECTION - TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE == 0 deg

DEFLECTION, deg

BLADE STATION, in
TORSION EQUILIBRIUM DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg
TORSION EQUILIBRIUM DEFLECTION - TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

CALCULATION
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- McDONNELL DOUGLAS HELICOPTER
- SIKORSKY

DEFLECTION, deg

BLADE STATION, in
BLADE TIP DEFLECTION - TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR

CALCULATION
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFLIGHTDYNAMICS (PFLT)

FLAP DEFLECTION, in

LEAD-LAG DEFLECTION, in
BLADE TIP DEFLECTION
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
- CASE 2, NONLINEAR AERO
- CASE 2, LINEAR AERO

FLAP DEFLECTION, in

LEAD-LAG DEFLECTION, in
BLADE TIP DEFLECTION
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

FLAP DEFLECTION, in

LEAD–LAG DEFLECTION, in

CALCULATION
○ CASE 2, NONLINEAR AERO
□ CASE 2, LINEAR AERO
BLADE TIP DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −12 deg

CALCULATIONS
+= UNDEFORMED
○ = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
Χ = AEROFLIGHTDYNAMICS (PFLT)
BLADE TIP DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −8 deg

CALCULATIONS
+ = UNDEFORMED
○ = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
× = AEROFLIGHTDYNAMICS (PFLT)
BLADE TIP DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg
BLADE TIP DEFORMATION - TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONAL SOFT ROTOR
PITCH ANGLE = 0 deg

CALCULATIONS

+= UNDEFORMED
O = BELL
□ = BOEING HELICOPTER
○ = MCDONNELL DOUGLAS
■ = SIKORSKY
X = AEROFIGHTDYNAMICS (PFLT)

LEAD-LAG DEFORMATION, in
FLAP DEFORMATION, in
BLADE TIP DEFLECTION – TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
BLADE TIP DEFLECTION - TASK 86e
LINEAR AERODYNAMIC COEFFICIENTS
CASE 2 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

CALCULATIONS
+ = UNDEFORMED
O = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
X = AEROFIGHTDYNAMICS (PFLT)
FLAP MODE FREQUENCY – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (GRASP)

FLAP MODE FREQUENCY, Hz

PITCH ANGLE, deg

-12 -8 -4 0 4 8 12
LEAD–LAG MODE DAMPING – TASK 861
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)

LEAD–LAG MODE DAMPING, 1/sec

PITCH ANGLE, deg

-12
-10
-8
-6
-4
-2
0
0
-12
-8
-4
0
4
8
12
LEAD–LAG MODE FREQUENCY – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (GRASP)
TORSION MODE DAMPING – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIIGHTDYNAMICS (GRASP)

TORSION MODE DAMPING, 1/sec

PITCH ANGLE, deg

-12 -8 -4 0 4 8 12
TORSION MODE FREQUENCY – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
Bell Helicopter Textron
Boeing Helicopter
McDonnell Douglas Helicopter
Sikorsky Aircraft
Aeroflightdynamics (GRASP)
FLAP EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg
FLAP EQUILIBRIUM DEFLECTION - TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg

DEFLECTION, in

-3 -2 -1 0 1 2 3

BLADE STATION, in

0 5 10 15 20 25 30 35 40

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)
FLAP EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 861
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg
LEAD—LAG EQUILIBRIUM DEFLECTION - TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg

DEFLECTION, in
0 0.2 0.4 0.6
-0.2 -0.4 -0.6 -0.8 -1 -1.2 -1.4

BLADE STATION, in
0 5 10 15 20 25 30 35 40

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg

DEFLECTION, in

BLADE STATION, in

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 861
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = –4 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg

DEFLECTION, in

CALCULATION
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFIIGHTDYNAMICS (GRASP)

BLADE STATION, in
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

BLADE STATION, in
DEFLECTION, in
\[ \text{CALCULATION} \]
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFIGHTDYNAMICS (GRASP)
TORSION EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg

DEFLECTION, deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (GRASP)

