TEST RESULTS FROM A DYNAMIC MODEL DYNAFLEX ROTOR

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Abstract

A one-fifth scale dynamic model of the Sikorsky Dynaflex rotor has been tested in hover and in forward flight conditions in the United Technologies Research Center Wind Tunnel. The Dynaflex rotor features an advanced composite structure which flexes to provide a constant speed universal joint action. Testing concentrated on confirming that the stability and dynamic response of the rotor were satisfactory. Lift conditions of up to .11 Ct/sigma and advance ratios as high as .46 were reached. Vibratory loads were comparable to those of articulated rotors. The Dynaflex rotor concept appears to be a practical concept from the standpoint of dynamic response and stability.

Introduction

Motivated by the desire to decrease complexity, weight, maintenance, and drag of the main rotor head, Sikorsky has undertaken the development of the Dynaflex rotor, a new concept for helicopter main rotor systems. The Dynaflex rotor is characterized by a bearingless rotor connected to the rotor shaft by a unique gimbal joint consisting of a spherical elastomeric bearing with comparitively flexible elastic restraint. The design has several advantages over articulated and pure bearingless rotor designs. Utilizing advances in composite material development, it offers lower weight and smaller parts count than conventional articulated rotors, while at the same time providing the option of a wide range of hub stiffness unavailable in inherently stiff pure bearingless designs. The spherical elastomeric bearing provides a constant-speed universal joint, greatly reducing Coriolis effects resulting from tip path plane tilt in articulated rotor systems. The Dynaflex rotor design is very clean aerodynamically, providing low drag, and a negative angle of zero lift so that hub downloads can be avoided at normal nose-down cruise attitudes.

Development of the Dynaflex rotor is described extensively in Reference 1. Two model rotor configurations based on a one fifth scale S-76 were fabricated and tested to demonstrate the feasibility of the concept and to evaluate the aeroelastic stability of the rotor. The first was a stiff-inplane configuration in which the first edgewise blade frequency was higher than the rotor speed. The second configuration was soft-inplane, in which the first edgewise blade frequency was lower than the rotor speed. The stiff in-plane model was tested in hover at reduced tip speed with nominal 100 percent rotor speed of 500 RPM. Rotor speeds ranged up to 650 RPM and collective pitch to 13.5 degrees. The rotor was stable over the entire test range (Fig. 1).

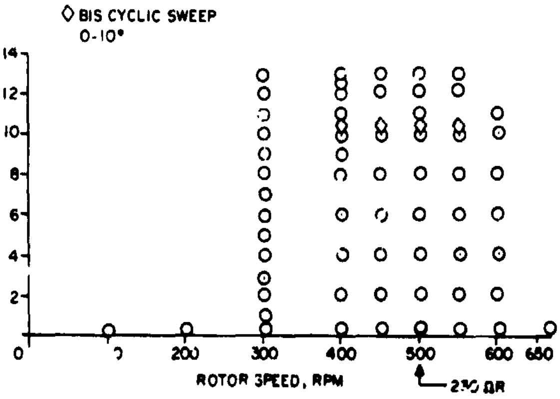

Fig. 1 Scope of Dynaflex reduced speed hover test.

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The soft-inplane Mach scale model was tested in hover at the Sikorsky hover stand and in forward flight in the UTRC wind tunnel. Hover test conditions included rotor speeds in excess of 1500 RPM (tip speed greater than 700 fps), and collective pitch up to 14 degrees. Forward flight testing covered a range of level flight conditions, with advance ratios up to 0.47 and Ct/sigma values up to 0.11 successfully achieved. Partial power descents and autorotation conditions up to 150 knots were also tested. The testing of the soft-inplane model is described in this paper.

Description of the Model

A drawing of the Dynaflex model rotor is shown in Fig. 2. The rotor incorporates composite twin C-flexbeams which accomodate flatwise, edgewise, and pitch change motions of the blades with respect to the hub. Blade pitch change is applied through a graphite/epoxy, torsionally stiff, torque shaft positioned between the twin flexbeams. The torque shaft is built into the blade/flexbeam juncture at its outboard end and restrained by ball-joint with radial slip at its inboard end. The flexbeams are rigidly fixed to the rotor hub, which in turn is connected to the rotor shaft through a spherical gimbal bearing. Hub stiffness is provided by the graphite epoxy gimbal spring, which is attached to the rotor shaft and blades. Fairings over the hub and flexbeams minimize the aerodynamic drag (Fig. 3).

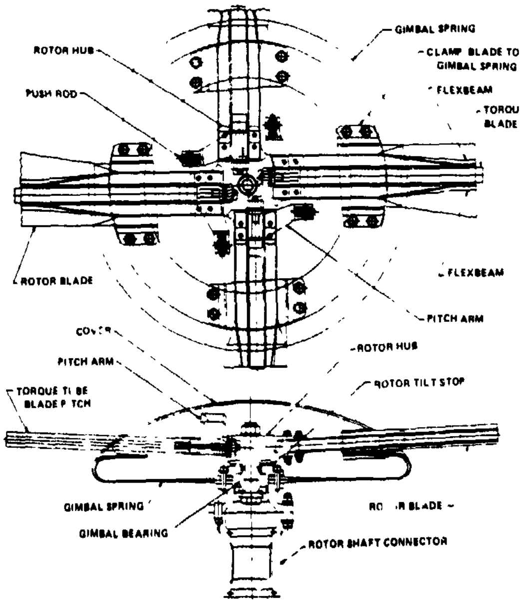
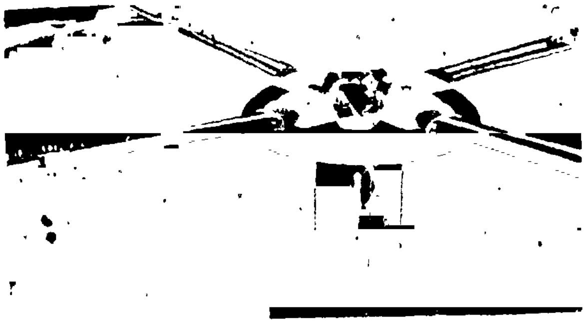


Fig. 2 Dynaflex rotor model.



