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LOW-TEMPERATURE TESTS OF ELASTOMERIC BEARING ROTORS ON AN OH-58 HELICOPTER IN THE CLIMATIC LABORATORY AT EGLIN AFB

C. H. Fagan

Bell Helicopter Company

Prepared for:

Army Air Mobility Research and Development Laboratory

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By

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EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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BELL HELICOPTER COMPANY
FORT WORTH, TEXAS

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13. ABSTRACT

The results of a program conducted to investigate the low-temperature characteristics of rotors equipped with elastomeric bearings are reported. An all-elastomeric, two-bladed main rotor and a production tail rotor, with elastomeric bearings installed in the flapping axis, were tested on an OH-58A helicopter. The test vehicle was tied down in the Climatic Hangar at Eglin Field, Florida, and 12 tests were conducted at temperatures of 70°F, 0°F, -25°F, -45°F, -55°F, and -65°F. Two main rotor pitch-change bearing configurations were evaluated. The first was fabricated from natural-rubber elastomer and the other from broad-temperature-range elastomer. No insurmountable problems were encountered; however, operating loads in the main rotor controls increased progressively with reductions in temperatures. A flight-test program is needed to investigate the magnitude of the combined low-temperature bearing-stiffness loads and loads created by in-flight rotor dynamics.

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This report was prepared by the Bell Helicopter Company, a Division of Textron Inc., under the terms of Contract DAAJ02-72-C-0058. It documents the results of cold-weather tests of an OH-58A helicopter equipped with elastomeric bearing main and tail rotor applications in the Eglin Air Force Base Climatic Laboratory Facility.

The feasibility of using elastomeric bearings in rotor applications has been demonstrated in both bench and flight test programs. The objective of this program was to investigate the stiffening characteristics of the elastomer in the bearing in an extreme cold environment and to determine the effect that this stiffening has on control loads and rotor natural frequency placement. Furthermore, the program yielded information regarding operational procedures and limitations for cold-weather operation.

The conclusions contained herein are concurred in by this Directorate.

The technical monitor for this contract was Mr. John W. Sobczak of the Military Operations Technology Division.

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Bell Helicopter Report 299-099-587

By

C. H. Fagan

Prepared by

Bell Helicopter Company
Fort Worth, Texas

for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

SUMMARY

Presented in this report are the results of a program to investigate the operating characteristics of helicopter rotors equipped with elastomeric bearings at low temperatures. A main rotor (designated Bell Helicopter Company Model 640), which has elastomeric bearings in the flapping and pitch change axes, and a tail rotor, with elastomeric bearings in the flapping axis, were evaluated on an OH-58A helicopter in the Climatic Laboratory at Eglin AFB, Florida. Testing consisted of twelve runs at controlled temperatures during which data were recorded continuously. Each simulated mission, of about 30 minutes duration, consisted of cyclic inputs at hover, minimum cruise, and maximum continuous cruise power conditions. Bearings fabricated from natural-rubber elastomer were evaluated at temperatures of 70°F, 0°F, -25°F, -35°F, and -45°F. In addition, new main rotor pitch change bearings, fabricated from broad temperature range elastomer, were installed and tests were conducted at -35°F, -45°F, -55°F, and -65°F temperatures.

Load versus temperature data are presented graphically for the main rotor controls, blade, yoke, and mast, and for the tail rotor mast and yoke. Main rotor data show that the cyclic and collective control loads increase with reduction in operating temperatures when below 0°F. The higher loads are caused by an increase in the pitch-change bearing's torsional spring rate with reduction in temperature. Expected load advantages with the broad temperature range parts were not realized.

Oscillatory loads for the main rotor controls increased by a factor of four over room temperature values. However, the aircraft was operable at low temperatures to -65°F. Also, pilot evaluation and test results indicate that the rotor as tested will operate normally in flight to a temperature of -35°F and that, with only minor changes to the control system, this rotor should be suitable for extensive flying at temperatures to -65°F.

FOREWORD

This report was prepared under Contract DAAJ02-72-C-0058, "Low-Temperature Testing of Elastomeric Bearings for Helicopter Rotor Applications," with the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory (USAAMRDL). The work was authorized by DA Task 1F162205A11901. The program was initiated on 12 April 1972, and the helicopter was ferried from Bell Helicopter Company (BHC), Fort Worth, Texas, to the Climatic Laboratory test facility at Eglin Air Force Base (AFB), Florida, on 31 May 1972.

Tests in the Climatic Laboratory were conducted on the original rotor configuration (natural-rubber elastomer bearings) at temperatures of 70°F, 0°F, -25°F, -35°F, and -45°F. New main rotor pitch-change bearings, fabricated from broad temperature range elastomer, were installed and additional tests were conducted at temperatures of -35°F, -45°F, -55°F, and -65°F. All of the elastomeric bearings used during this program were manufactured by Lord Kinematics, Erie, Pennsylvania. The helicopter was returned to the BHC facility at Fort Worth, Texas, on 21 June 1972.

The program was conducted under the technical cognizance of Messrs. J. N. Daniel and J. Sobczak of the Military Operations Technology Division of the Eustis Directorate. Principal Bell personnel associated with the program were Messrs. L. Arrick, W. Cresap, C. Fagan, and T. Gardner. In addition, technical assistance was received from Messrs. J. Huggins and A. T. Ross in the Climatic Laboratory at Eglin AFB, Florida.

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INTRODUCTION

In 1964, Bell Helicopter Company (BHC) initiated a program to investigate elastomeric bearings (EBs) for application to rotor systems. Since that time, several main and tail rotors which used EBs in both flapping and blade pitch-change axes have been flight evaluated (References 1 and 2). An all-elastomeric bearing main rotor (designated Model 640) was flight tested on an OH-58A helicopter in 1971. This rotor, used for the low-temperature tests described in this report, has two conic EBs in each blade grip to accommodate the blade pitch motions and carry blade centrifugal force and bending loads. Also, radial EBs are used in the hub flapping axis.

Even though low-temperature dynamic bench tests have been conducted on individual EBs, no low-temperature work had been accomplished on EB rotor systems prior to the tests described in this report. Since helicopters may be required to operate in Arctic climates, questions concerning low-temperature operation for any new rotor must be answered before it can be considered suitable for production. An OH-58A production helicopter was evaluated at low temperatures in the Climatic Laboratory at Eglin AFB, Florida, in 1969 (Reference 3). However, with those production rotors, oil-lubricated roller bearings were used in the main rotor, and tetrafluoroethylene-impregnated-fabric bearings were used in the tail rotor.

The program discussed herein was initiated to obtain basic low-temperature ground operational information for helicopters equipped with EBs. Rotor loads and motions were monitored for twelve tests during which power settings and control motions simulated actual flights of 23 to 41 minutes duration. Specific test objectives were to determine if low-temperature stiffening of the elastomer would cause excessive loads in the controls, to investigate the effects of elastomer stiffening on rotor natural frequency placement, and to establish operational limitations or special operating procedures needed at extremely low temperatures.

DESCRIPTIONS

TEST FACILITY

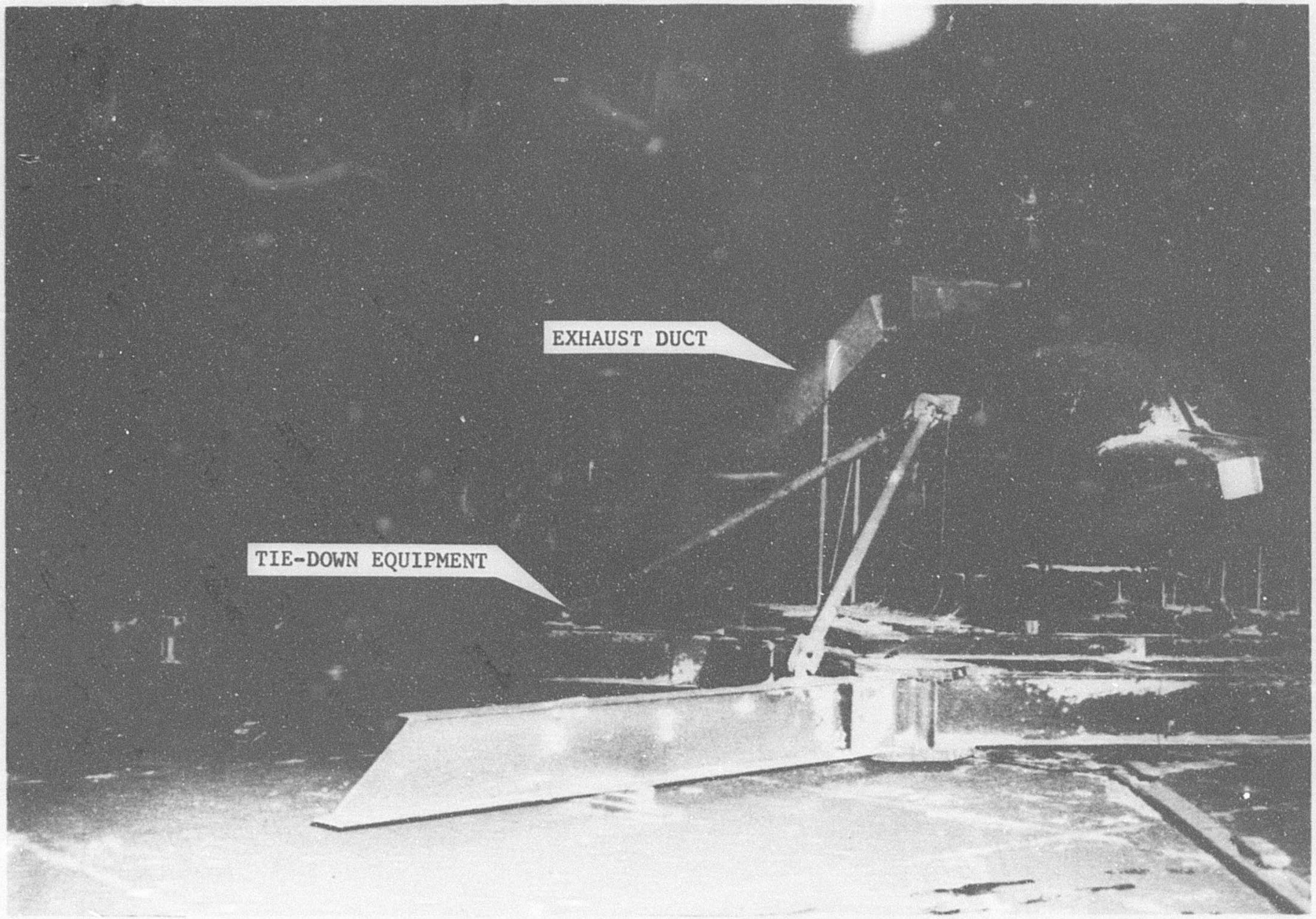
Low-temperature tests were conducted in the Climatic Laboratory at Eglin AFB, Florida. Government-furnished tie-down equipment was used to secure the helicopter in the main chamber of the laboratory hangar as shown in Figure 1. The total volume of the hangar, which is 250 feet wide, 200 feet deep, and 70 feet high at the center, is approximately 3,282,500 cubic feet. Several tests can be conducted simultaneously; however, only minor other tests were conducted in the chamber during this program. The test facility is capable of maintaining temperatures from a high of 165°F to a low of -65°F, as well as creating controlled humidity, snow, rain, icing, wind, sand, and dust conditions. Temperature changes between tests were made at a rate of about 10 degrees per hour. Temperature increase of a few degrees was experienced during most of the runs even with the hangar refrigeration equipment operating.

TEST VEHICLE

A production OH-58A helicopter was used as the test vehicle. An all-elastomeric two-bladed main rotor and a production tail rotor equipped with elastomeric flapping bearings were installed for the low-temperature tests. Also, additional equipment installed consisted of a main rotor brake, a mid-travel cyclic stick stop (±6° fore and aft and ±3.5° lateral), an experimental winterization kit, and indicators on the pilot's instrument panel to give the cyclic stick position and engine oil pressure.

