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LOW-TEMPERATURE TESTING OF AN AH-IG HELICOPTER EQUIPPED WITH ELASTOMERIC FLAPPING AND FEATHERING BEARINGS IN THE MAIN ROTOR

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Low-temperature testing of an AH-1G helicopter equipped with a main rotor incorporating elastomeric flapping and feathering bearings was conducted in the McKinley Climatic Laboratory at Eglin AFB, Florida. The purpose of the test was to determine the low-temperature service suitability of the elastomeric bearings.

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EUSTIS DIRECTORATE POSITION STATEMENT

The effort discussed herein is an accurate description of the characteristics of elastomeric bearings when installed on an aircraft in an extreme cold arctic environment. It is believed that this information is applicable not only in the determination of the suitability of the test helicopter used in this program for cold-weather operation, but also in describing operational characteristics that will likely be encountered in other aircraft using these bearings. As such, this data lends itself for reference purposes to another Eustis Directorate sponsored effort, entitled "Design Criteria for Elastomeric Bearings."

The test is part of a total effort being sponsored by the U. S. Army Aviation Systems Command and the Eustis Directorate, USAAMRDL, to determine the service suitability of an elastomeric bearing hub for the AH-1G helicopter. The remaining efforts under the Eustis Directorate contract include fatigue testing of the hub components and service flight testing, each of which will be the subject of a separate report. 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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For the purpose of establishing a baseline, and to determine any low-temperature problems peculiar to the AH-1G which would prejudice testing of the elastomeric bearings, the standard Model 540 main rotor was tested first.

The test temperature range was +70°F to -65°F for both rotors. At each test temperature, the AH-1G was operated over a power and cyclic blade pitch spectrum which simulated as nearly as possible the values to be found in flight. Blade and control system loads and positions, and fuselage vibrations, were monitored and recorded during the test runs.

The test did not disclose any low-temperature characteristics of the all-elastomeric-bearing main rotor which would preclude satisfactory operation. However, if the rotor is started at temperatures of -55°F or below, high vibration levels and a rotor out-of-track condition will probably result if the elastomeric pitch-change bearings on opposing sides of the mast are at substantially differing temperatures as a result of preflight warming of the transmission compartment. The bearings may be warmed equally, prior to start, using a simple field-manufactured canvas hub cover to duct heated air from the transmission compartment to the hub during the required heating of the transmission input shaft coupling seals.

Cold-weather flight testing of the all-elastomeric-bearing main rotor is required to validate and extend the information obtained from this test in the Climatic Laboratory.

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INTRODUCTION

The use of elastomeric bearings in the AH-1G main rotor has been investigated by Bell Helicopter Company (BHC) since 1969. Work began with development of elastomeric flapping bearings for the AH-1G under sponsorship of the U. S. Army Aviation Systems Command. U. S. Army AH-1G helicopters are now being retrofitted with elastomeric flapping bearings.

The investigation of elastomeric pitch-change bearings, sponsored by the Eustis Directorate, was begun in 1970. The results of flight test of an experimental all-elastomeric main rotor on the AH-1G are reported in USAAVLABS TR 71-16.*

The present effort (under this contract) is to evaluate the suitability of all-elastomeric rotors under field conditions. The contracted work includes a fatigue test, a cold-weather test, and a field service evaluation. The purpose of this document is to report the results of the Climatic Hangar testing.

The purpose of the Climatic Hangar testing was to investigate the effects of low temperatures on the all-elastomeric AH-1G main rotor hub while the rotor was operated through a representative power and blade angle spectrum. The original intent was to test the standard AH-1G rotor, a natural rubber elastomeric bearing (EB) hub, and a broad-temperature-range (BTR) EB hub. However, because of the satisfactory performance of the natural rubber hub, the BTR hub was not evaluated. Instead, additional testing of the natural rubber hub was performed.