Dynaflex rotor model without fairings installed

Dynaflex rotor model with fairings installed

Fig. 3 Dynaflex rotor model with and without hub fairings.

The model was designed to be a one-fifth scale S-76 main rotor, with gimbal spring to provide approximately the same hub moment constant achieved with the S-76 articulated main rotor with its four percent flapping hinge offset. Existing S-76 articulated rotor model blades were modified for use on the model rotor. The modifications consisted of cutting off the inboard end of the blade and locally reinforcing the inner end of the remaining blade for a blade-to-flexbeam attachment clevis. The Dynaflex model attributes are shown in Table 1.

ATTRIBUTE	REDUCED SPEED TEST (STIFF IN-PLANE)	MACH SCALE TEST (SOFT IN-PLANE)
TIP SPEED, ΩR, FT/SEC	230	675
1st FLATWISE COLLECTIVE FREQ, ω_{F1}/Ω	1.10	1.082
1st EDGEWISE FREQ, ω_{E1}/Ω	1.44	69
1st TORSION FREQ, ω_{T1}/Ω	16.3	5.13
2nd FLATWISE COLLECTIVE FREQ, ω_{F2}/Ω	3.22	2.48
GIMBAL STIFFNESS, IN.-LB/DEG	16	90
GIMBAL FREQUENCY, $\nu_G = \sqrt{1+\frac{K_G}{\frac{N}{2} I_B \Omega^2}}$	1.032	1.021
PRECONE AT HUB, DEG	2.5	2.5

Table 1. Dynaflex rotor attributes.

Description of Rotor Tests

Full scale speed testing of the Dynaflex model rotor took place in two phases. The first phase, hover testing, was undertaken with the objective of verifying aeroelastic and aeromechanical stability of the rotor concept for a wide range of rotor speeds, collective and cyclic pitches.

Hover testing took place at the Sikorsky Aircraft Model Rotor Test Stand. The test rig incorporates a gimbal support for a rotor strain gage balance, with adjustable springs and dampers across the gimbal pivots to provide detuning of support modes from unfavorable coupling with rotor modes. An electric motor drives the rotor through a universal joint coincident with the gimbal axes. The rig is mounted on a hydraulic ram to permit performance testing at various heights above the ground. Instrumentation was provided to measure flexbeam assembly flatwise and edgewise bending moments, forward and aft flexbeam tension, blade flatwise and edgewise bending moments, pushrod load, gimbal spring tilt, and gimbal spring strain. The rotor strain gage balance measured the six rotor force and moment components. Rig vibration was measured by six accelerometers.

Rotor hover testing was preceded by a shake test to determine rig natural mode properties. The G400 coupled rotor-fuselage aeroelastic analysis program was used with these properties to assess rotor and rig mechanical stability. Rig dynamic properties were improved by adding mass to the rotor hub.

Test conditions consisted of a rotor speed sweep at 4 degrees collective pitch, followed by collective pitch sweeps at various rotor speeds, and cyclic pitch sweeps at constant rotor speed and collective pitch settings. The scope of the hover test conditions is presented in Fig. 4. Rotor stability was probed for each test condition. The general procedure followed after proceeding to a new operating condition was to drive the support system with an electrodynamic shaker, using a slow sine sweep between 2 and 50 Hz. Support system mode frequency and damping could be evaluated from the shaker drive transfer function, as supplied on-line by an HP 5423 Dynamic Analysis System. Damping of progressing and regressing edgewise modes was evaluated by tuning the shaker to the fixed system frequency corresponding to the mode of interest. Tuning was accomplished by maximizing the response of the edgewise flexbeam gage as the shaker frequency was varied in the neighborhood of the fixed system frequency. After tuning the shaker to the proper frequency, the force level was abruptly terminated and the transient response of the edgewise gage was passed through a non-harmonic detector and recorded on an oscillograph. Damping was analyzed manually with the log decrement method.

After successful completion of the first phase of testing, forward flight testing began in the 18 foot diameter United Technologies Research Center Wind Tunnel. The primary purpose of this phase of testing was to confirm that dynamic response and stability were satisfactory over a range of simulated flight conditions. In addition, the test provided an opportunity to assess the behavior of blade, flexbeam, and gimbal spring load and stress as a function of gimbal tilt at various flight conditions. The test also provided data with which aeroelastic analyses could be correlated.