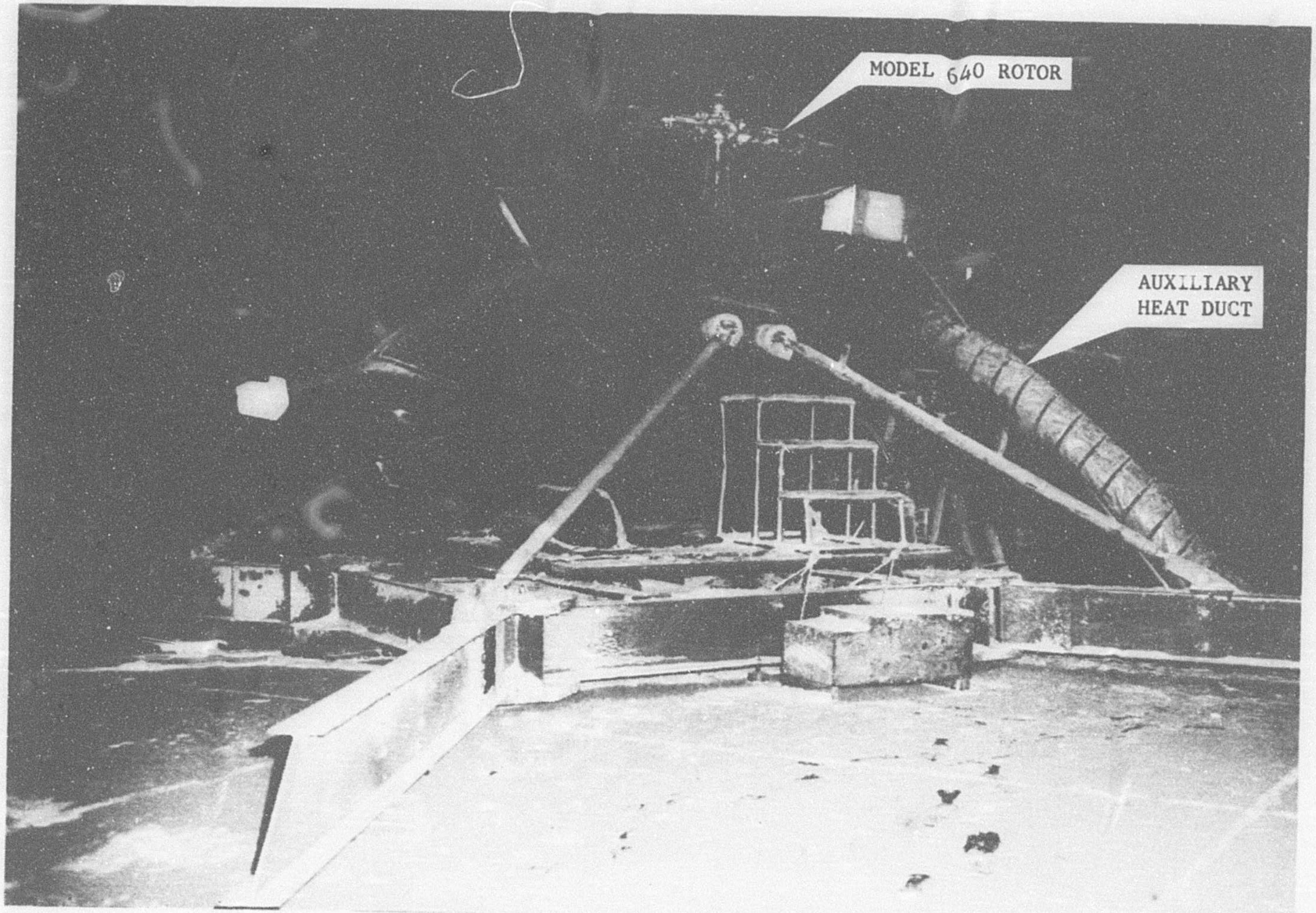
TEST ROTORS

A Model 640 main rotor was evaluated during this program. This rotor used production OH-58 blades modified inboard to pick up the blade bolts and give a rotor diameter of 35.3 feet. The flexbeam type hub is shown in Figure 2 with one grip disassembled. Figure 3 is a photograph of the rotor taken just prior to the test at -45°F temperature. With this rotor, two conic EBs are used in each blade grip to carry the blade centrifugal force, transfer blade bending and shear loads, and allow blade pitch-change motions. Also, two radial EBs are used to transfer the hub loads to the mast and accommodate flapping motions.



(a.) View Showing Engine Exhaust Duct

Figure 1. OH-58 Test Helicopter



(b.) View Showing Auxiliary Heater Duct
Figure 1. Continued.

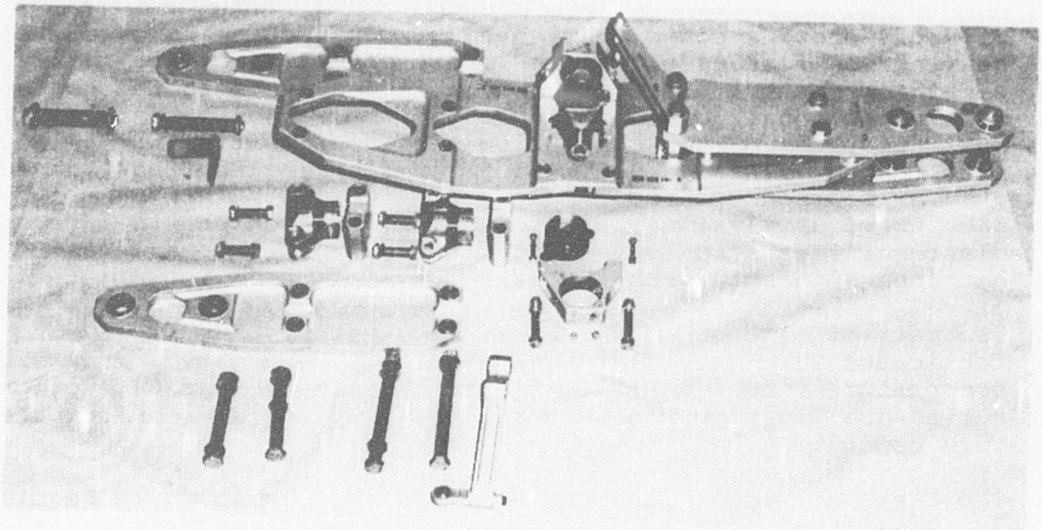


Figure 2. All-Elastomeric-Bearing Hub.

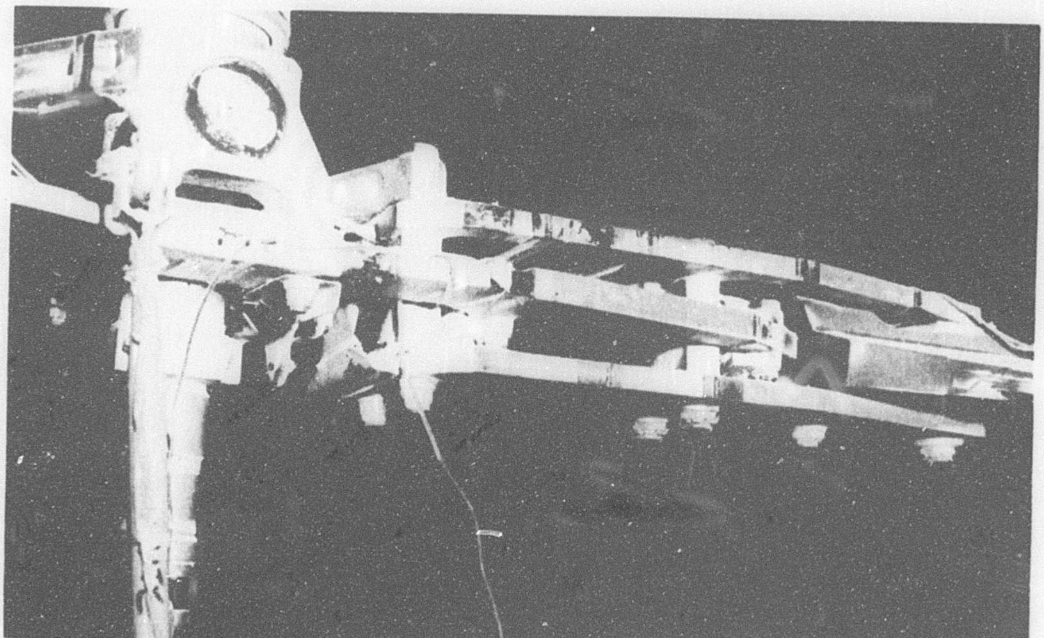


Figure 3. All-Elastomeric-Bearing Rotor at -45°F Temperature.

Figure 4 shows a conic EB with a quarter section removed. This bearing consists of alternate layers of elastomer and metal separator sheets. The conic shape design was selected to obtain multidirectional load-carrying capability, thus performing the dual functions of the conventional blade retention strap and pitch-change bearings. A main rotor flapping bearing with a quarter section removed is shown in Figure 5. This bearing is made up of an elastomer pad (consisting of concentric layers of elastomer separated by steel cylinders) and inner and outer housings with attachment lugs.

Two sets of pitch-change EBs were evaluated. The first was fabricated from natural-rubber elastomer; the other, from broad-temperature-range (BTR) elastomer. Torsional load deflection curves are given in Figure 6 for the bearings at room-temperature conditions.

The test tail rotor flapping assembly used is shown in Figure 7. Details of this assembly are shown on Bell's Drawing 640-011-800. Remaining tail rotor parts and the controls were production configuration parts.

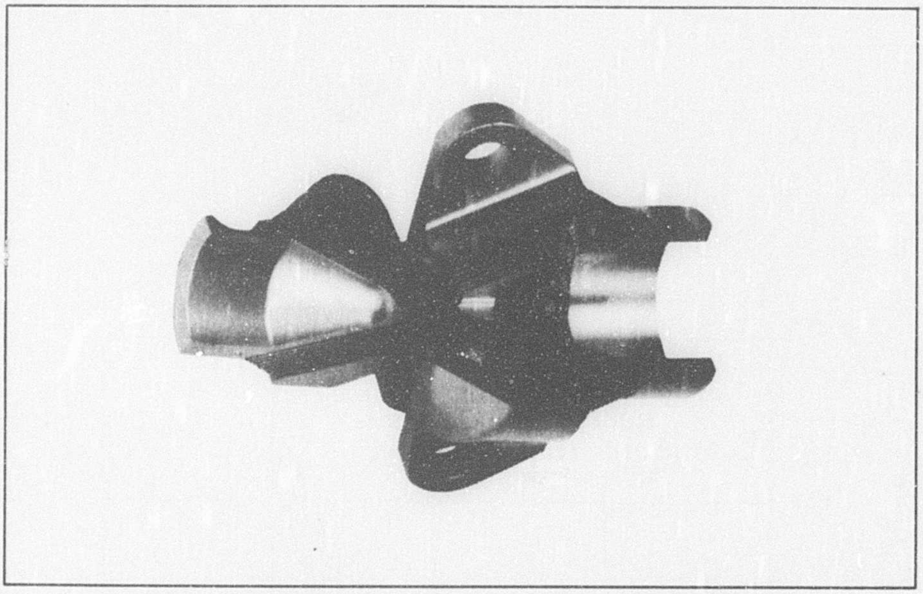


Figure 4. Main Rotor Pitch-Change Bearing.

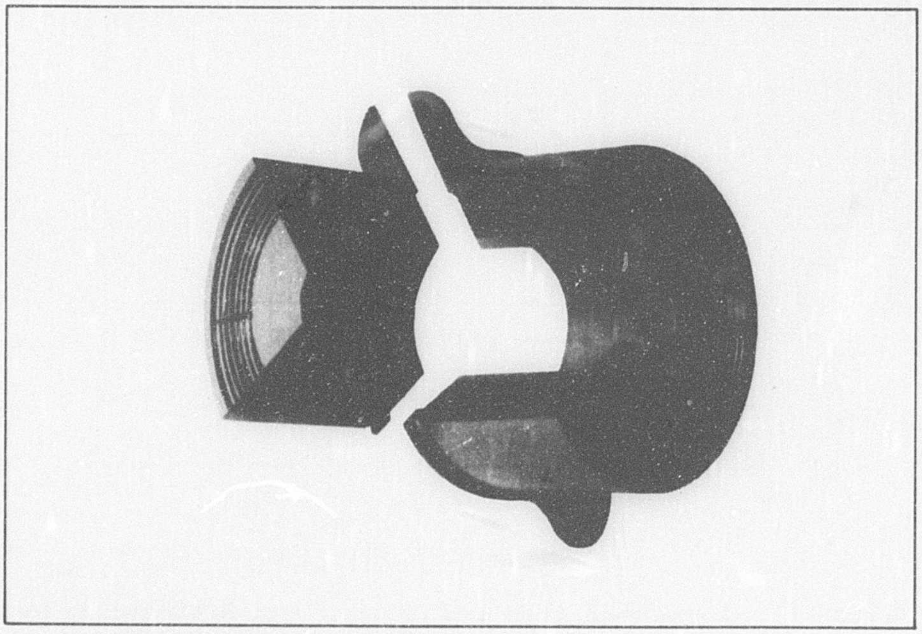


Figure 5. Main Rotor Flapping Bearing.