BLADE STATION, in
TORSION EQUILIBRIUM DEFLECTION - TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AERODYNAMICS (GRASP)

DEFORMATION, deg

BLADE STATION, in
TORSION EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −4 deg
TORSION EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROPROFLIGHTDYNAMICS (GRASP)
TORSION EQUILIBRIUM DEFLECTION - TASK 86I
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (GRASP)

DEFLECTION, deg

BLADE STATION, in
TORSION EQUILIBRIUM DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFLIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg

CALCULATION
+= UNDEFORMED
○= BELL HELICOPTER TEXTRON
□= BOEING HELICOPTER
●= MCDONNELL DOUGLAS HELICOPTER
■= SIKORSKY AIRCRAFT
⨯= AEROFLIGHTDYNAMICS (GRASP)

FLAP DEFLECTION, in

LEAD–LAG DEFLECTION, in
BLADE TIP DEFLECTION - TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg

CALCULATION
+= UNDEFORMED
O = BELL HELICOPTER TEXTRON
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS HELICOPTER
■ = SIKORSKY AIRCRAFT
× = AEROFLIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg
BLADE TIP DEFLECTION — TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 — TORSIONALLY SOFT ROTOR
FITCH ANGLE = 0 deg

CALCULATION
+ = UNDEFORMED
○ = BELL HELICOPTER TEXTRON
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS HELICOPTER
■ = SIKORSKY AIRCRAFT
× = AERFLIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg

CALCULATION
+ = UNDEFORMED
O = BELL HELICOPTER TEXTRON
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS HELICOPTER
■ = SIKORSKY AIRCRAFT
× = AEROFLIGHTDYNAMICS (GRASP)
BLADE TIP DEFLECTION – TASK 86f
NONLINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

CALCULATION
+= UNDEFORMED
O=BELL HELICOPTER TEXTRON
□=BOEING HELICOPTER
●=MCDONNELL DOUGLAS HELICOPTER
■=SIKORSKY AIRCRAFT
X=AEROFLIGHTDYNAMICS (GRASP)
FLAP MODE DAMPING – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (PFLT)
FLAP MODE FREQUENCY - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (PFLT)

FLAP MODE FREQUENCY, Hz

PITCH ANGLE, deg

-12 -8 -4 0 4 8 12
LEAD–LAG MODE DAMPING – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (PFLT)
LEAD—LAG MODE FREQUENCY – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROPHIGHTDYNAMICS (PFLT)

LEAD—LAG MODE FREQUENCY, Hz

PITCH ANGLE, deg
TORSION MODE FREQUENCY – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (PFLT)

TORSION MODE FREQUENCY, Hz

PITCH ANGLE, deg

30 35 40 45 50 55 60

-12 -8 -4 0 4 8 12
FLAP MODE DAMPING
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO
LEAD–LAG MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO

LEAD–LAG MODE FREQUENCY, Hz

PITCH ANGLE, deg
TORSION MODE DAMPING
TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO
FLAP MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO

FLAP MODE FREQUENCY, Hz

PITCH ANGLE, deg

0.0
5.0
10.0
15.0
20.0
25.0
30.0
LEAD–LAG MODE DAMPING
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO

LEAD–LAG MODE DAMPING, 1/sec

PITCH ANGLE, deg
LEAD–LAG MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

CALCULATION
CASE 6, NONLINEAR AERO
CASE 8, LINEAR AERO

LEAD–LAG MODE FREQUENCY, Hz

PITCH ANGLE, deg
TORSION MODE FREQUENCY
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO
FLAP MODE DAMPING
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO

FLAP MODE DAMPING, 1/sec

PITCH ANGLE, deg
FLAP MODE FREQUENCY
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO

FLAP MODE FREQUENCY, Hz

PITCH ANGLE, deg

0.0  5.0  10.0  15.0  20.0  25.0  30.0
-12 -8  -4   0   4   8   12
LEAD–LAG MODE DAMPING
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO