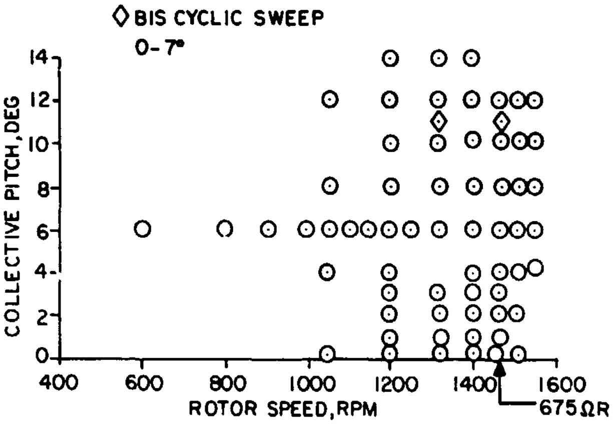


Fig. 4 Scope of Dynaflex Mach scale hover test.

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The test plan called for a shake test of the wind tunnel test rig, followed by hover testing, and finally a series of simulated flight conditions, including level flight, partial powered descents, and autorotation at a variety of lifts and forward speeds. Pitch moment variation, simulating fore and aft center of gravity, was also included in the test envelope. The model configuration and instrumentation were essentially the same as for the hover testing described above. Modal properties of the rotor rig as installed in the wind tunnel are listed in Table 2.

FREQUENCY (Hz)	MASS (LB-SEC**2/IN.)	DAMPING	X (AFT)	Y (STBD)	Z (VERT)	ROLL (LEFT)	PITCH (UP)
3.15	0758	.042	0 0	1 0	0 0	0 0	0 0
5 47	334	020	0.0	1 0	0 0	-.0606	0 0
6 75	261	049	1.0	0.0	0 0	0 0	0606
36 5	127	021	1 0	0 0	0 0	0 0	0 0
56 2	.149	.136	0 0	0 0	1 0	0 0	0 0

Table 2. Wind tunnel rig modal properties.

Fig. 5 shows the Dynaflex rotor as installed in the UTRC wind tunnel. Simulated flight conditions were achieved by setting the model rotor speed at the desired value with zero collective pitch, raising the tunnel velocity to that of the simulated flight condition, and then iterating on shaft angle, collective pitch, and cyclic pitch until desired levels of rotor lift, propulsive force, gimbal tilt, and hub moment were reached. Probing of edgewise mode stability was carried out as it was in the hover testing described above.

Fig. 5 Dynaflex rotor installation at UTRC wind tunnel.

The test envelope achieved for simulated level flight conditions is presented in Fig. 6. Fig. 7 shows the test conditions at which variations in rotor pitch moment were investigated. Figs. 8 and 9 present the conditions for partial power descent and autorotation. The variations in rotor speed were not applied as originally planned, but were the result of blade limitations at the higher forward speed conditions. The limitations were manifest as a blade instability which showed characteristics of those occurring for blades with aft chordwise center of gravity. The same blade instability was encountered with the blades mounted on a fully-articulated hub in a configuration that had previously been tested and found to be fully stable. Subsequent measurement of the model blades confirmed that rearward migration of the center of gravity had occurred in the course of their modification, use, and repair over a period of several years. Despite the restrictions imposed by blade limitations a valuable body of data was acquired.

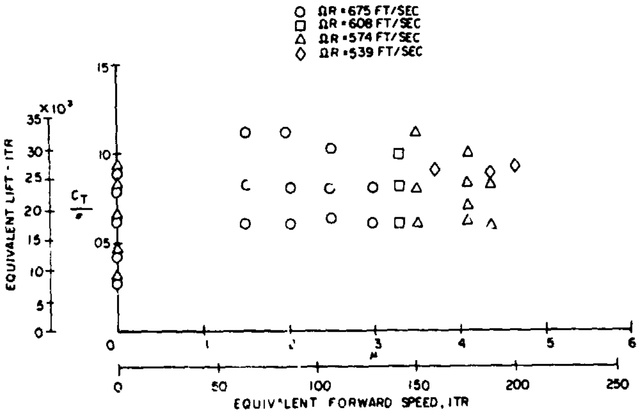

Fig. 6 Dynaflex model test conditions - level flight trim.

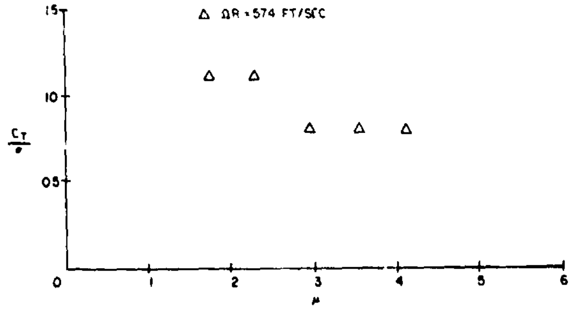

Fig. 7 Dynaflex model test conditions - level flight pitching moment variation.

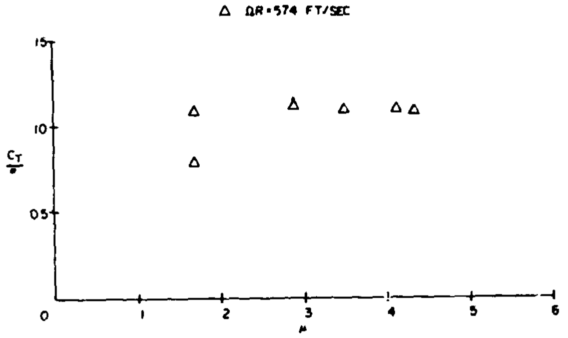

Fig. 8 Dynaflex model test condition - partial power descent.