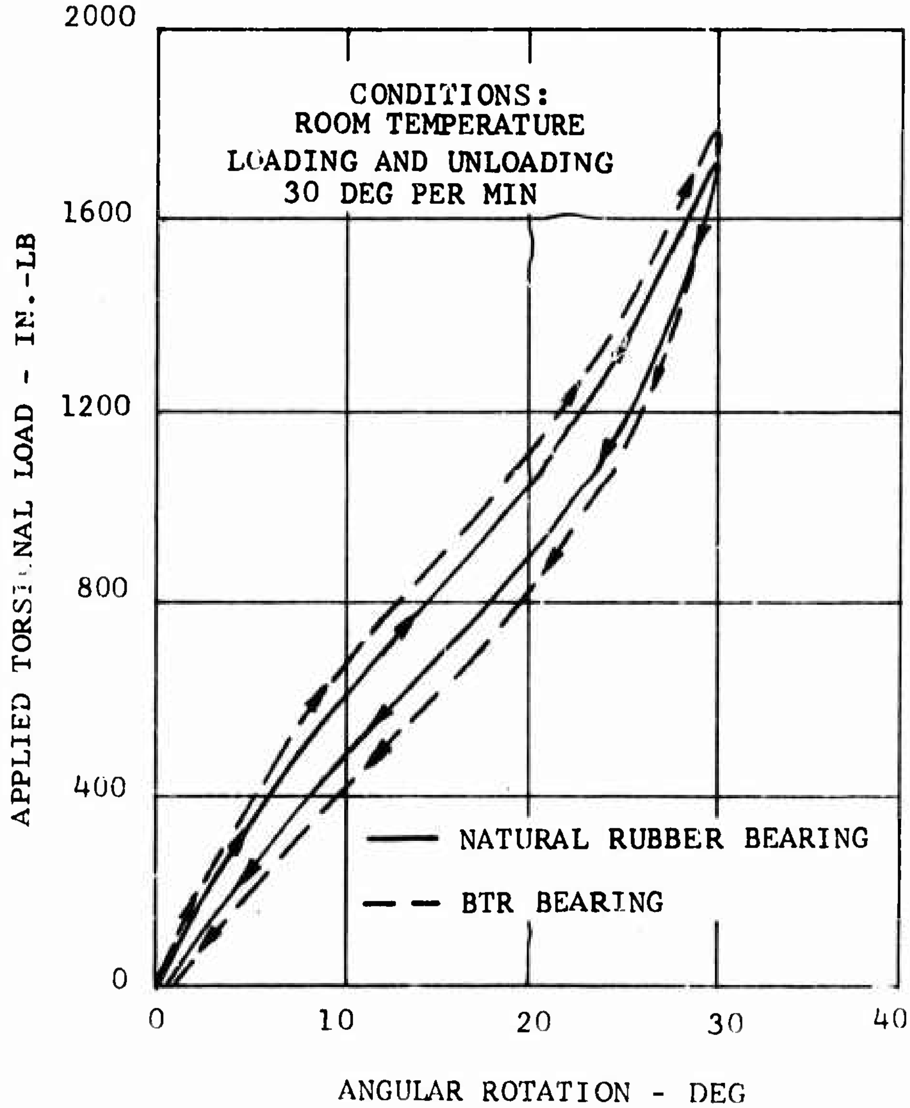


Figure 6. Torsional Load Deflection and Hysteresis for Natural Rubber and BTR Pitch-Change Bearings.

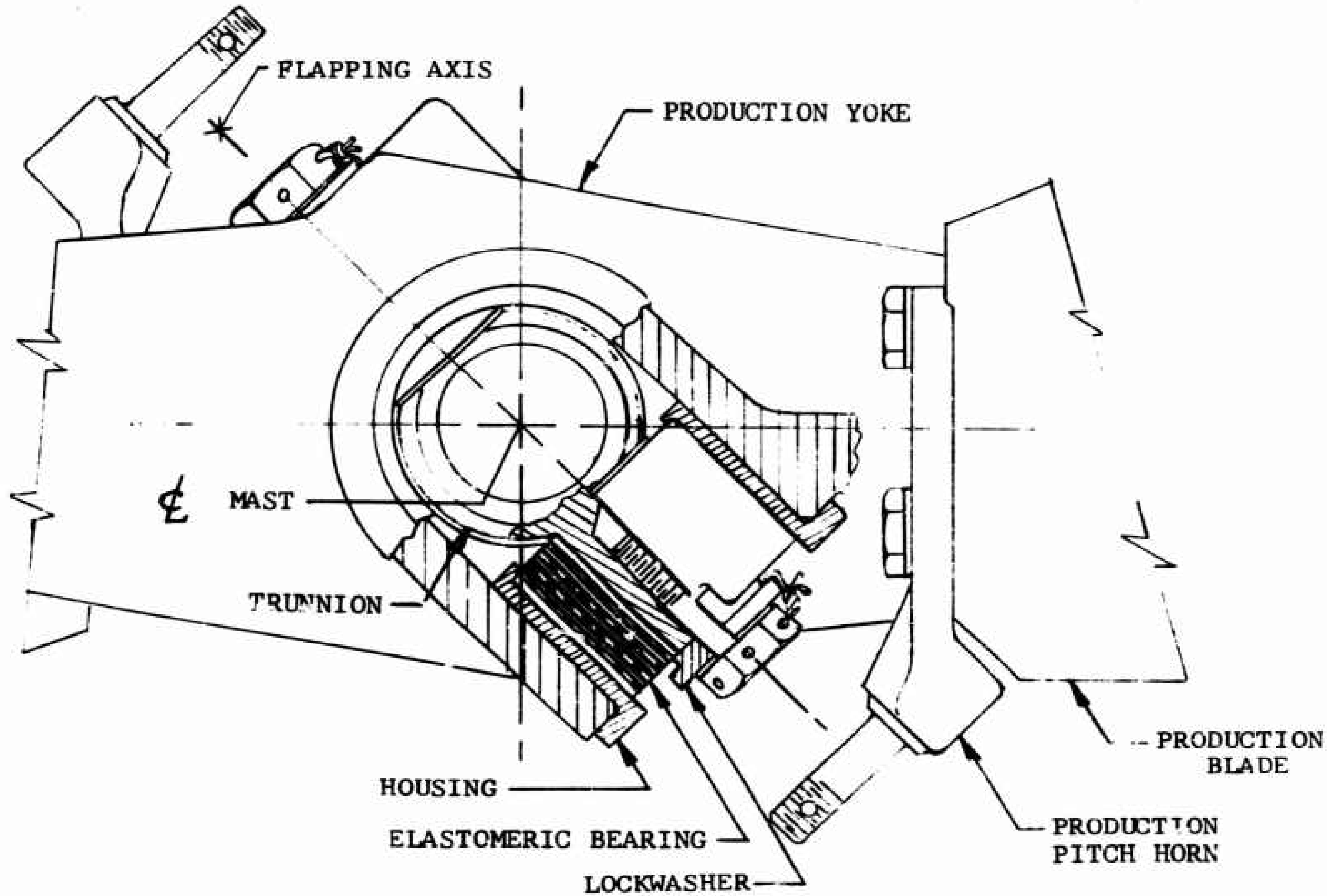


Figure 7. Elastomeric Bearing Flap Assembly - OH-58A Tail Rotor.

TESTS CONDUCTED

Twelve runs were conducted, using two main rotor pitch-change EB configurations, at the test conditions listed in Table I. The pilot made an effort to execute all stick inputs at the same rate per the Figure 8 mission profile.

PRIMARY CONFIGURATION

Natural-rubber bearings were tested in the main rotor pitch-change axis and in the flapping axis of the main and tail rotors. Eight tests were conducted per the mission profile in Figure 8, and at the conditions listed in Table I. With this configuration, both normal and adverse rotor positions were used during soak periods prior to tests at 0°F, -25°F, and -45°F. Normal position is defined as that in which the cyclic stick is in a neutral position, the collective stick is in the most down position, and the main and tail rotors are square with the mast. The adverse position was with the cyclic stick forward (against mid-travel stops), the collective stick in a mid-travel position, and the main rotor flapped aft 5 degrees. This soak position represents the most adverse condition expected for operation in low-temperature environments.

SECONDARY CONFIGURATION

This configuration was the same as the primary one except that BTR elastomeric bearings were used in the blade pitch-change axis of the main rotor. After installation of the new bearings, the main rotor was found to be out of track. Since the out-of-track condition was not expected to create a loads problem, and since tracking is time consuming at low temperatures, the condition was not corrected. Four runs were conducted, per Table I, in accordance with the Figure 8 mission profile, except for the -55°F and -65°F tests, during which cyclic stick inputs were of a lesser magnitude at the beginning of the test to prevent possible damage to the main rotor controls. However, an operational power of 272 horsepower was reached, and cyclic inputs were made to the mid-travel stops. The 10-minute minimum cruise operation (see Figure 8) was not conducted during the -65°F test because of inadequate heat in the helicopter cabin which resulted in pilot and flight test engineer discomfort and fatigue.

TABLE I. TESTS CONDUCTED

Date (1972)	Run No.	Ambient Temp. (°F)	Soak Time (Hr)	Run Time (Min)	M/R Pitch Bearing Config.	Rotor Soak Position	Comments
5 June	1	70	-	29	Natural Rubber		——
6 June	2	0	10	23	↑	Normal	Two starts aborted. Heated fuel controls prior to run.
7 June	3	0	21	30	|	Adverse	Heated fuel controls prior to run.
8 June	4	-25	24	27	|	Normal	First run aborted. Heated engine oil & fuel controls.
8 June	5	-25	4	26	|	Adverse	Heated engine oil & fuel controls.
9 June	6	-35	15	26	|	Normal	First two starts aborted. Reheated engine oil & fuel controls.
12 June	7	-45	59	30	↓	Normal	Heated engine oil, fuel controls, and hyd. boost cylinders prior to start. First run aborted and heat reapplied for Runs 7, 9, 10, 11 and 12.
13 June	8	-45	21	30	Natural Rubber	Adverse	
15 June	9	-35	10	27	BTR Elastomer	Normal	
16 June	10	-45	20	33	↑	↑	
17 June	11	-55	20	41	↓	↓	
18 June	12	-65	20	37	BTR Elastomer	Normal	

KEY EVENTS

1. Hover Power (No Cyclic)
2. Stir Stick to Mid-Travel Stops
3. Maximum Continuous Power
4. F/A Cyclic Input to Mid-Travel Stops (6° Forward Cyclic)
5. F/A Cyclic Input to Mid-Travel Stops (Boost-Off)
6. Start of Continuous Operation With 2° Forward Cyclic (Minimum Cruise Power)
7. End of Continuous Operation With 2° Forward Cyclic
8. F/A Cyclic Input to Mid-Travel Stops (Boost-Off) (272 Hp)

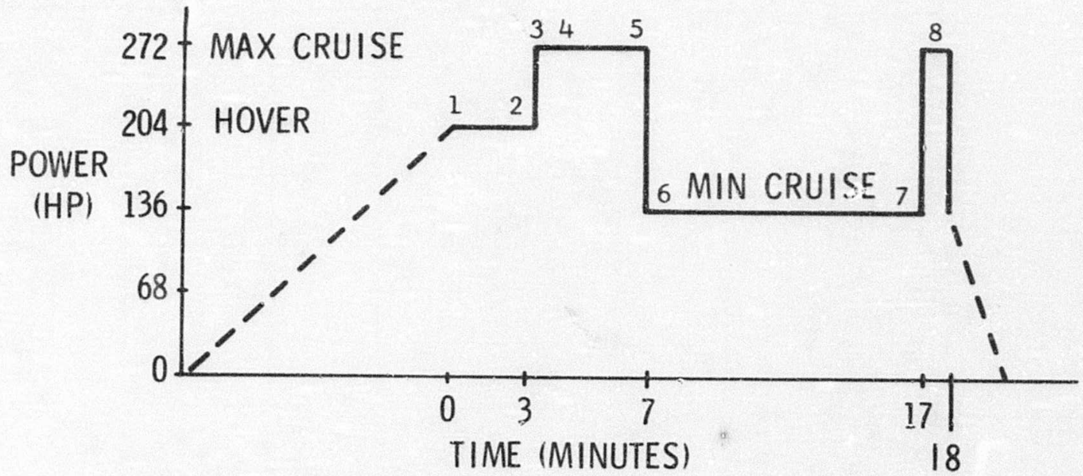


Figure 8. Mission Profile.

OPERATING PROCEDURES

Prior to the start of each ground run, a check of stick motions was made for the cyclic and collective controls to investigate possible excess stiffnesses. As expected, the forces required to move the sticks became progressively higher with colder temperatures. After "cold soak" at a temperature of -45°F, the cyclic and collective controls became almost unmovable. A check of the collective lever forces and loads in the pitch links revealed that a significant amount of these forces was attributable to the hydraulic boost system. To expedite the rotor tests (reduce warm-up time), heat was applied to the hydraulic boost cylinders prior to runs at -45°F and lower temperatures. Also, prior to all ground runs at -25°F and colder temperatures, it was necessary to heat the engine oil and the instrument oil line to obtain adequate indicated oil pressure. With some tests the initial runs were aborted until additional heat could be applied to the engine oil (noted in Table I). The significance of this operation is that the elastomeric bearings underwent some motion prior to the actual test and data acquisition. These false starts were of short duration, and a time of approximately ten minutes elapsed before restart.