*Fagan, Castle H., FLIGHT EVALUATION OF ELASTOMERIC BEARINGS IN AN AH-1G HELICOPTER MAIN ROTOR, USAAVLABS Technical Report 71-16, Bell Helicopter Company Report No. 299-099-485, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, March 1971.

DISCUSSION

DESCRIPTION OF TEST HARDWARE

The Test Vehicle

The AH-1G test vehicle, incorporating the BHC Model 540 all-elastomeric main rotor, is shown in Figure 1.

A Model 540 elastomeric grip and extension assembly is shown in Figure 2. The location of the elastomeric bearings may be determined by noting the position of the bearing retention bolts which project through the upper and lower sides of the grip.

Figure 3 shows the 540 grip, extension, and feathering bearings in a disassembled condition. The bearings have been placed in their approximate location with respect to the extension plate.

Figure 1. AH-1G Test Vehicle.

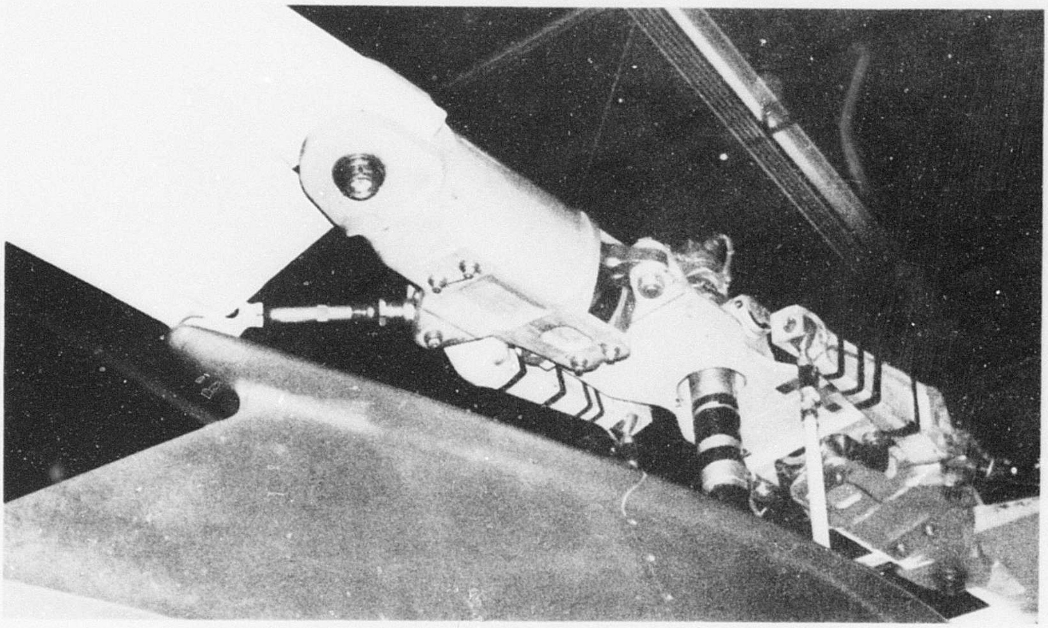


Figure 2. Model 540 Elastomeric Grip and Extension Assembly.