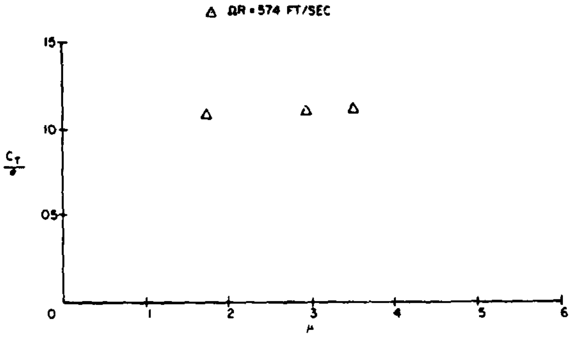

Fig. 9 Dynaflex model test conditions - autorotation.

Results

The Dynaflex model rotor was stable over the entire hover test envelope. Damping levels for the regressing edgewise mode were low, but positive. No control difficulties were encountered when the tip path plane was tilted by cyclic pitch inputs of up to [illegible] degrees. Figs. 10 and 11 show the variation in regressing edgewise mode damping ratio with rotor speed for hover testing at the Sikorsky test stand and at the UTRC wind tunnels respectively. Damping of the regressing edgewise mode tended to increase slightly with increased collective pitch. Progressing edgewise mode damping was higher than that of the regressing mode. Fig. 12 shows the variation in progressing edgewise mode damping with collective pitch. Comparison of results from the G400 aeroelastic analysis and test data reveals similar trends in damping with collective pitch for hover. Attempts to correlate G400 with forward flight data from the model wind tunnel test were not successful. Resolution of mathematical difficulties encountered during the execution of the G400 computer program is currently being pursued.

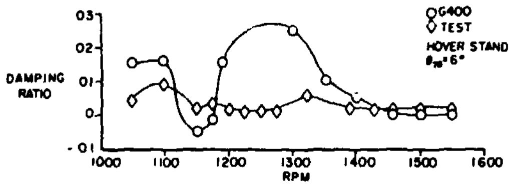

Fig.10 Regressing edgewise mode damping - hover conditions Sikorsky hover stand.

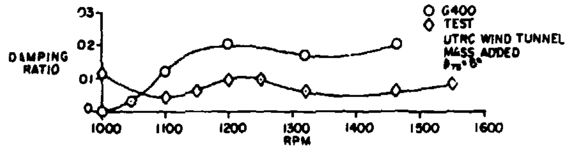

Fig.11 Regressing edgewise mode damping - hover conditions UTRC wind tunnel.

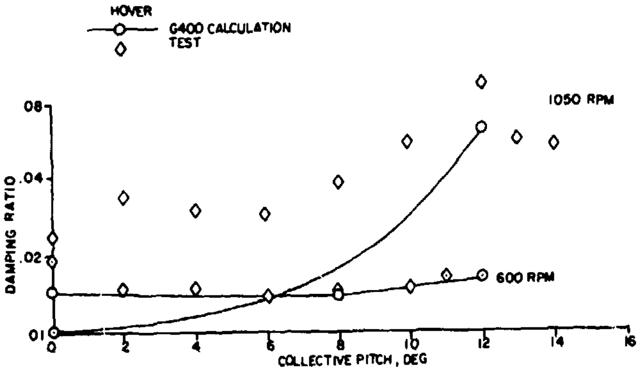

Fig.12 Progressing edgewise mode damping - hover conditions UTRC wind tunnel.

In forward flight testing, the regressing edgewise mode was the only rotor system mode that could be excited with reasonable consistency by the fixed system shaker. Damping ratio for this mode is plotted against advance ratio for various operating conditions in Figs. 13, 14, and 15. The damping variation with level flight lift, forward speed or rotational speed condition displays no clear trending, although application of positive pitching moment, partial power descent, or autorotation appear to cause damping to be generally lower.

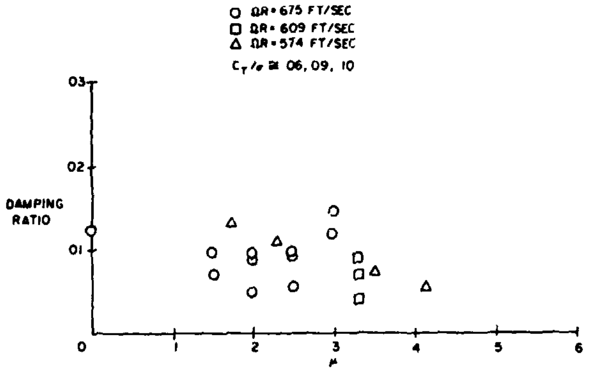

Fig.13 Dynaflex rotor edgewise mode damping - level flight trim conditions.

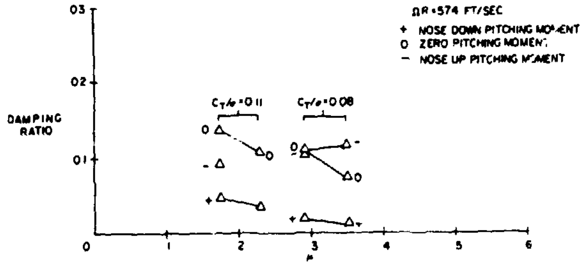

Fig.14 Dynaflex rotor edgewise damping - level flight pitching moment variation.