Each test was conducted at 354 rpm with a pilot and a flight test engineer in the helicopter. One Bell Helicopter employee was stationed outside the hangar to operate a hangar door which allowed outlet of the engine exhaust gases. Data acquisition equipment and operators, helicopter crew chief, and hangar personnel were located in a test booth about 70 feet from the helicopter in the main hangar chamber. All personnel, including a fire marshall and refrigeration system operator, were kept in communication by an intercom system.

PILOT EVALUATION

Cyclic and collective control limits were investigated by the pilot to determine the effects of low-temperature stiffening of the main rotor EBs on helicopter operation. During hydraulic boost-off operation, the collective lever was moved to the most up position by the pilot during each test. Also, cyclic stick inputs were executed during boost-off operation to evaluate travel limits and possible feedback loads.

No control limitations were experienced at low-temperature operation to -35°F. Even though collective stick maximum motion for hydraulic boost-off operation was less than for 90°F temperature operation, the power developed was about the same because of the higher air density. Control inputs were rate limited at temperatures of -45°F and below for hydraulic boost-off operation. At -45°F and -55°F, the maximum up collective that the pilot pulled resulted in 200 horsepower, which is about that required for in-ground-effect hover. At -65°F, the maximum boost-off collective resulted in only 170 horsepower; and for boost on, 275 horsepower was obtained. Also, for all of the temperatures, full-down collective was easily achieved and the force required was similar to that for normal temperature operation.

DATA ACQUIRED AND REDUCED

Loads and motions, for the instrumentation channels listed below, were monitored and recorded continuously on two direct-write recording oscillograph machines. Locations of the instrumentation gages are given in Figures 9 and 10. Data were reduced for key events (1) through (8) per Figure 8 and at 1-minute intervals between events 6 and 7.

MAIN ROTOR

Item	Parameter	Units
Yoke Sta. 3.5	Beam Bending Moment	in.-lb
Yoke Sta. 7.8	Chord Bending Moment	in.-lb
Blade Sta. 31.25 (Red)	Beam Bending Moment	in.-lb
Mast Sta. 14.0	Parallel Bending Moment	in.-lb
Pitch Link (Red)	Axial Load (Link in	lb
Pitch Link (White)	Axial Load compression	lb
Collective Link	Axial Load for minus	lb
L.H. Cyclic Link	Axial Load values)	lb
R.H. Cyclic Link	Axial Load	lb

Main rotor blade feathering and flapping motions were monitored; however, these data were later found to be inaccurate. These motion data were acquired using rotary potentiometers mounted on sheet metal brackets. Icing and increased friction in linkage bearings at low temperatures created resistance to motion which resulted in bending of the potentiometer support structure, thus providing faulty data.

TAIL ROTOR

Item	Parameter	Units
Yoke Sta. 1.8	Beam Bending Moment	in.-lb
Yoke Sta. 1.8	Chord Bending Moment	in.-lb
Rotor Mast	Parallel Bending Moment	in.-lb
Rotor Flap Hinge	Flapping Angle	deg

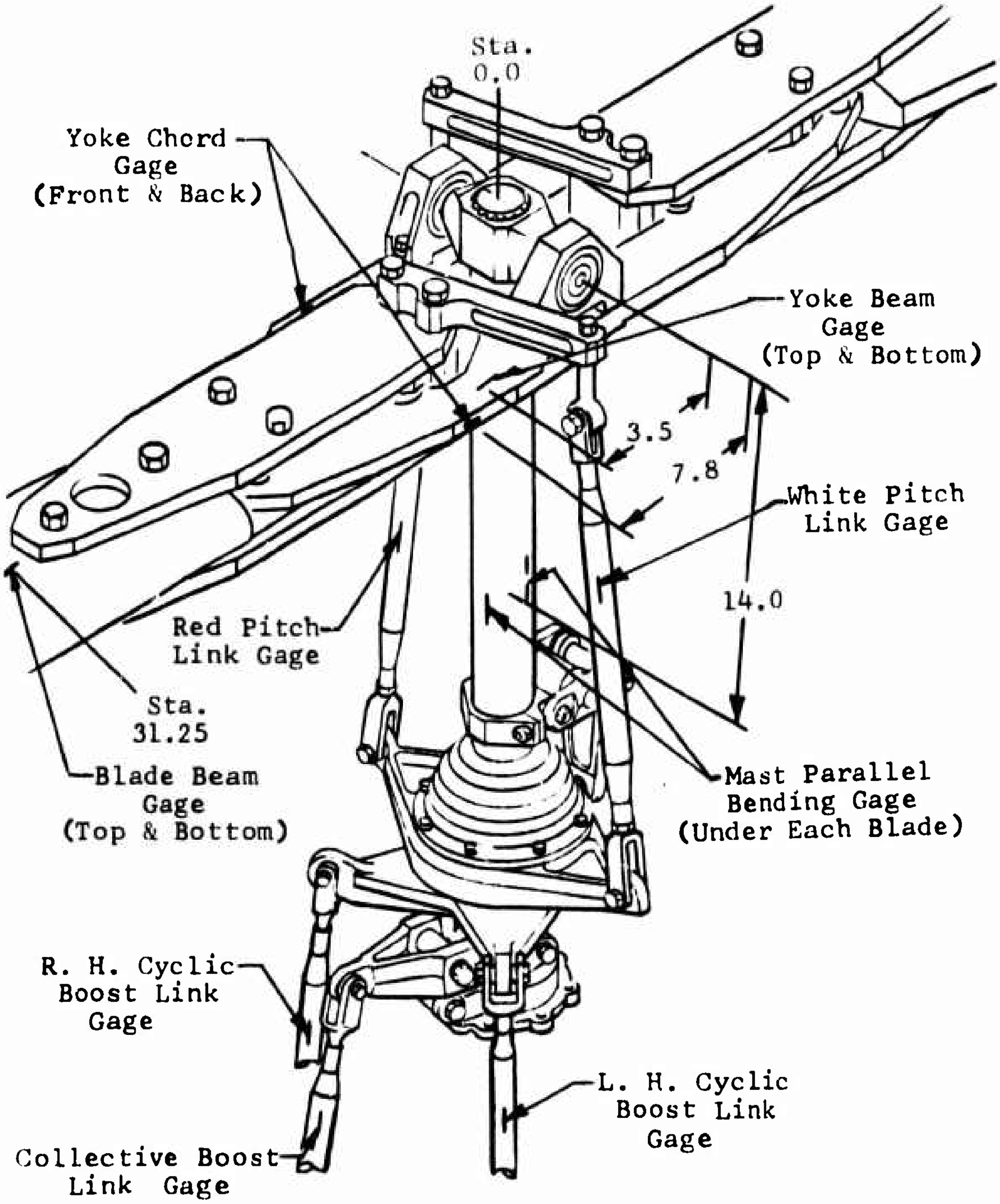


Figure 9. Main Rotor Hub and Controls Instrumentation.

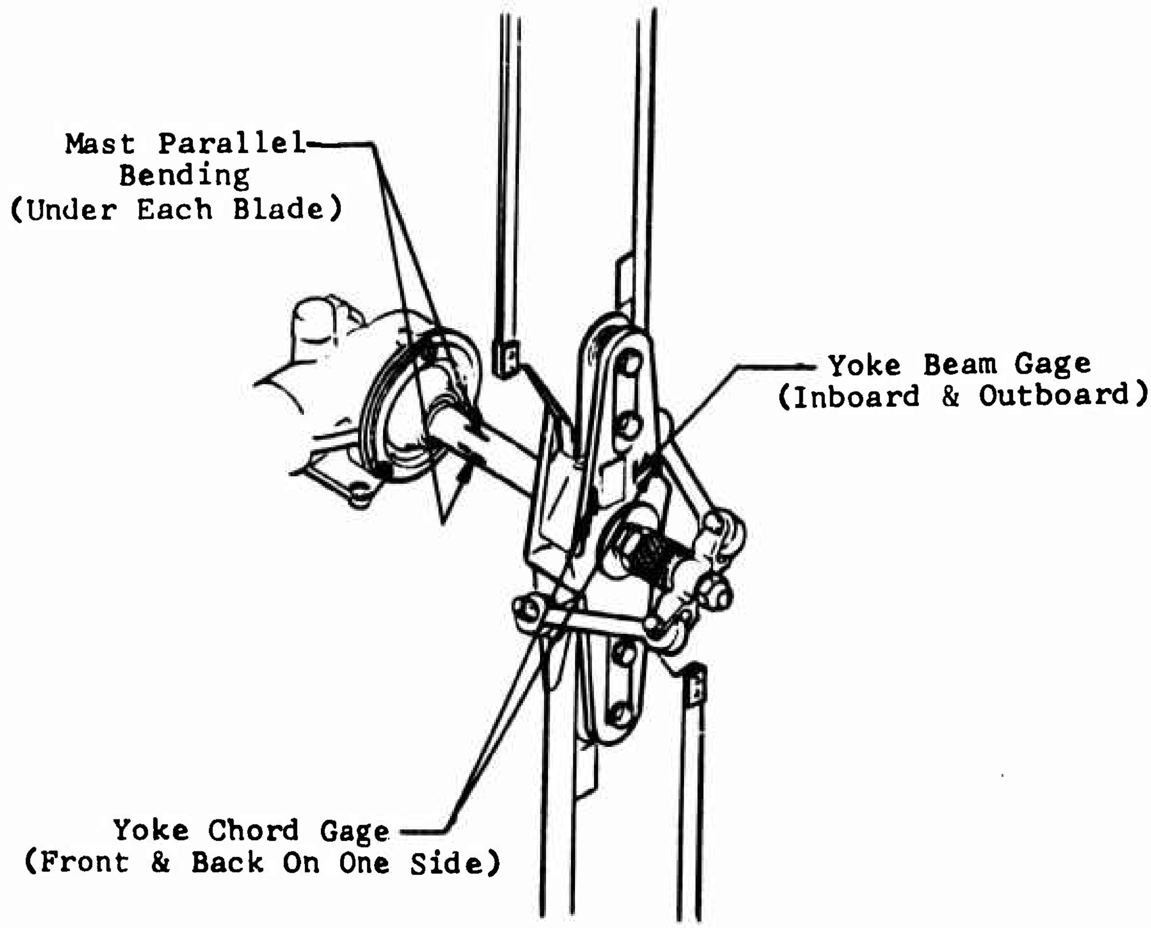


Figure 10. Tail Rotor Instrumentation.

DATA DISCUSSION

Load versus temperature data are presented graphically in Figures 11 through 19 for the main rotor and controls and in Figures 20 through 23 for the tail rotor. All data are for ground run operation at 354 main rotor rpm.

Maximum oscillatory loads recorded during forward cyclic inputs to the mid-travel stop and at a power setting of 272 horsepower (see Figure 8, event 4, 5, or 8) are given in Figures 11 through 17. Also, average pitch-link oscillatory loads obtained during the simulated minimum cruise operation (Figure 8, events 6 to 7) are given in Figure 18. Control system loads presented in Figures 11, 12, 13 and 18 are progressively higher with lower temperatures. For example, values for -65°F operation are four to five times higher than those recorded during room temperature operation. Loads measured at the cyclic boost link were used to monitor the loads going into the cylinder support assembly for the cyclic and collective actuators. The support assembly is structurally the most critical component for the control system. Calculated allowable oscillatory loads of ±265 and ±662 pounds are the boost link loads which correspond to the infinite life and maneuver operation respectively for the support structure. Maximum recorded load was ±492 pounds. Control system loads recorded from start to hover power operation were lower than the infinite life loads calculated for the parts. Rotor blade, yoke, and mast loads do not change with reductions in ambient temperatures as shown by Figures 14 through 17. During tests with the second configuration, the red pitch-link loads recorded were higher than those for the white pitch link (Figure 12). This difference is attributed to the blades being out of track after the new pitch-change bearings were installed. The out-of-track condition is also responsible for the increase (over the first configuration) in the yoke beam loads shown in Figure 16.

Mean loads for the collective boost link (at 272 steady horsepower, Figure 8, event 3) increased progressively with lower temperatures (Figure 19). In fact, hydraulic boost capability was reached at -45°F temperature operation with maximum up collective. The higher values recorded for operation at -55°F and -65°F were obtained by boost plus pilot effort. However, for full down collective, the mean collective boost link loads were less than 100 pounds for all tests. Also, the variations were not consistent with changes in temperature.