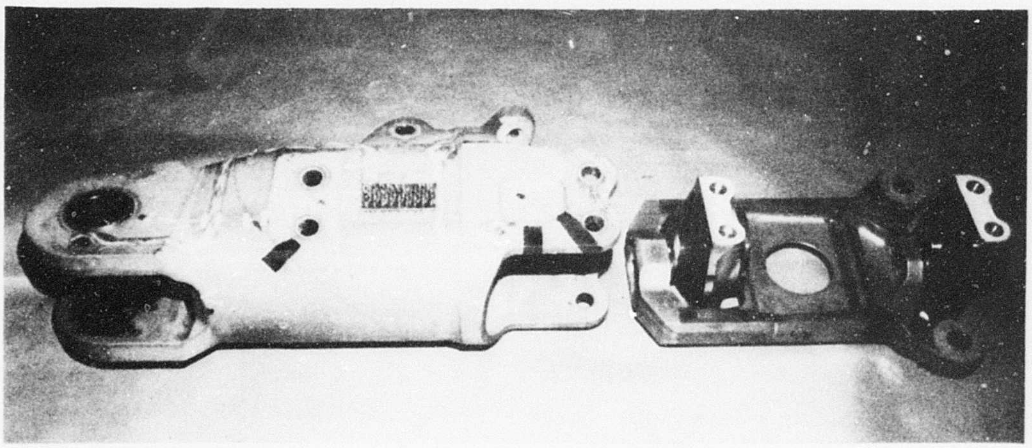


Figure 3. Disassembled Model 540 Elastomeric Grip, Extension, and Bearings.

The LM 726-4 bearing is shown in Figure 4. A sectioned bearing is shown in Figure 5 to explain the general construction of the elastomeric layers.

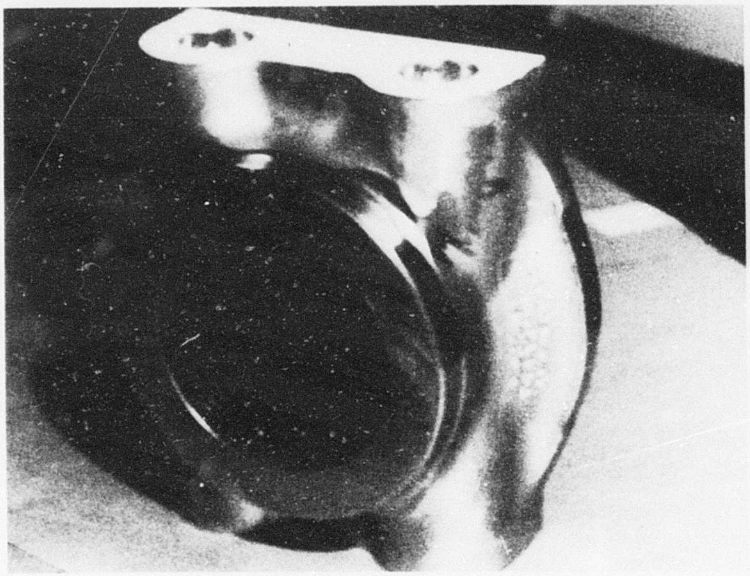


Figure 4. LM 726-4 Elastomeric Bearing.

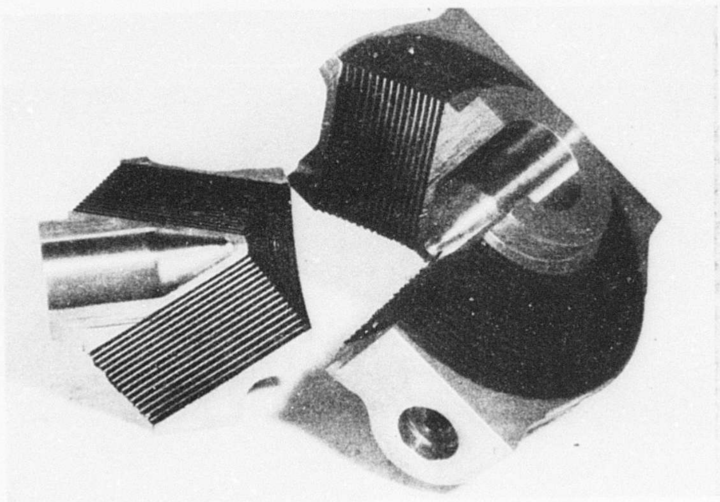


Figure 5. Sectioned Elastomeric Bearing.

The elastomeric flapping bearing is shown in Figure 6. This bearing is presently being retrofitted to U. S. Army AH-1G helicopters.