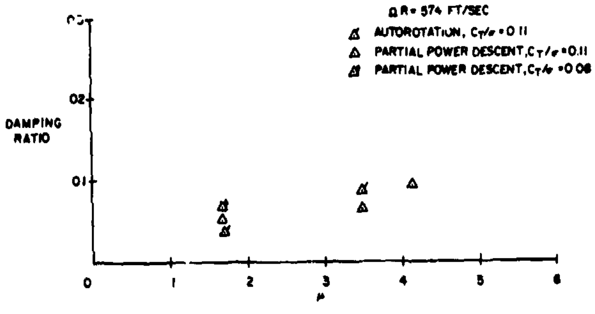

Fig.15 Dynaflex rotor edgewise damping - partial power descent and autorotation conditions.

Steady-state records of each of the simulated flight conditions were acquired to permit the assessment of blade and gimbal loads and strains, model rig vibrations, and the appropriate rotor forces and moments. Rotor forces and moments were non-dimensional and converted to coefficients, facilitating comparison with full scale and model data from other rotor configurations. The operation of the rotor at reduced tip speed to avoid blade instabilities altered the dynamic scaling parameters. At the 539 ft/sec tip speed, for example, the first edgewise blade frequency was .8 cycles per revolution, rather than the .68 cycles per revolution at the 675 ft/sec tip speed. The principal effect of operation at the reduced tip speed is to simulate a rotor with higher elastic stiffness.

Data from simulated level flight conditions with gimbal tilt essentially zero are exhibited in Figs. 15 - 19. Nordimensional one-half peak-to-peak pushrod load, flexbeam edgewise bending moment, and blade flatwise bending moment are plotted against advance ratio in these figures. The factors used for nondimensionalization are the conventional ones used in forming rotor blade loading parameters such as CT/sigma and CPM/sigma. Data from equivalent forward flight conditions taken during the S-76 dynamically scaled model test conducted in 1976 are also presented in the figures. These data show similarity in flatwise bending moments and pushrod loads for the Dynaflex and articulated rotor. This similarity suggests that the Dynaflex rotor blade flatwise and torsion loading outboard are similar to those on an articulated rotor, and provides evidence that the Dynaflex rotor's outboard blade requires no special design considerations beyond those for an articulated rotor.

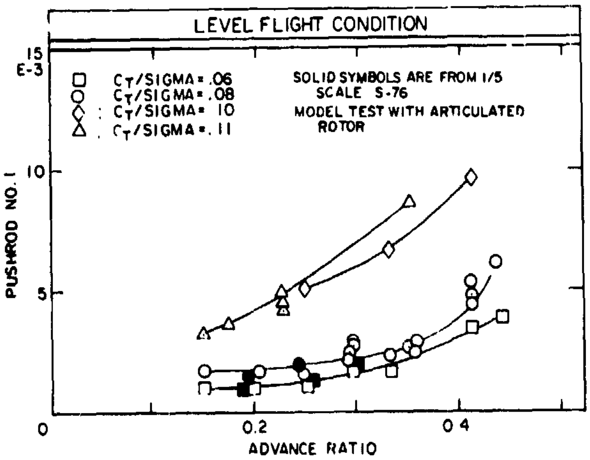

Fig.16 Half peak to peak pushrod coefficient/solidity, level flight trim conditions.

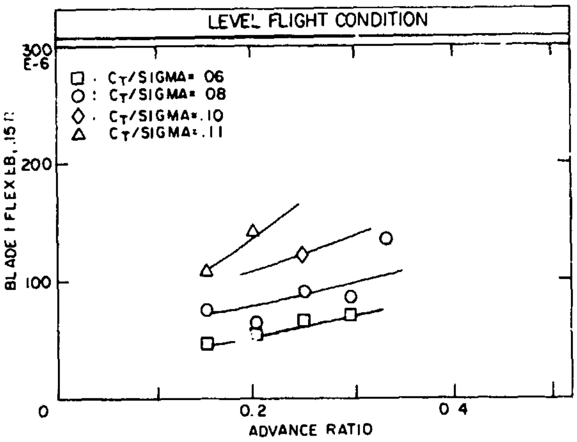

Fig.17 Half peak to peak flexbeam edgewise bending moment coefficient/solidity, level flight trim conditions.

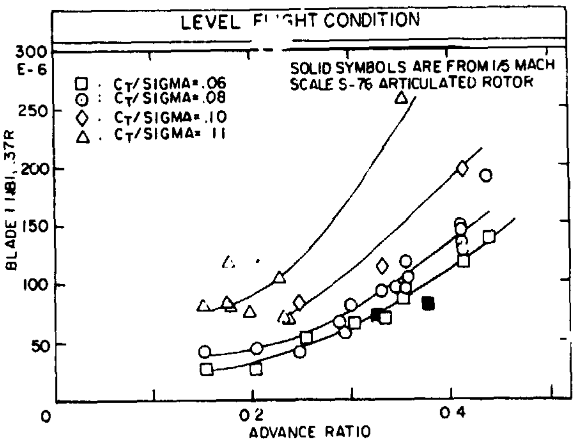

Fig.18 Half peak to peak blade flatwise bending moment coefficient/solidity at 0.37R, level flight trim conditions.