With this main rotor configuration, the pitch-change bearings are indexed for no torsional load at 8 degrees up collective. The data discussed above and in Figure 19 indicate that bearing indexing should be changed to 12 degrees up collective. Calculations indicate that this change would reduce the loads in Figure 19 by about 80 pounds for room temperature operation and possibly more for extremely low temperatures.

A preliminary evaluation was made of the data after the second test at -45°F temperature with the primary configuration. It was concluded that if tests were conducted at -65°F, the control system loads would exceed the calculated allowable limits. Thus, the decision was made to install BTR pitch-change bearings in the main rotor. Final results for the two configurations are compared in Figures 14 through 19 for tests at -35°F and -45°F temperatures. The comparison shows that the BTR pitch-change bearings do not provide a measurable load advantage. Also, the rate-of-load increase with temperature reductions indicates that for the two configurations the loads would be about the same for operation at temperatures to -65°F. It is unfortunate that hangar availability did not permit testing of the natural rubber parts to -65°F, since further evaluation of the data indicates that the test loads would not have exceeded the calculated allowables for the control system. Natural rubber parts are expected to have a longer service life than the BTR parts, and therefore they are considered to be the most suitable of the two configurations for this rotor application.

Presented in the Appendix are main rotor white and red pitch link loads, L.H. and R.H. cyclic boost link loads, collective boost link loads, and tail rotor yoke beam loads and flapping motions (Figure 8, key events 1 through 8).

All tail rotor data presented in Figures 20 through 23 are the maximum values recorded for operation at conditions of key events 3, 4, 5, and 8 of Figure 8. The only change noted in tail rotor performance is an increase in yoke beam oscillatory loads (maximum of ±631 in.-lb, Figure 21). However, the magnitude of these loads is low when compared with the allowable of ±1000 in.-lb for infinite service life for the yoke.

Tail rotor flapping data are presented in the Appendix. These data were obtained using a rotary potentiometer, and the variations in mean values between runs are believed to be in error--caused by slipping or deflection in the support structure for the potentiometer. Flapping (oscillatory) data show that changes in temperature do not affect the magnitude of the motion appreciably.

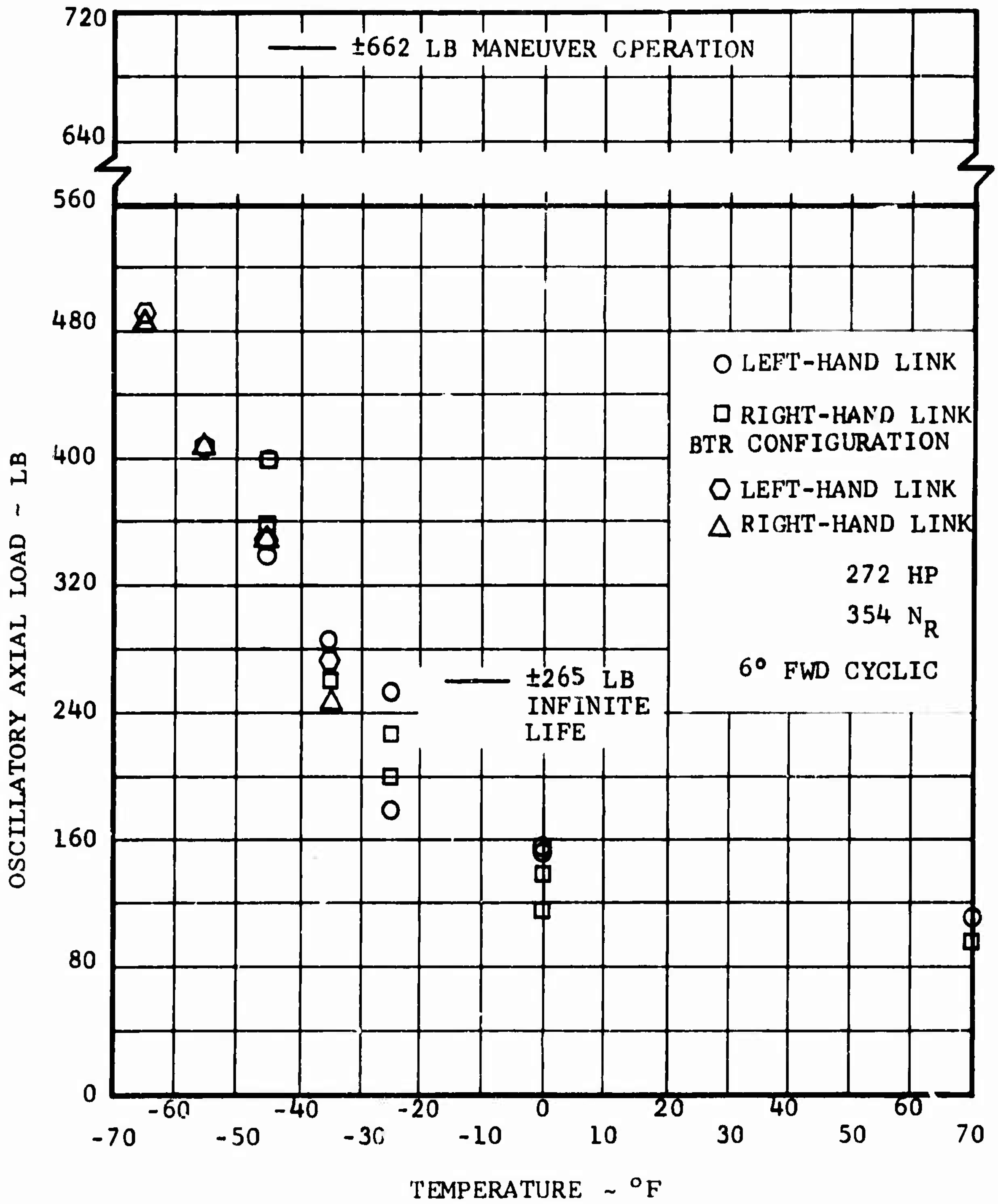


Figure 11. Cyclic Boost Link Oscillatory Loads Versus Temperature.

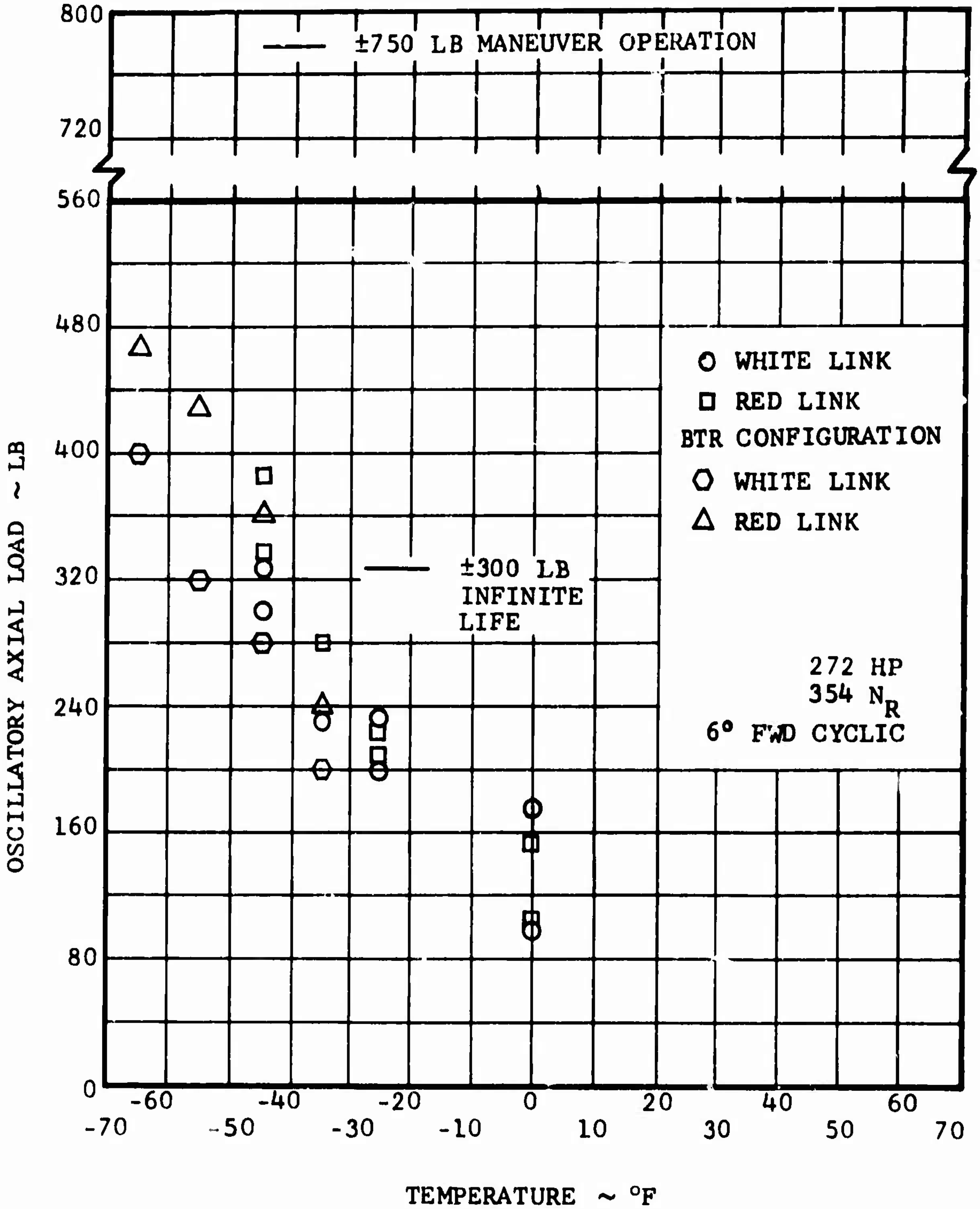


Figure 12. Main Rotor Oscillatory Pitch Link Load Versus Temperature.

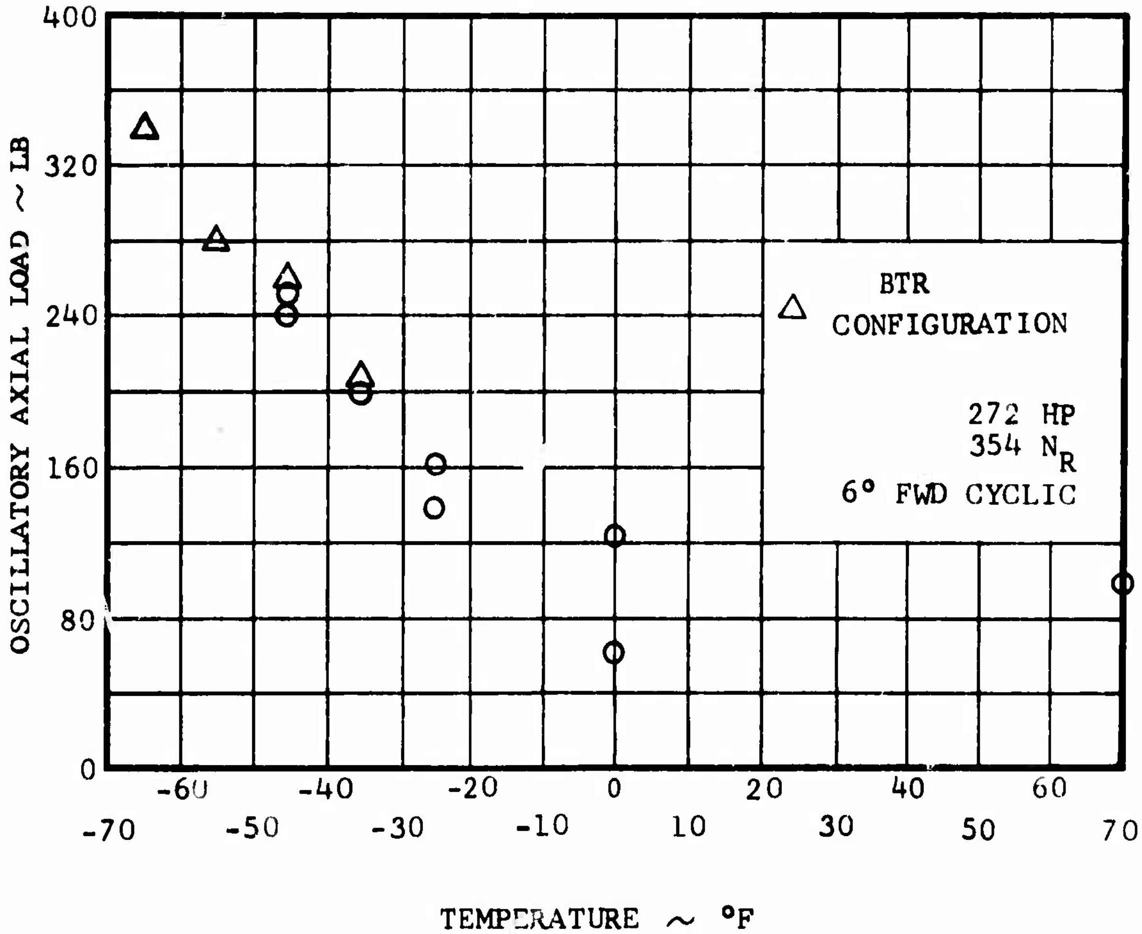


Figure 13. M/R Collective Boost Link Oscillatory Loads Versus Temperature.