LEAD–LAG MODE DAMPING, 1/sec

PITCH ANGLE, deg
TORSION MODE FREQUENCY
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
CASE 6, NONLINEAR AERO
CASE 8, LINEAR AERO

TORSION MODE FREQUENCY, Hz

PITCH ANGLE, deg
FLAP MODE DAMPING
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO

FLAP MODE DAMPING, 1/sec

PITCH ANGLE, deg
LEAD—LAG MODE FREQUENCY
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO
TORSION MODE DAMPING
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
CASE 6, NONLINEAR AERO
CASE 6, LINEAR AERO

TORSION MODE DAMPING, 1/sec

PITCH ANGLE, deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -12 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = –4 deg

DEFLECTION, in

BLADE STATION, in

CALCULATION
BELL
BOEING HELICOPTER
MCDONNELL DOUGLAS
SIKORSKY
FLAP EQUILIBRIUM DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg

DEFLECTION, in

BLADE STATION, in
FLAP EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
FLAP EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg

DEFLECTION, in

-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0

BLADE STATION, in

0 5 10 15 20 25 30 35 40

CALCULATION

- BELL
- BOEING HELICOPTER
- MCDONNELL DOUGLAS
- SIKORSKY
FLAP EQUILIBRIUM DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −12 deg

DEFLECTION, in

BLADE STATION, in

CALCULATION
BELL
BOEING HELICOPTER
MCDONNELL DOUGLAS
SIKORSKY
LEAD-LAG EQUILIBRIUM DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg

CALCULATION
BELL
BOEING HELICOPTER
MCDONNELL DOUGLAS
SIKORSKY

DEFORMATION, in
0.8 0.4 0.2 0 0.2 0.4 0.6 0.8 1.0 1.2
-1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0

BLADE STATION, in
0 5 10 15 20 25 30 35 40

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LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −4 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg
LEAD–LAG EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg
TORSION EQUILIBRIUM DEFLECTION – TASK 66g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −12 deg

DEFLECTION, deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY

BLADE STATION, in
TORSION EQUILIBRIUM DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg
TORSION EQUILIBRIUM DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -4 deg
TORSION EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg
TORSION EQUILIBRIUM DEFLECTION – TASK 86G
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg
TORSION EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY
TORSION EQUILIBRIUM DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

DEFLECTION, deg

BLADE STATION, in
BLADE TIP DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR

CALCULATION

- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFLIGHTDYNAMICS (PFLT)

FLAP DEFLECTION, in

LEAD-LAG DEFLECTION, in
BLADE TIP DEFLECTION
TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

CALCULATION
  1) CASE 6, NONLINEAR AERO
  2) CASE 8, LINEAR AERO

LEAD–LAG DEFLECTION, in

FLAP DEFLECTION, in

0.0
0.5
1.0
1.5
2.0

-3.0
-2.0
-1.0
-0.5
0.0
BLADE TIP DEFLECTION
TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

CALCULATION
○ CASE 6, NONLINEAR AERO
□ CASE 6, LINEAR AERO

FLAP DEFLECTION, in

LEAD-LAG DEFLECTION, in
BLADE TIP DEFLECTION
TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

CALCULATION
○ CASE 6, NONLINEAR AERO
□ CASE 6, LINEAR AERO
BLADE TIP DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = -8 deg

CALCULATIONS
+ = UNDEFORMED
○ = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
× = AEROFLIGHTDYNAMICS (PFLT)
BLADE TIP DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = −4 deg

FLAP DEFLECTION, in

LEAD–LAG DEFLECTION, in

CALCULATIONS
+ = UNDEFORMED
O = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
× = AEROFIGHTDYNAMICS (PFLT)
BLADE TIP DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 0 deg

CALCULATIONS
+ = UNDEFORMED
O = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
X = AEROFLIGHTDYNAMICS (PFLT)
BLADE TIP DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 4 deg