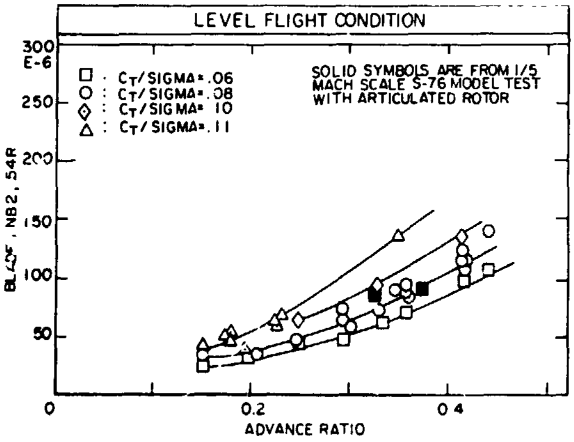

Fig.19 Half peak to peak blade flatwise bending moment coefficient/solidity at 0.54R, level flight trim conditions.

Test data from simulated partial power descent and autorotation conditions, as well as comparative data from level flight conditions are presented in Figs. 20 - 23. Comparison reveals no unusual response due to partial power descent nor due to autorotation.

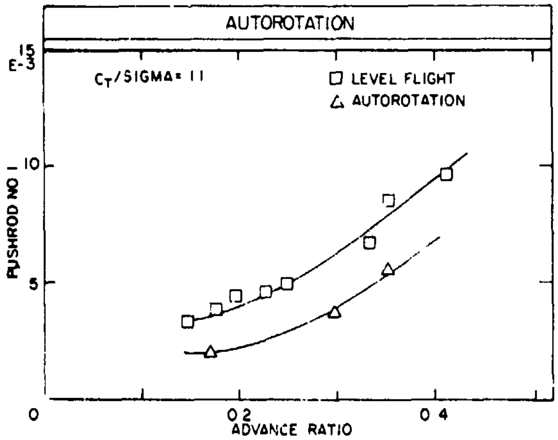

Fig.20 Half peak to peak pushrod coefficient/solidity, partial power descent conditions.

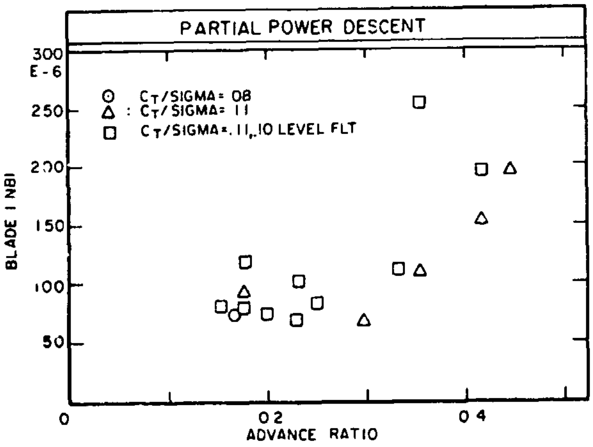

Fig.21 Half peak to peak blade flatwise bending moment coefficient/solidity at 0.37R, partial power descent conditions.

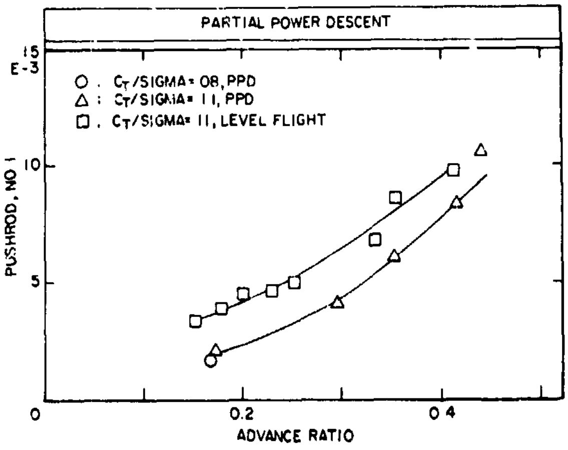

Fig.22 Half peak to peak pushrod coefficient/solidity, autorotation conditions.

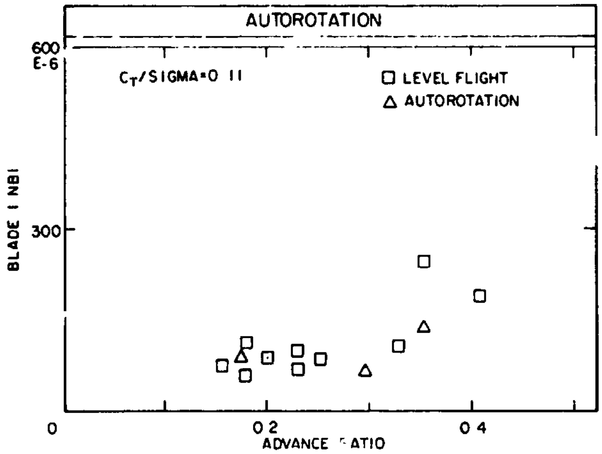

Fig.23 Half peak to peak blade flatwise bending moment coefficient/ solidity at 0.37R, autorotation conditions.

Results from pitching moment variation are presented in Figs. 24 - 27. Fig. 24 shows the gimballed hub one-per-rev tilt angle amplitudes reached during the pitch moment variation test conditions, along with the corresponding rotor shaft angle relative to zero pitching moment shaft angle. The gimbal tilt is roughly two-thirds of the shaft angle increment, i.e. tip path plane tilt consists of roughly two thirds gimbal tilt and one third first harmonic blade bending. Fig. 25 shows one-half peak-to-peak inner gimbal strain amplitude as a function of advance ratio. Gimbal strain is not affected by forward speed or lift, rather it appears to be a function of gimbal tilt.