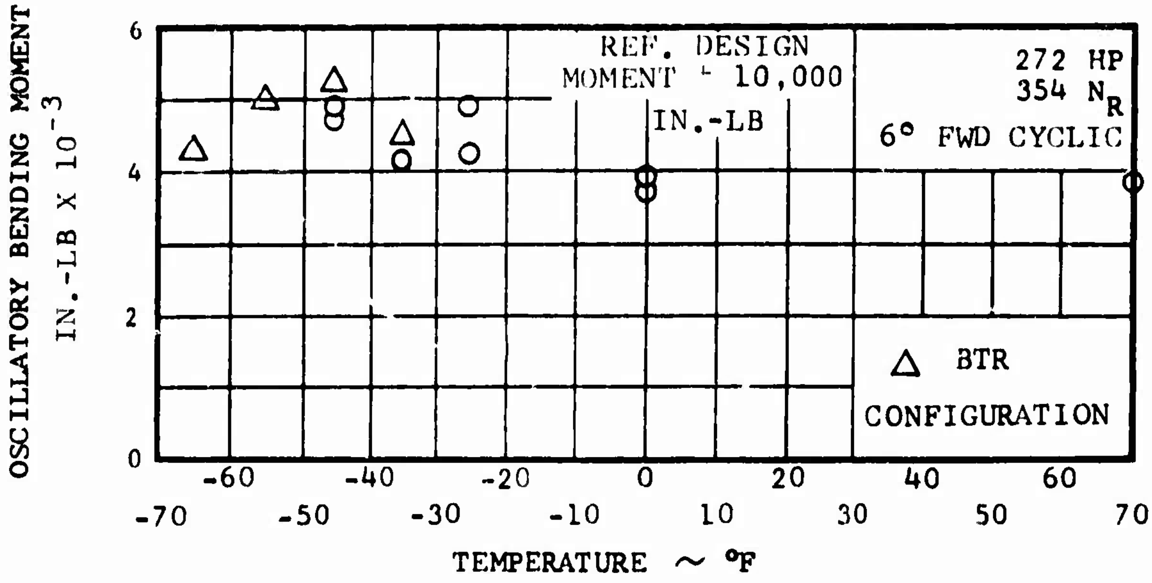


Figure 14. Main Rotor Mast Parallel Oscillatory Bending Moments Versus Temperature.

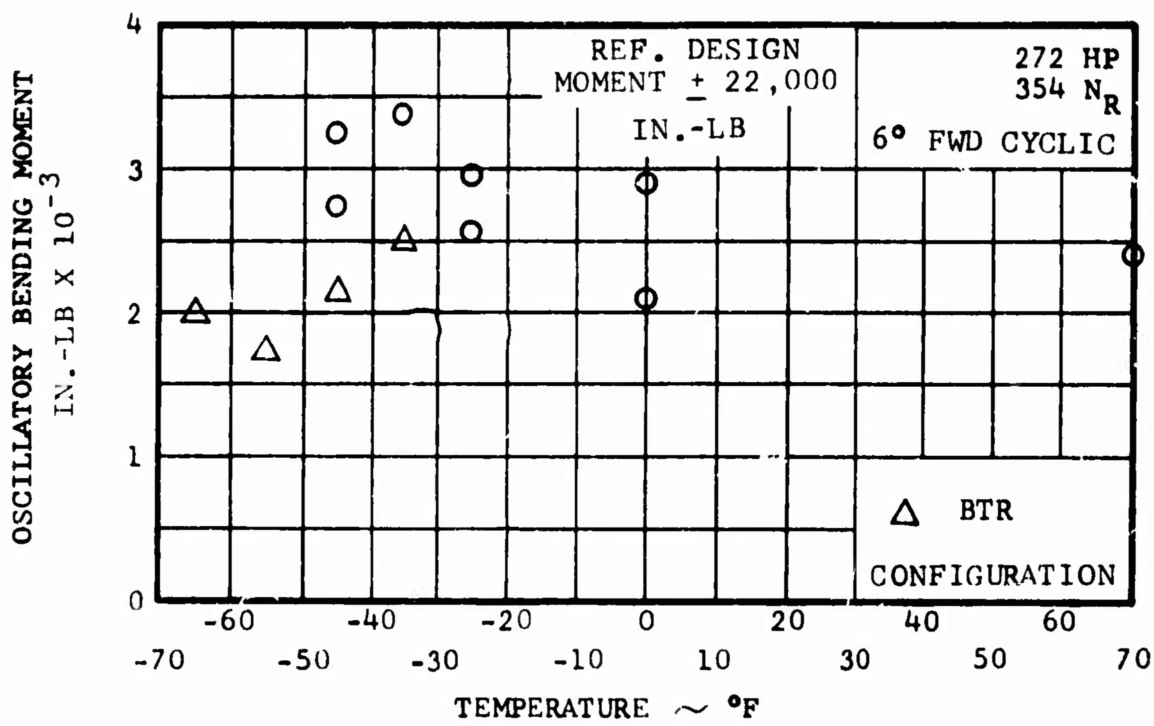


Figure 15. Main Rotor Blade Beam Oscillatory Bending Moments (Sta. 31.25) Versus Temperature.

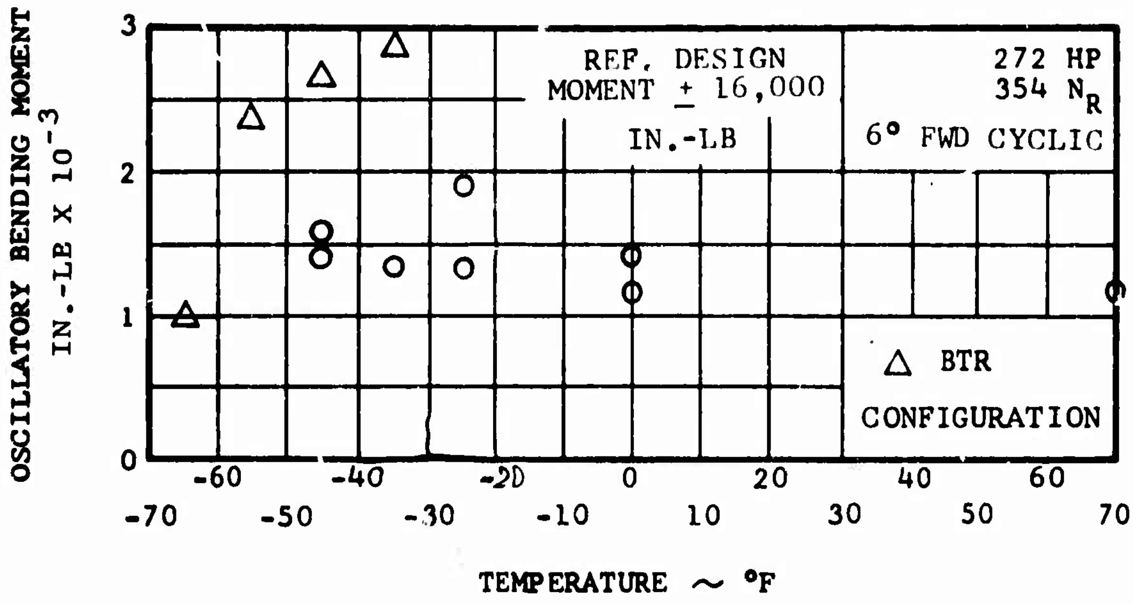


Figure 16. Main Rotor Yoke Beam Oscillatory Bending Moments (Sta. 3.5) Versus Temperature.

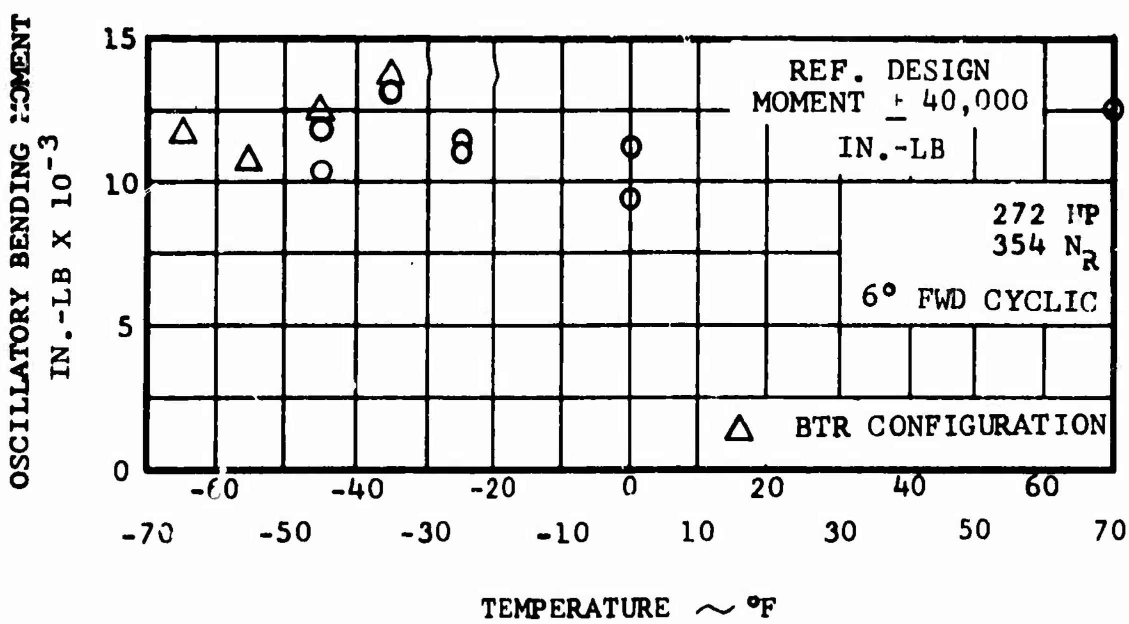


Figure 17. Main Rotor Yoke Chord Oscillatory Bending Moments (Sta. 7.8) Versus Temperature.

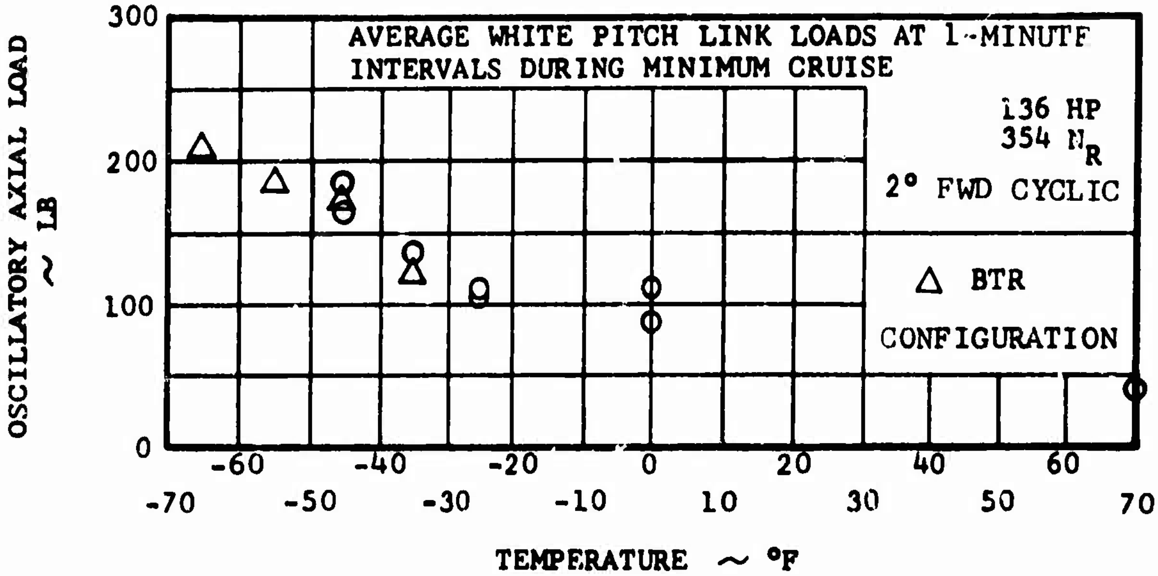


Figure 18. Minimum Cruise White M/R Pitch Link Oscillatory Loads Versus Temperature.