CALCULATIONS
+ = UNDEFORMED
O = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
X = AEROFLIGHTDYNAMICS (PFLT)
BLADE TIP DEFLECTION - TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 - TORSIONALLY SOFT ROTOR
PITCH ANGLE = 8 deg

CALCULATIONS
++ = UNDEFORMED
O = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
× = AEROFIGHTDYNAMICS (PFLT)
BLADE TIP DEFLECTION – TASK 86g
LINEAR AERODYNAMIC COEFFICIENTS
CASE 6 – TORSIONALLY SOFT ROTOR
PITCH ANGLE = 12 deg

CALCULATIONS
+ = UNDEFORMED
O = BELL
□ = BOEING HELICOPTER
● = MCDONNELL DOUGLAS
■ = SIKORSKY
X = AEROFIGHTDYNAMICS (PFLT)
1st FLAP MODE FREQUENCY IN A VACUUM – TASK 86b
CASE 2 – TORSIONALLY SOFT ROTOR

MODAL FREQUENCY, Hz

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (PFLT)
AEROFIGHTDYNAMICS (GRASP)

ROTOR SPEED, rpm
1st LEAD–LAG MODE FREQUENCY IN A VACUUM – TASK 86b
CASE 2 – TORSIONALLY SOFT ROTOR
2nd FLAP MODE FREQUENCY IN A VACUUM – TASK 86b
CASE 2 – TORSIONALLY SOFT ROTOR

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm

CALCULATION

BELL HELICOPTER Textron
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (PFLT)
AEROFIGHTDYNAMICS (GRASP)
MODAL FREQUENCIES IN A VACUUM – TASK 86b
CASE 2 – TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

Modes
- 1st Flap Mode
- 1st Lead-Lag Mode
- 1st Torsion Mode
- 2nd Flap Mode

Modal Frequency, Hz

Rotor Speed, rpm
MODAL FREQUENCIES IN A VACUUM – TASK 86b
CASE 2 – TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

MODES
- 1st FLAP MODE
- 1st LEAD–LAG MODE
- 1st TORSION MODE
- 2nd FLAP MODE

MODAL FREQUENCY, Hz

0.0  10.0  20.0  30.0  40.0  50.0  60.0

ROTOR SPEED, rpm

0  200  400  600  800  1000
MODAL FREQUENCIES IN A VACUUM – TASK 86b
CASE 2 – TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

MODES
- 1st FLAP MODE
- 1st LEAD-LAG MODE
- 1st TORSION MODE
- 2nd FLAP MODE

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm
MODAL FREQUENCIES IN A VACUUM – TASK 86b
CASE 2 – TORSIONALLY SOFT ROTOR
AEROFLIGHTDYNAMICS (PFLT)

MODES
- 1st FLAP MODE
- 1st LEAD–LAG MODE
- 1st TORSION MODE
- 2nd FLAP MODE

MODAL FREQUENCY, Hz

ROTOR Speed, rpm
MODAL FREQUENCIES IN A VACUUM – TASK 86b
CASE 2 – TORSIONALLY SOFT ROTOR
AEROFIIGHTDYNAMICS (GRASP)

MODES
- 1st FLAP MODE
- 1st LEAD–LAG MODE
- 1st TORSION MODE
- 2nd FLAP MODE
1st FLAP MODE FREQUENCY IN A VACUUM – TASK 86c
CASE 6 – TORSIONALLY SOFT ROTOR

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (PFLT)
AEROFLIGHTDYNAMICS (GRASP)
1st LEAD–LAG MODE FREQUENCY IN A VACUUM – TASK 86c
CASE 6 – TORSIONALLY SOFT ROTOR

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFIGHTDYNAMICS (PFLT)
AEROFIGHTDYNAMICS (GRASP)
1st TORSION MODE FREQUENCY IN A VACUUM - TASK 86c
CASE 6 - TORSIONALLY SOFT ROTOR