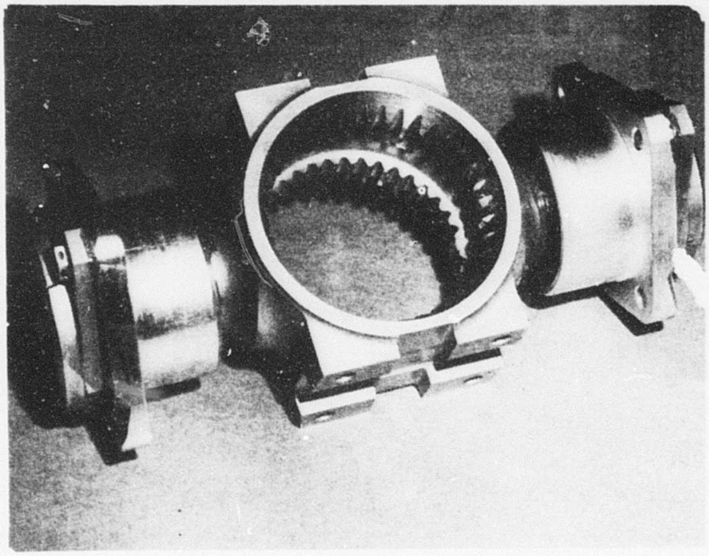


Figure 6. Elastomeric Flapping Bearing.

In addition to the all-elastomeric bearing 540 hub, a standard 540 hub was tested first to provide baseline information and to determine if problems peculiar to the basic AH-1G would adversely influence testing of the elastomeric hub.

TEST INSTRUMENTATION

Test data was recorded on three oscillographs, one of which was a direct-write machine. The following values, considered essential for safety-of-operation determination, were recorded on the direct-write machine:

1. Collective boost tube axial load.
2. Longitudinal cyclic boost tube axial load.
3. Lateral cyclic boost tube axial load.

4. Red blade pitch angle.

5. Yoke beam bending, Station 5.0.

6. Yoke chord bending, Station 8.0.

7. Blade beam bending, Station 46.

8. Main rotor pitch red link axial load.

9. Red drag brace axial load.

10. Extension beam bending, Station 26.12.

11. Extension chord bending, Station 26.12.

12. Pylon longitudinal tilt angle.

The following values were recorded on the two standard oscillographs. These data were processed daily and analyzed prior to the succeeding test.

1. Main rotor (red blade) chordwise bending moment, Station 60.

2. Main rotor (red blade) chordwise bending moment, Station 135.

3. Main rotor (red blade) chordwise bending moment, Station 210.

4. Main rotor (red blade) beamwise bending moment, Station 60.

5. Main rotor (red blade) beamwise bending moment, Station 135.

6. Main rotor (red blade) beamwise bending moment, Station 210.

7. Main rotor white pitch link axial load.

8. Lift link axial load.

9. Mast parallel bending, 44 inches below spline centerline.

10. Mast perpendicular bending, 44 inches below spline centerline.

11. Mast torsion, 44 inches below spline centerline.
12. Main rotor azimuth.
13. Collective stick position.
14. Cyclic stick position, F/A.
15. Cyclic stick position, lateral.
16. Inner elastomeric bearing shell temperature (red blade).
17. Outer elastomeric bearing shell temperature (red blade).
18. Main rotor flapping.
19. Pilot vertical acceleration.
20. Transmission acceleration, F/A (upper mast bearing).
21. Transmission acceleration, lateral (upper mast bearing).
22. Extension beam bending, Station 20.75.
23. Extension chord bending, Station 20.75.

The following values were displayed on the pilot's instrument panel:

1. Cyclic boost tube oscillatory load.
2. Cyclic stick position, longitudinal.
3. Cyclic stick position, lateral.
4. Collective stick position.

LM 726-4 elastomeric pitch-change bearings with thermocouples embedded in the elastomer were provided by the Eustis Directorate. The thermocouples were inserted one inch into four separate elastomer layers to provide temperature measurements over a representative cross section. These bearings were kept in the "warm room" until termination of a test run, then placed atop the test hub, and thermocouple outputs monitored on a recording device inside the warm room. In this manner, a conservative estimate of test bearing temperature behavior during the cold soak period was possible.