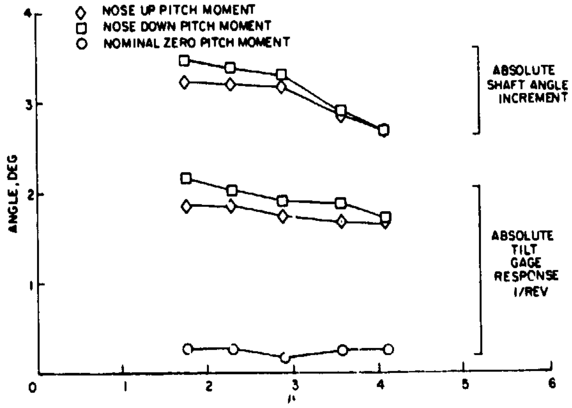

Fig.24 Gimbal and thrust vector tilt, pitching moment variation conditions.

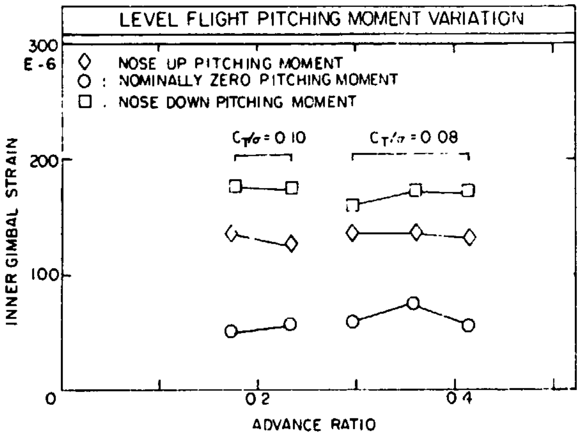

Fig.25 Inner gimbal strain, pitching moment variation.

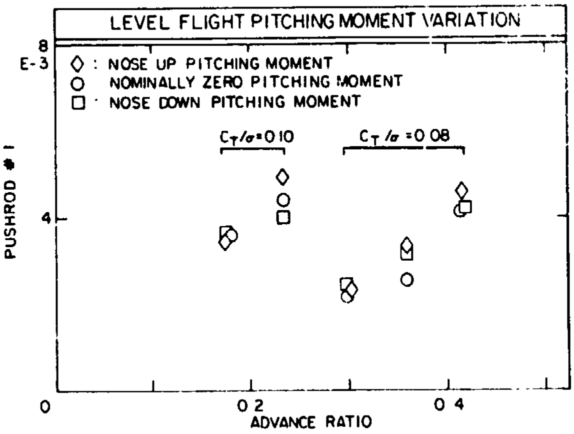

Fig.26 Half peak to peak pushrod coefficient/solidity, pitching moment variation.

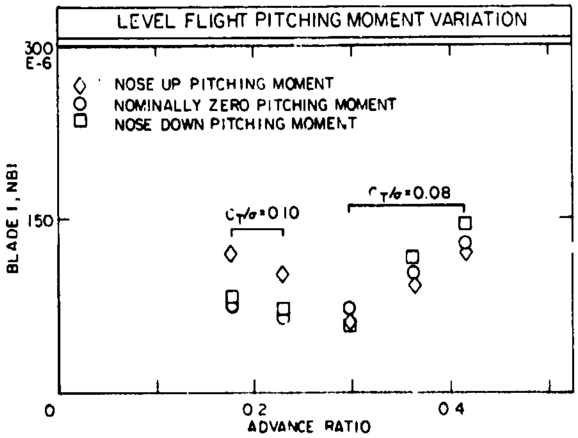

Fig.27 Half peak to peak blade flatwise bending moment coefficient/ solidity at 0.37R, pitching moment variation.

Concluding Remarks

Wind tunnel testing of the Dynaflex model rotor confirmed that the present rotor concept is feasible, offering considerable promise for advancing the state of the art for helicopter main rotor systems. Within the flight conditions boundary imposed by blade limitations, the rotor showed itself to be stable and relatively insensitive to forward flight condition. The rotor offers simplicity and lower drag than articulated rotors without sacrificing low blade loads and good flying qualities. Edgewise mode damping is quite low as no auxiliary damping device nor advantageous flap lag coupling provisions have been made. Continuing development will address this issue.

References

1. Fradenburgh, E.A., and Carlson, R.G., "The Sikorsky Dynaflex Rotor - an Advanced Main Rotor System for the 1990's," Paper No. A-84-40-17-8000, American Helicopter Society 40th Annual Forum, Arlington, VA, May 1984.

DISCUSSION
Paper No. 5

TEST RESULTS FROM A DYNAMIC MODEL DYNAFLEX ROTOR

Charles F. Niebanck
and
Robert K. Goodman

Jing Yen, Bell Helicopter: One thing is not quite clear to me, that is, what is the advantage of using a gimballed hub versus a conventional articulated hub?

Goodman: There are a couple of advantages. The first is the simplicity of the design--there are fewer parts involved and some of the other design objectives were to reduce weight. There are many composite materials which are incorporated in this design which haven't been [used] in conventional articulated rotors. In the design which we showed here, the hub fairing is an integral part of the rotor head and this decreases the download on the rotor in forward flight where there is a forward pitch angle. These are primarily the motivations for it.

Bob Taylor, Boeing Vertol: Did you obtain any test data to show the beneficial effect of constant rotor velocity on inplane rotor loads?