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm

CALCULATION
- BELL HELICOPTER TEXTRON
- BOEING HELICOPTER
- MCDONNELL DOUGLAS HELICOPTER
- SIKORSKY AIRCRAFT
- AEROFLIGHTDYNAMICS (PFLT)
- AEROFLIGHTDYNAMICS (GRASP)
2nd FLAP MODE FREQUENCY IN A VACUUM – TASK 86c
CASE 6 – TORSIONALLY SOFT ROTOR

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT
AEROFLIGHTDYNAMICS (PFLT)
AEROFLIGHTDYNAMICS (GRASP)
MODAL FREQUENCIES IN A VACUUM - TASK 86c
CASE 6 - TORSIONALLY SOFT ROTOR
BELL HELICOPTER TEXTRON

MODES
- 1st FLAP MODE
- 1st LEAD-LAG MODE
- 1st TORSION MODE
- 2nd FLAP MODE

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm
MODAL FREQUENCIES IN A VACUUM - TASK 86c
CASE 6 - TORSIONALLY SOFT ROTOR
BOEING HELICOPTER

MODES
- 1st FLAP MODE
- 1st LEAD-LAG MODE
- 1st TORSION MODE
- 2nd FLAP MODE

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm
MODAL FREQUENCIES IN A VACUUM - TASK 86c
CASE 6 - TORSIONALLY SOFT ROTOR
MCDONNELL DOUGLAS HELICOPTER

MODES
- 1st FLAP MODE
- 1st LEAD–LAG MODE
- 1st TORSION MODE
- 2nd FLAP MODE

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm
MODAL FREQUENCIES IN A VACUUM – TASK 86c
CASE 6 – TORSIONALLY SOFT ROTOR
SIKORSKY AIRCRAFT

MODES
• 1st FLAP MODE
• 1st LEAD-LAG MODE
• 1st TORSION MODE
• 2nd FLAP MODE

MODAL FREQUENCY, Hz

0.0 10.0 20.0 30.0 40.0 50.0 60.0

ROTOR SPEED, rpm

0 200 400 600 800 1000
MODAL FREQUENCIES IN A VACUUM - TASK 86c
CASE 6 - TORSIONALLY SOFT ROTOR
AEROFIIGHTDYNAMICS (PFLT)

MODES
- 1st FLAP MODE
- 1st LEAD-LAG MODE
- 1st TORSION MODE
- 2nd FLAP MODE

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm
FLAP MODE FREQUENCY - TASK 86h
SIMPLIFIED ROTOR WITHOUT PRECONE

CALCULATION

BELL HELICOPTER TEXTRON
BOEING HELICOPTER
McDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT

PITCH ANGLE, deg

FLAP MODE FREQUENCY, Hz
LEAD–LAG MODE DAMPING – TASK 86h
Simplified Rotor Without Precone

Calculation
Bell Helicopter Textron
Boeing Helicopter
McDonnell Douglas Helicopter
Sikorsky Aircraft

Lead–Lag Mode Damping, 1/sec

Pitch Angle, deg

-14.0
-12.0
-10.0
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
-12 -8 -4 0 4 8 12
LEAD–LAG MODE FREQUENCY – TASK 86h
SIMPLIFIED ROTOR WITHOUT PRECONINE