Test Vehicle Tie-Down

The method of anchoring the AH-1G to the Climatic Hangar test stand is shown in Figures 7 and 8. The tie-down was accomplished by the following methods:

- Landing skid tubes were fastened to the test stand by U-bolts.
- The BHC standard transmission tie-down tool was attached to the test stand.
- A specially manufactured fixture attached to the wing mounting lugs (wings were removed) and to a steel tripod, which was attached to the test stand. The fixture was attached to the tripod by means of a spindle, which allowed the tripod to react lift and torque, but not pitching moments.
- A 5/8-inch steel cable was passed through the aft mooring ring (redesigned) and attached to two 5000-pound concrete blocks resting on the hangar floor.
- The elevator was replaced by a dummy elevator spar with tie-down fittings on either end. Each side of this spar was attached to a 5000-pound concrete block by a 5/8-inch cable.
- The tail skid was attached to two 5000-pound concrete blocks by means of a specially manufactured adapter on the skid. The purpose of this tie-down was to restrain lateral motion of the tail boom in the event of failure of some other tie-down component.

TEST PROCEDURES

Prior to each test, the helicopter was "soaked" at the test temperature for at least 10 hours. The main and tail rotor blades and canopy were covered during this period to prevent the formation of ice. The red rotor blade was tied down in the 45-degree azimuth position. The collective stick was placed at full down after each engine shutdown, and the collective accumulator was turned "on" to hold it at full down.

Prior to engine starts at temperatures below -25°F, heat was applied to the main transmission drive shaft couplings, in the manner prescribed by the Operator's Manual (TM55-1520-221-10). The annular space between the main rotor mast and the upper transmission compartment cowling was closed, by stuffing

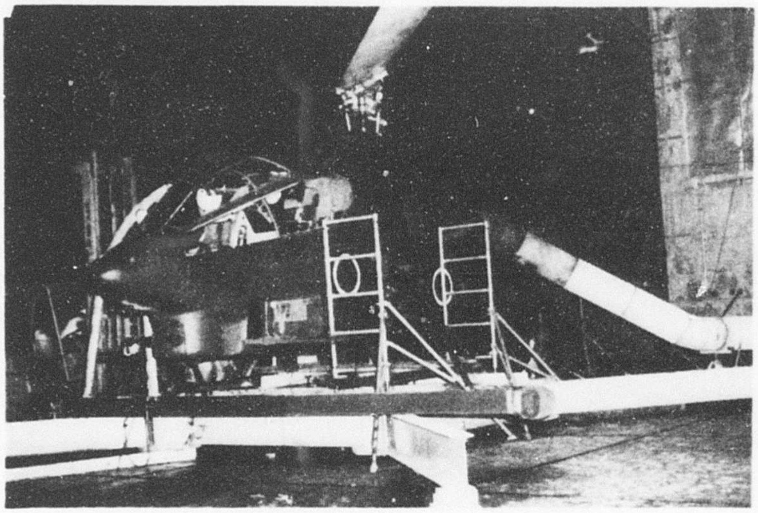


Figure 7. AH-1G Test Tie-Down.

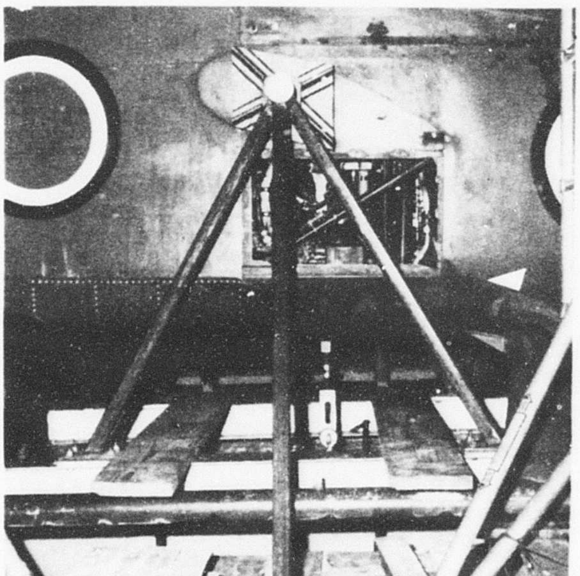


Figure 8. AH-1G Test Tie-Down.

an old parachute canopy into the space, to prevent heated air from rising and warming the elastomeric pitch-change bearings.