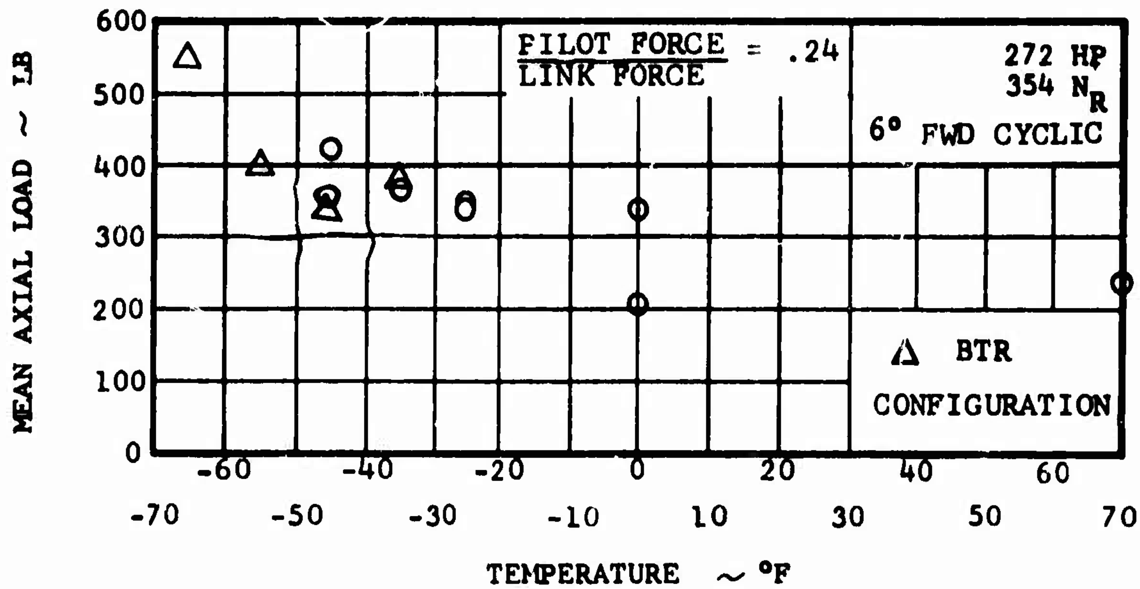


Figure 19. Collective Boost Link Mean Loads Versus Temperature.

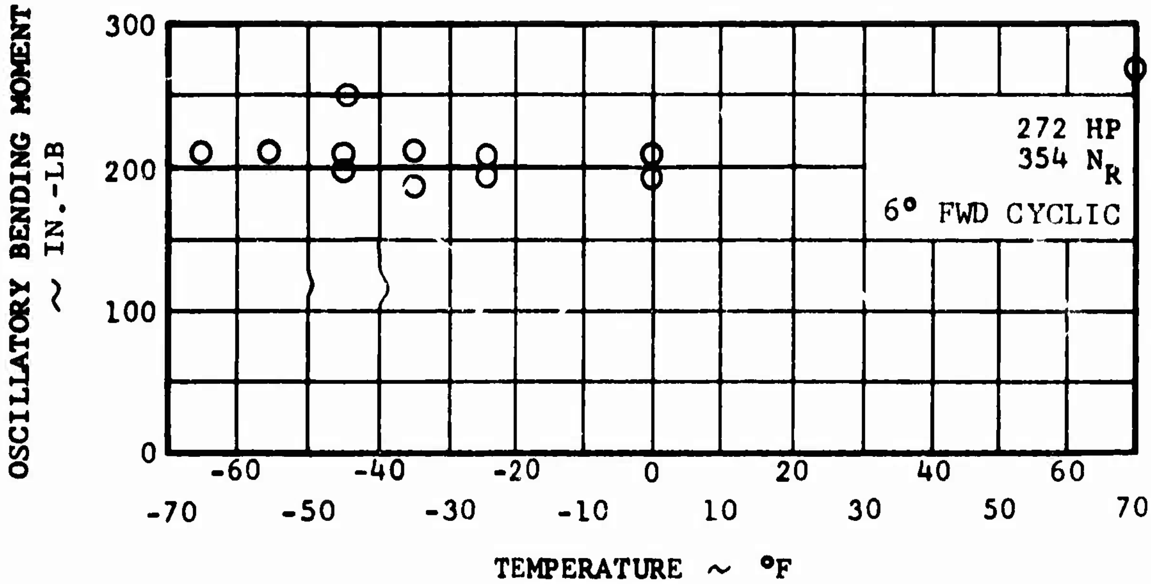


Figure 20. Tail Rotor Mast Parallel Oscillatory Bending Moments Versus Temperature.

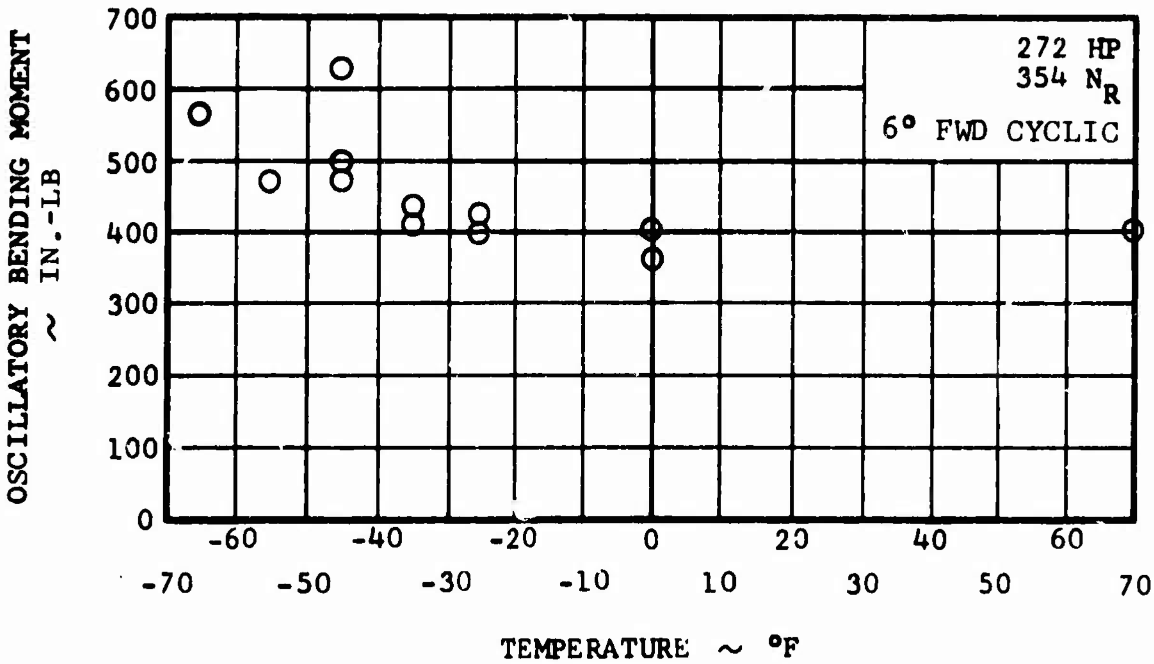


Figure 21. Tail Rotor Red Yoke Beam Oscillatory Bending Moments (Sta. 1.8) Versus Temperature.

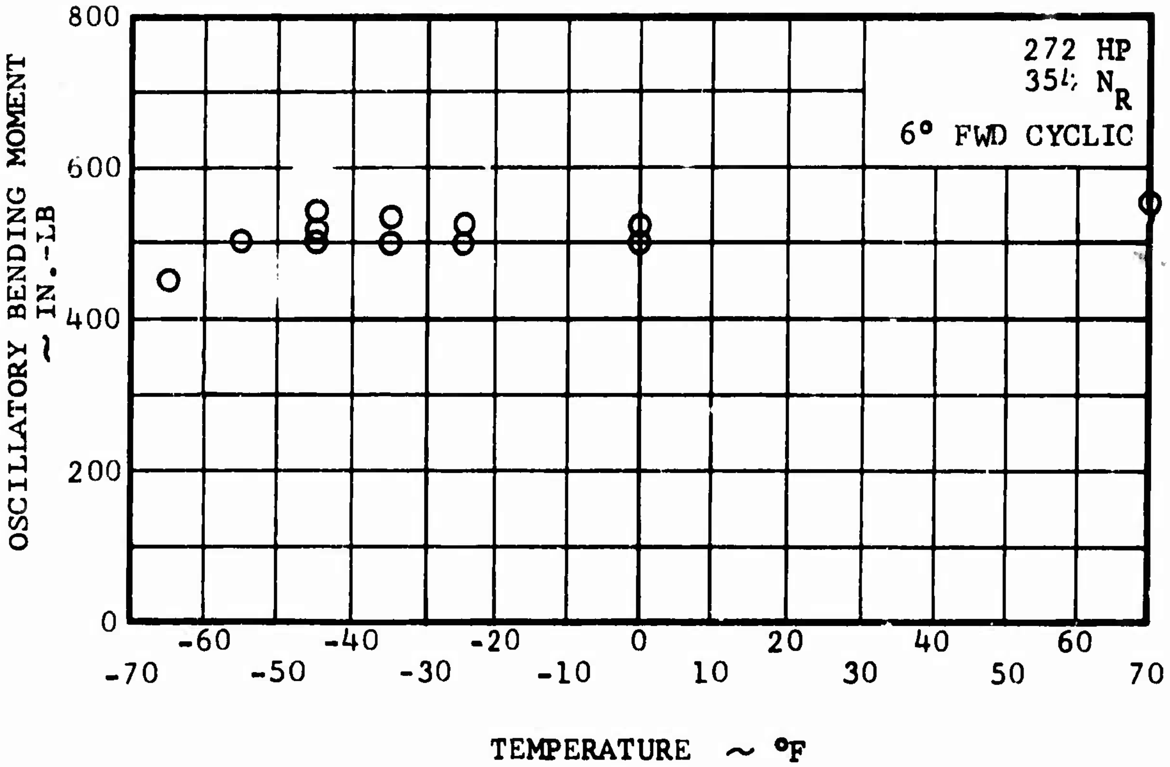


Figure 22. Tail Rotor Red Yoke Chord Oscillatory Bending Moments (Sta. 1.8) Versus Temperature.

CONCLUSIONS

An all-elastomeric bearing main rotor and a tail rotor with EBs in the flapping axis were tested on an OH-58A helicopter, while tied down in the Climatic Laboratory at Eglin Field, Florida. Test results indicate that for both rotors no major problems exist for operation to a low temperature of -65°F. With the flapping assemblies in the main and tail rotors, no problems were encountered and no changes are recommended for low-temperature operation. The main rotor pitch-change EBs performed satisfactorily except that operating loads in the controls increased progressively with reductions in temperature. The higher loads may require redesign or a reduction in service life for some control parts for extensive operation at temperatures below -45°F. Also, flare capability may be limited, because of high steady collective control loads, at temperatures below -55°F for hydraulic boost-off autorotation. These loads can be reduced to some extent without impairing normal flight characteristics, by reindexing the pitch-change bearings.

These conclusions are based on tie-down operations and cyclic control inputs limited to mid-travel by stops. A low-temperature flight test program is needed to investigate the magnitude of combined bearing stiffness loads and loads created by in-flight rotor dynamics, steady collective stick loads during boost-off autorotation, and other remaining questions concerning flight characteristics of rotors equipped with EBs in extreme low-temperature environments.

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3. Donaldson, Neal J., CLIMATIC LABORATORY TEST OH-58A HELICOPTER EQUIPPED WITH XM27E1 MACHINE GUN ARMAMENT SYSTEM, Project 68-53, U.S. Army Aviation Systems Test Activity, Edwards Air Force Base, California, July 1970.

APPENDIX

TABULATED GROUND-RUN TEST RESULTS

All data presented in Tables II through VIII were acquired during ground run in the Climatic Hangar at 354 main rotor rpm.

Test conditions for runs 1 through 11 are the same as that given in Figure 8.