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT

LEAD–LAG MODE FREQUENCY, Hz

PITCH ANGLE, deg
TORSION MODE DAMPING – TASK 86h
SIMPLIFIED ROTOR WITHOUT PRECONE

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT

TORSION MODE DAMPING, 1/sec

PITCH ANGLE, deg
TORSION MODE FREQUENCY – TASK 86h
SIMPLIFIED ROTOR WITHOUT PRECONE

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT

TORSION MODE FREQUENCY, Hz

PITCH ANGLE, deg

30.0
35.0
40.0
45.0
50.0
55.0
60.0

-12
-8
-4
0
4
8
12
FLAP MODE DAMPING – TASK 86i
SIMPLIFIED ROTOR WITH 5 deg. PRECONE

CALCULATION
BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT

FLAP MODE DAMPING, 1/sec

PITCH ANGLE, deg
FLAP MODE FREQUENCY – TASK 86i
SIMPLIFIED ROTOR WITH 5 deg. PRECONE

CALCULATION

BELL HELICOPTER TEXTRON
BOEING HELICOPTER
MCDONNELL DOUGLAS HELICOPTER
SIKORSKY AIRCRAFT

FLAP MODE FREQUENCY, Hz

PITCH ANGLE, deg
LEAD–LAG MODE DAMPING – TASK 86I

SIMPLIFIED ROTOR WITH 5 deg PRECONE

CALCULATION

BELL HELICOPTER TEXTRON

BOEING HELICOPTER

MCDONNELL DOUGLAS HELICOPTER

SIKORSKY AIRCRAFT

LEAD–LAG MODE DAMPING, 1/sec

PITCH ANGLE, deg

-14.0

-12.0

-10.0

-8.0

-6.0

-4.0

-2.0

0.0

2.0

4.0

6.0

8.0

10.0

12.0

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MODAL DAMPING – TASK 84-2
CONFIGURATION 3, PITCH ANGLE = 9 deg
BELL HELICOPTER TEXTRON

MODE
○ REGRESSING LEAD–LAG
○ BODY PITCH
□ BODY ROLL

MODAL DAMPING, 1/sec

-14

-12

-10

-8

-6

-4

-2

0

2

400 500 600 700 800 900 1000

UNSTABLE

ROTOR SPEED, rpm
MODAL FREQUENCY – TASK 84–2
CONFIGURATION 3, PITCH ANGLE = 9 deg
BELL HELICOPTER TEXTRON

MODE
○ REGRESSING LEAD–LAG
◇ BODY PITCH
□ BODY ROLL

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm
REGRESSING LEAD–LAG MODE DAMPING – TASK 84–2
CONFIGURATION 3, PITCH ANGLE = 9 deg
BELL HELICOPTER TEXTRON

![Graph showing regressing lead-lag mode damping against rotor speed. The graph indicates instability at certain rotor speeds.](image-url)
MODAL DAMPING – TASK 84–2
CONFIGURATION 3, PITCH ANGLE = 9 deg
BOEING HELICOPTER

MODE
○ REGRESSING LEAD–LAG
◇ BODY PITCH
□ BODY ROLL

MODAL DAMPING, 1/sec

UNSTABLE

ROTOR SPEED, rpm

-14
-12
-10
-8
-6
-4
-2
0
2
400 500 600 700 800 900 1000
MODAL FREQUENCY - TASK 84-2
CONFIGURATION 3, PITCH ANGLE = 9 deg
SIKORSKY AIRCRAFT

MODE
○ REGRESSING LEAD-LAG
♦ BODY PITCH
□ BODY ROLL

MODAL FREQUENCY, Hz

400 500 600 700 800 900 1000
ROTOR SPEED, rpm
MODAL DAMPING - TASK 84-2
CONFIGURATION 3, PITCH ANGLE = 9 deg
AEROFIIGHTDYNAMICS

MODE
○ REgressing LEAD-LAG
○ BODY PITCH
□ BODY ROLL

MODAL DAMPING, 1/sec

UNSTABLE

ROTOR SPEED, rpm
MODAL FREQUENCY – TASK 84–2
CONFIGURATION 3, PITCH ANGLE = 9 deg
AERONAUTICS

MODE
○ REGressing LEAD–LAG
◊ BODY PITCH
□ BODY ROLL

MODAL FREQUENCY, Hz

400 500 600 700 800 900 1000
ROTOR SPEED, rpm

1 2 3 4 5 6 7 8

REGRESSING LEAD–LAG MODE DAMPING – TASK 84–2
CONFIGURATION 3, PITCH ANGLE = 9 deg
AEROFIGHTDYNAMICS

REGRESSING LEAD–LAG MODE DAMPING, 1/sec

ROTOR SPEED, rpm

UNSTABLE
MODAL DAMPING – TASK 86j
CONFIGURATION 5, PITCH ANGLE = 9 deg
BELL HELICOPTER TEXTRON
REGRESSING LEAD–LAG MODE DAMPING – TASK 86j
CONFIGURATION 5, PITCH ANGLE = 9 deg
BELL HELICOPTER TEXTRON