The elastomeric hub was usually cold soaked with the cyclic stick offset to 62.5 percent lateral and longitudinal cyclic to provide an adverse soaking condition which might produce control loads when rotating. At each test temperature, the helicopter was started and operated through a test profile which simulated the engine power and blade angles experienced by an AH-1G rotor when the vehicle was flown through the following mission:

- Normal start
- Full-power takeoff
- Ten minutes cruise at 120 knots
- Ten minutes cruise at V_H
- Five minutes hover with neutral cg (no cyclic blade pitch required)
- Three minutes cruise at V_H
- Normal shutdown

It would have been desirable to perform a test which duplicated the pitch-change bearing effects to be found in operational flying; but, for many reasons, climatic hangar testing cannot exactly simulate low-temperature operational flying. The principal difficulties arise from the flapping/feathering relationship resulting from stationary (zero airspeed) rotor operation, and the increased thrust/power ratio obtained when operating at zero skid height. Two facets of the problem are discussed below:

- When the vehicle is tied down, blade feathering and flapping angles are almost equal, since the vehicle is not in forward motion. Therefore, large blade feathering angles cannot be achieved without producing excessive flapping angles.
- The application of rotor power representative of flight values is not practical for two reasons. First, since the rotor is flapping through abnormally large angles, large thrusts must be avoided to preclude excessive pylon tilt and

resulting transmission input shaft coupling misalignment. Second, since ground effect is large, less rotor power is required to produce a given thrust. Therefore, rotor power must be reduced below that used for a corresponding operational flight condition.

For the reasons stated above, it was not possible to operate the rotor through the power and blade feathering ranges experienced in actual flight. The power levels were selected to produce the same rotor thrust in the test as the rotor would have produced in flight. Blade feathering angles which duplicated those found in flight were used up to a limit value of 6 degrees.

In addition to the mission elements described above, one other was required at low temperatures, where elastomeric pitch-change bearing torsional stiffness prevented immediate imposition of the 5 degrees of cyclic pitch on the blade that was required for a full-power takeoff. It was therefore necessary to "warm" the bearing by producing cyclic motion, causing internal bearing temperature to rise as a result of hysteresis heating. The test plan stipulated the holding of a constant oscillatory pitch link load by increasing cyclic pitch as the bearings warmed, but it proved to be more practical to simply hold enough cyclic control to produce just-tolerable vibrations at the pilot's seat until 5 degrees of cyclic motion was obtained.