Goodman: Well, we did have edgewise damping or edgewise strain gauges on the model. We had quite a bit of problems with those. We lost them fairly early, rather, we lost several of them throughout the test primarily because the strain levels in the blades were higher than the gauges could handle. We do have some vibratory information from the edgewise gauges and basically it is comparable to articulated rotors. They did not bear out substantial reduction in force levels because of the Coriolis effects. They did not support that at this point.

Peretz Friedmann, University of California, Los Angeles: I'm not sure I understand. That's probably because I can't figure out your drawing precisely. What is the difference between the Dynaflex rotor, a conventional hingeless rotor, a bearingless rotor--could you please try and explain? If there are any differences then which of these is best in your opinion?

Goodman: Do you have a copy of the proceedings? There is a fundamental difference--the most unique feature I suppose is the gimballed joint. It enables you to have stiff flexbeams so that you don't have problems with blade droop and yet it allows you to have the hub moment of an articulated rotor and then as I already discussed previously the advantages over an articulated rotor are lower parts count and aerodynamic considerations for the hub. I guess if that doesn't answer your question, maybe we can talk about it afterwards.

Henry Velkoff, Ohio State University: Did you have any measurements of the torsional frequencies of the hub itself? You are basically using a pseudo-Hooks joint which is taken out elastically and with that tilt you should be getting a second harmonic variation which is analogous to the Coriolis flapping trim. Did you see anything like that? There is always the argument whether the shaft takes it out or the blades take it out. Did you happen to see what the second harmonic torsion looked like?

Goodman: Let's see. I'm not sure I understand your question. I'm kind of new to this game. Are you talking about a yawing vibration?

Velkoff: A torsional one. In any Hooks joint it's not a constant angular velocity. You're going to get a first harmonic and a second harmonic. The second harmonic in a Hooks [joint] is ideally the same as the second harmonic Coriolis term of flapping. So the argument, to quote my friends at Bell, [is] "you never see that," but I'm just curious to see whether you actually find it in this case.

Goodman: I personally did not see it, but I would not have known I was looking for it. Perhaps Jerry can bail me out.

Jerry Miao, Sikorsky Aircraft: Maybe I can help Bob out a little bit. Yes, we put in shear gauges in the drive torque shell, but unfortunately they all ran out very quickly. So I cannot answer that question, but I'm sure what you said is true, Hank. I'm sure the two/rev probably will come through, but it probably is a smaller order of magnitude [that] we cannot help. Another thing to answer Peretz's question a little bit. In this paper Bob has [given] he refers to an earlier paper presented at the 1984 AHS Forum written by Fradenburgh and Carlson and they discuss this gimballed rotor quite a bit. Essentially the major feature is you have a gimbal in the center of the hub so you figure the rotor is going to have vibratory forces and moments coming through that joint. The moments are eliminated just like for an articulated hinge; you eliminate all the moment transfer across the hinge.

Bob Ormiston, U.S. Army Aeromechanics Laboratory: I was interested in the question about Coriolis loads and I'm surprised you didn't see a reduction. I noticed in the paper you did have some measured inplane loads. Do you know how those compare to, say, an articulated or other type rotor? Could you make an estimate of the comparison? Are they about the same?

Goodman: I can't answer that off the top of my head. I'm trying to recall now whether or not we did include any of the edgewise force level data in there.

Charles Niebanck: I think those gauges went out before we could really get very much.

Goodman: I guess the question would arise where do we get our edgewise damping calculations from and we had a variety of edgewise gauges on the blade. For instance we had tension gauges on each of the twin flexbeams so, for instance, when we would get edgewise motion going we would see this interaction of tensile strain on these two flexbeam gauges. So at times we would be using log decrement of edgewise [oscillation] on those gauges to establish damping levels and yet the calibration was not accurate enough to be able to really establish what the edgewise vibration amplitude truly was. We were looking at relative amplitudes.

Ormiston: I just want to close and jump into this controversy here. I think the rotor is different from a Hooks joint situation, so I don't think you should get the kind of loads in there that Hank was saying we should. We've talked about this before. I think it should be a constant speed and you should show up with a reduction in the inplane loads, but I would be very curious to find out what actually happened if you ever run the test again.

Goodmann: Yes. Well we are planning on it.

William Warmbrodt, NASA Ames Research Center: Two questions. You showed that you acquired quite a bit of data at low collective pitch settings and yet the paper doesn't present any stability results below a C_T of 0.05 and I was wondering what was the trend at low thrust on the rotor. Also are you pleased with the damping levels that you saw, on the order of 0.01 or less critical damping ratio, throughout the operational envelope?

Goodman: I'll answer the second part first. We are not completely satisfied with that and currently we are working on a Dynaflex rotor, I guess as an ITR candidate, and the design of that is introducing means by which edgewise damping can be increased. The first part of your question--why we didn't present stability results for lower lift conditions? It wasn't a part of our test plan. We wanted to establish a flight condition which was comparable to S-76 level flight conditions. That was the basis for the flight condition we chose.

Bob Hansford, Westland Helicopters: I noticed from the diagram at the end of your report that you had a supercritical lag frequency of 1.44.

Goodman: That was for Froude-scale testing I believe.

Hansford: But did you look at any variations of your lag frequency with blade pitch and couplings between flap and lag motions?

Goodman: We didn't see a considerable amount. I don't have the exact placement of the frequencies with pitch variation present, but there wasn't a large variation. We didn't look that closely at it.