Key event and condition:

1. Hover Power (No Cyclic)
2. Stir Stick to Mid-Travel Stops
3. Maximum Continuous Power
4. F/A Cyclic Input to Mid-Travel Stops (6° Forward Cyclic)
5. F/A Cyclic Input to Mid-Travel Stops (Boost-Off)
6. Start of Continuous Operation With 2° Forward Cyclic (Minimum Cruise Power)
7. End of Continuous Operation With 2° Forward Cyclic
8. F/A Cyclic Input to Mid-Travel Stops (Boost-Off) (272 hp)

Test conditions for run 12 (-65°F) were as follows:

Key event and condition:

1. Hover Power (No Cyclic)
2. 5° Forward Cyclic Input at 204 hp
3. Maximum Continuous Power (272 hp)
4. F/A Cyclic Input to Mid-Travel Stops (6° Forward Cyclic) (204 hp)
5. Stir Cyclic Hydraulic Boost-Off (204 hp)
6. Minimum Cruise Power With 2° Forward Cyclic
7. Power Check Boost-On
8. Stir Cyclic Hydraulic Boost-On (136 hp)

TABLE II. MAIN ROTOR RED PITCH LINK AXIAL LOADS (LB)

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	70°F	1	0°F	2	0°F	3	-25°F	4
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	-135	77	-97	47	-47	107	-146	68
2	-122	115	-178	93	-34	171	-128	231
3	-105	56	-148	55	-94	77	-193	64
4	-165	50	-220	110	-90	150	-180	223
5	-139	81	-165	55	-86	128	-175	193
6	-63	56	-51	59	30	124	-64	133
7	-59	34	64	191	17	86	-73	107
8	-127	77	-144	59	-68	146	-193	141

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	-25°F	5	-35°F	6	-45°F	7	-45°F	8
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	-135	57	-130	86	-134	134	-101	119
2	-118	214	-117	264	-121	441	-128	322
3	-153	48	-147	104	-181	164	-150	159
4	-183	210	-177	281	-168	384	-146	331
5	-188	205	-168	255	-121	311	-123	291
6	-48	100	-39	134	4	264	18	203
7	-22	65	-48	151	-39	177	-4	198
8	-214	179	-186	194	-164	294	-119	278

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	-35°F	9	-45°F	10	-55°F	11	-65°F	12
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	-225	260	-187	54	-187	152	-194	122
2	-176	53	-205	428	-138	433	-167	428
3	-247	62	-223	54	-219	49	-279	117
4	-234	234	-183	361	-205	259	-158	464
5	-225	216	-161	321	-174	433	32	275
6	-84	128	-13	156	0	223	5	230
7	-97	115	-36	143	-9	187	-333	72
8	-238	212	-196	268	31	388	-23	311

TABLE III. MAIN ROTOR WHITE PITCH LINK AXIAL LOADS (LB)

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	70°F	1	0°F	2	0°F	3	-25°F	4
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	-153	40	-132	70	-45	63	-115	80
2	-144	128	-154	66	-31	148	-173	173
3	-188	75	-189	66	-94	67	-186	53
4	-188	110	-162	101	-58	175	-186	231
5	-175	106	-198	101	-67	157	-111	137
6	-70	44	-75	92	45	81	9	71
7	-79	53	-44	114	40	85	-53	108
8	-171	119	-202	97	-99	125	-204	115

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	-25°F	5	-35°F	6	-45°F	7	-45°F	8
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	-122	50	-63	72	-167	122	-106	134
2	-113	258	-193	193	-41	367	-79	310
3	-190	90	-121	85	-190	163	-176	166
4	-172	199	-152	233	-81	326	-88	301
5	-186	204	-193	193	-163	244	-93	296
6	-32	95	-13	139	-27	172	9	157
7	-18	118	-9	170	-32	176	14	227
8	-208	163	-103	184	-145	262	-111	277

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	-35°F	9	-45°F	10	-55°F	11	-65°F	12
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	-23	208	-167	46	-154	136	-203	109
2	-176	83	-97	291	-103	309	-61	364
3	-231	56	-236	60	-234	47	-269	109
4	-227	180	-106	282	-173	238	-19	406
5	-217	190	-166	222	-89	323	85	274
6	-56	129	9	148	0	215	28	274
7	-65	129	-23	171	-9	178	-321	76
8	-208	199	-194	194	-33	295	-9	312

TABLE IV. MAIN ROTOR L.H. CYCLIC BOOST LINK AXIAL LOADS (LB)

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	70°F	1	0°F	2	0°F	3	-25°F	4
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	15	57	24	45	35	49	35	61
2	32	152	101	157	21	127	135	206
3	43	78	52	59	14	78	51	45
4	-14	113	-35	147	-7	148	48	183
5	32	103	-17	115	-11	138	68	158
6	11	53	14	91	4	74	13	84
7	25	39	28	84	18	74	19	96
8	-35	113	-24	108	-18	124	71	154

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	-25°F	5	-35°F	6	-45°F	7	-45°F	8
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	40	62	74	88	14	94	-18	98
2	171	294	201	265	90	457	200	331
3	58	73	49	78	-7	137	11	134
4	7	254	21	282	40	400	11	338
5	18	236	49	226	115	338	80	284
6	51	80	7	127	61	176	47	149
7	29	116	35	148	18	176	87	189
8	25	171	74	194	68	277	29	284

Key Event	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
	-35°F	9	-45°F	10	-55°F	11	-65°F	12
	Mean	Osc.	Mean	Osc.	Mean	Osc.	Mean	Osc.
1	4	258	68	54	51	117	59	66
2	29	65	306	407	-206	374	176	411
3	36	51	61	54	66	37	44	44
4	58	269	94	346	15	228	213	492
5	73	218	7	310	48	407	-154	250
6	62	134	130	194	29	198	147	264
7	65	138	86	158	55	172	62	55
8	-40	207	22	245	95	426	11	312

TABLE V. MAIN ROTOR R.H. CYCLIC BOOST LINK AXIAL LOADS (LB)

Key Event	70°F Mean	Run 1 Osc.	0°F Mean	Run 2 Osc.	0°F Mean	Run 3 Osc.	-25°F Mean	Run 4 Osc.
	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
1	42	71	67	59	85	115	105	82
2	101	131	152	152	-126	141	-187	202
3	38	75	63	70	44	96	71	71
4	38	75	67	118	-125	133	261	202
5	75	90	78	63	126	126	224	187
6	49	49	93	85	126	118	153	138
7	23	23	78	78	89	118	138	108
8	172	75	100	93	-111	118	187	164

Key Event	-25°F Mean	Run 5 Osc.	-35°F Mean	Run 6 Osc.	-45°F Mean	Run 7 Osc.	-45°F Mean	Run 8 Osc.
	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
1	8	53	109	86	150	127	130	114
2	-253	238	265	296	474	474	-295	311
3	60	83	152	121	177	154	185	146
4	-257	227	316	261	420	397	357	351
5	215	230	285	246	332	316	292	299
6	57	140	156	140	293	278	193	201
7	-18	98	176	168	204	189	185	201
8	-177	155	215	199	316	285	268	284

Key Event	-35°F Mean	Run 9 Osc.	-45°F Mean	Run 10 Osc.	-55°F Mean	Run 11 Osc.	-65°F Mean	Run 12 Osc.
	TEST AMBIENT TEMPERATURES AND RUN NUMBERS							
1	229	259	72	42	158	112	125	94
2	53	46	336	374	447	424	464	402
3	34	65	-11	65	27	58	121	90
4	252	244	374	343	281	258	429	484
5	-187	210	-217	233	432	409	214	222
6	145	130	214	191	235	212	253	238
7	134	134	179	164	208	177	-23	94
8	233	217	-214	259	416	401	355	316

TABLE VI. MAIN ROTOR COLLECTIVE BOOST LINK AXIAL LOADS (LB)

Key Event	70°F Mean	1 Osc.	0°F Mean	2 Osc.	0°F Mean	3 Osc.	-25°F Mean	4 Osc.
1	222	43	257	43	137	72	256	54
2	293	122	318	125	29	144	371	184
3	243	43	339	39	209	58	342	54
4	297	47	339	46	68	126	407	148
5	343	79	328	43	36	115	418	137
6	125	54	136	57	32	105	169	97
7	125	25	125	54	14	72	159	87
8	145	100	414	64	256	105	159	151

TEST AMBIENT TEMPERATURES AND RUN NUMBERS

Key Event	-25°F Mean	5 Osc.	-35°F Mean	6 Osc.	-45°F Mean	7 Osc.	-45°F Mean	8 Osc.
1	241	48	290	70	262	80	312	86
2	401	230	426	243	531	291	143	248
3	345	48	382	81	360	98	417	86
4	189	160	456	198	550	251	529	244
5	409	163	437	187	448	222	473	210
6	149	104	110	74	215	178	184	131
7	130	63	154	118	178	135	203	128
8	193	134	121	151	33	186	462	207

TEST AMBIENT TEMPERATURES AND RUN NUMBERS

Key Event	-35°F Mean	9 Osc.	-45°F Mean	10 Osc.	-55°F Mean	11 Osc.	-65°F Mean	12 Osc.
1	459	254	283	40	368	83	402	71
2	257	37	588	309	638	360	623	270
3	386	40	334	33	398	38	544	56
4	239	209	610	257	563	150	646	345
5	481	180	485	228	120	278	-60	128
6	191	96	191	121	180	143	229	154
7	202	92	173	121	192	124	511	45
8	176	176	154	191	330	263	300	203

TABLE VII. TAIL ROTOR YOKE BEAM MOMENTS, STA. 1.8 (IN.-LB)

Key Event	70°F Run 1 Mean	Osc.	0°F Run 2 Mean	Osc.	0°F Run 3 Mean	Osc.	-25°F Run 4 Mean	Osc.
1	1044	241	1397	575	986	246	1027	370
2	1044	101	1150	329	904	411	1027	288
3	1044	101	1315	411	1027	370	1150	329
4	1285	402	1232	411	904	329	1191	288
5	1245	282	1150	329	945	288	1068	411
6	1165	201	1191	370	904	246	986	164
7	1205	161	1191	205	986	329	1109	205
8	1526	322	1232	411	1150	329	1191	370

Key Event	-25°F Run 5 Mean	Osc.	-35°F Run 6 Mean	Osc.	-45°F Run 7 Mean	Osc.	-45°F Run 8 Mean	Osc.
1	1220	379	1136	368	1136	463	1094	421
2	967	379	1009	421	1094	421	925	421
3	1136	379	1220	463	1178	421	1052	547
4	1094	421	1009	252	1007	421	1052	463
5	1094	421	1051	379	1051	379	1051	631
6	1178	336	967	294	1051	294	1178	505
7	1051	379	925	252	1094	336	967	379
8	1051	379	1009	421	1094	505	1052	463

Key Event	-35°F Run 9 Mean	Osc.	-45°F Run 10 Mean	Osc.	-55°F Run 11 Mean	Osc.	-65°F Run 12 Mean	Osc.
1	1293	345	991	215	1120	517	1810	948
2	1249	388	991	474	1077	388	1206	345
3	1379	345	991	474	1034	431	1249	560
4	1249	388	948	345	1077	474	1120	345
5	1293	431	819	388	1034	431	1206	345
6	1249	302	905	302	1206	431	1206	345
7	1293	345	991	302	948	345	1249	388
8	1336	388	948	431	1034	259	1034	345

TABLE VIII. TAIL ROTOR FLAPPING MOTION (DEGREES FROM MAST)

Key Event	70°F Mean	1 Osc.	0°F Mean	2 Osc.	0°F Mean	3 Osc.	-25°F Mean	4 Osc.
1	.08	2.06	.41	1.66	.70	1.28	.17	1.24
2	.16	2.48	.25	1.57	.62	1.70	.25	1.33
3	.29	3.11	.33	1.82	.50	1.49	.25	1.82
4	.25	2.40	.46	1.95	.62	1.61	.17	1.66
5	.29	2.86	.25	1.90	.54	1.78	.21	2.03
6	.46	1.70	.41	1.74	.11	1.32	.25	.91
7	.54	1.94	.37	1.28	.50	1.24	.33	1.49
8	.33	2.65	.41	2.07	.37	1.61	.04	2.11

Key Event	-25°F Mean	5 Osc.	-35°F Mean	6 Osc.	-45°F Mean	7 Osc.	-45°F Mean	8 Osc.
1	.25	1.57	.73	1.98	.68	1.47	.17	1.30
2	.37	1.61	.96	1.75	.73	1.53	.23	1.36
3	.21	1.61	.90	2.60	.62	2.09	.06	2.31
4	.25	2.40	.85	2.09	.73	2.32	.23	1.81
5	.37	1.53	.79	1.92	.68	2.26	.11	2.37
6	.41	1.41	1.01	1.47	.73	.96	.28	1.30
7	.37	1.20	.96	1.41	.68	1.13	.23	1.02
8	.29	1.61	.96	2.88	.51	2.32	.17	1.64

Key Event	-35°F Mean	9 Osc.	-45°F Mean	10 Osc.	-55°F Mean	11 Osc.	-65°F Mean	12 Osc.
1	.90	1.13	.57	1.13	.69	1.13	.73	1.19
2	.79	1.58	.79	1.13	.51	1.86	.73	1.75
3	1.18	2.77	.79	1.58	.51	2.32	.57	1.13
4	.73	2.77	.69	2.15	.40	1.87	.68	1.70
5	.90	2.83	.73	2.88	.34	2.07	.62	1.07
6	1.02	1.70	.73	1.53	.51	1.07	.62	.85
7	1.02	1.70	.69	1.13	.62	1.07	.62	2.09
8	.85	2.43	.69	2.26	.57	.67	.45	.90