REGRESSING LEAD–LAG MODE DAMPING, 1/sec

ROTOR SPEED, rpm

UNSTABLE
MODAL DAMPING — TASK 86j
CONFIGURATION 5, PITCH ANGLE = 9 deg
SIKORSKY AIRCRAFT
REGRESSING LEAD–LAG MODE DAMPING – TASK 86j
CONFIGURATION 5, PITCH ANGLE = 9 deg
SIKORSKY AIRCRAFT

![Graph showing regressing lead-lag mode damping vs. rotor speed. The graph indicates a stable region below 700 rpm and an unstable region above 900 rpm.](image)
MODAL DAMPING – TASK 86j
CONFIGURATION 5, PITCH ANGLE = 9 deg
U.S. ARMY AEROFIGHTDYNAMICS

MODE
○ REGRESSING LEAD-LAG
○ BODY PITCH
□ BODY ROLL

MODAL DAMPING, 1/sec

UNSTABLE

ROTOR SPEED, rpm
REGRESSING LEAD–LAG MODE DAMPING – TASK 86j
CONFIGURATION 5, PITCH ANGLE = 9 deg
U.S. ARMY AEROFIGHTDYNAMICS

![Graph showing regressing lead–lag mode damping against rotor speed. The graph plots damping values against rotor speed in RPM, with a trend line indicating instability at higher speeds. The data points are shown as circular markers.]
MODAL DAMPING - TASK 36k
CONFIGURATION 5, PITCH ANGLE = 0 deg
BELL HELICOPTER TEXTRON

MODE
- REGRESSING LEAD–LAG
- BODY PITCH
- BODY ROLL
- INFLOW

MODAL DAMPING, 1/sec

UNSTABLE

ROTOR SPEED, rpm
MODAL FREQUENCY - TASK 86k
CONFIGURATION 5, PITCH ANGLE = 0 deg
BELL HELICOPTER TEXTRON

MODE
- REGRESSING LEAD-LAG
- BODY PITCH
- BODY ROLL
- INFLOW

MODAL FREQUENCY, Hz

ROTOR SPEED, rpm
REGRESSING LEAD–LAG MODE DAMPING – TASK 86k
CONFIGURATION 5, PITCH ANGLE = 0 deg
BELL HELICOPTER TEXTRON
REGRESSING LEAD–LAG MODE DAMPING – TASK 86k
CONFIGURATION 5, PITCH ANGLE = 0 deg
SIKORSKY AIRCRAFT

REGRESSING LEAD–LAG MODE DAMPING, 1/sec

UNSTABLE

ROTOR SPEED, rpm
MODAL DAMPING – TASK 86k
CONFIGURATION 5, PITCH ANGLE = 0 deg
U.S. ARMY AEROSPACEFLIGHTDYNAMICS

MODE
- REGRESSING LEAD–LAG
- BODY PITCH
- BODY ROLL

MODAL DAMPING, 1/sec

UNSTABLE
MODAL FREQUENCY - TASK 86k
CONFIGURATION 5, PITCH ANGLE = 0 deg
U.S. ARMY AEROFIGHTDYNAMICS

MODE
○ REgressing LEAD-LAG
○ BODY PITCH
□ BODY ROLL

MODAL FREQUENCY, Hz

400 500 600 700 800 900 1000

ROTOR SPEED, rpm
# Rotorcraft Aeromechanical Stability—Methodology Assessment: Phase 2 Workshop

## Abstract
Helicopter rotor aeroelastic and aeromechanical stability predictions for four data sets were made using industry and government stability analyses and compared with data at a workshop held at Ames Research Center, August 2-3, 1988. The present report contains the workshop comparisons.

## Key Words
Aeromechanical stability, Rotorcraft aerodynamics, Aerodynamic stability, Helicopter futures.

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