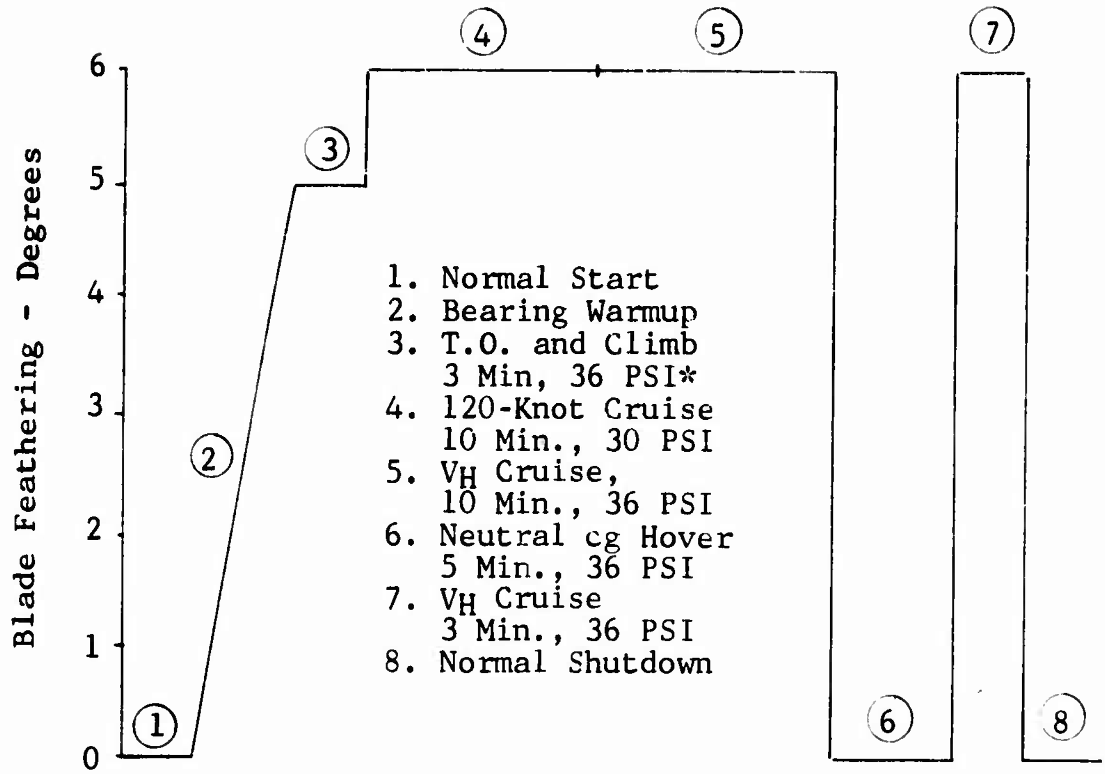
Low collective pitch is generally used for ground operation. This results in reduced coning angles because of the predominance of centrifugal force. If large amounts of blade feathering are applied at low collective blade angles, unacceptable oscillatory loads can result. Therefore, nominal collective pitch (approximately 2000 pounds of lift) was used during warmup of the pitch-change bearings.

The resulting mission profile is shown in Figure 9 on the following page.

RESULTS

General

The test vehicle was located in one corner of the Climatic Hangar which placed walls to the left and rear of the test vehicle, approximately 25 feet from the edge of the main rotor disc. This location was necessary to keep the test vehicle clear of a section of the hangar where ice was forming on overhead structure, and to allow the simultaneous presence of another test vehicle in the hangar. In addition, three small



*Engine Torque Pressure

Figure 9. Test Mission Profile.

structures (warm rooms) were located in the right front quadrant of the aircraft, also about 25 feet from the edge of the main rotor disc. The presence of these restrictions to rotor flow possibly contributed to aircraft vibration and scatter of the data.

Standard Hub

The standard 540 hub was operated at +70°F, -25°F, -45°F, and -65°F. Because of a delayed hangar entry and the limited amount of time available for the test, the 0°F test was not conducted.

Stiffening of the natural rubber elastomeric transmission mounts with decreasing temperature was evidenced by increased fuselage vibration and decreased pylon tilt. Figure 10 depicts decreasing pylon tilt, at the beginning of event 3, with decreasing temperature.

As each mission progressed, the transmission mounts warmed, pylon spring rate decreased, and fuselage vibration diminished for a given operating condition. Figure 11 shows the variation of pylon tilt during a run at -65°F, for events 4 (6 degrees cyclic, 30 psi torque) and 5 (6 degrees cyclic, 34 psi torque).

The original test plan called for 36 psi of engine torque at 6 degrees of forward cyclic to represent the V_H condition. At 70°F, during the tie-down checkout run, this condition produced 1 degree of pylon tilt and caused overheating of the transmission input shaft couplings. The engine torque at 6 degrees of forward cyclic was reduced to 34 psi, and all subsequent tests were performed at this condition.

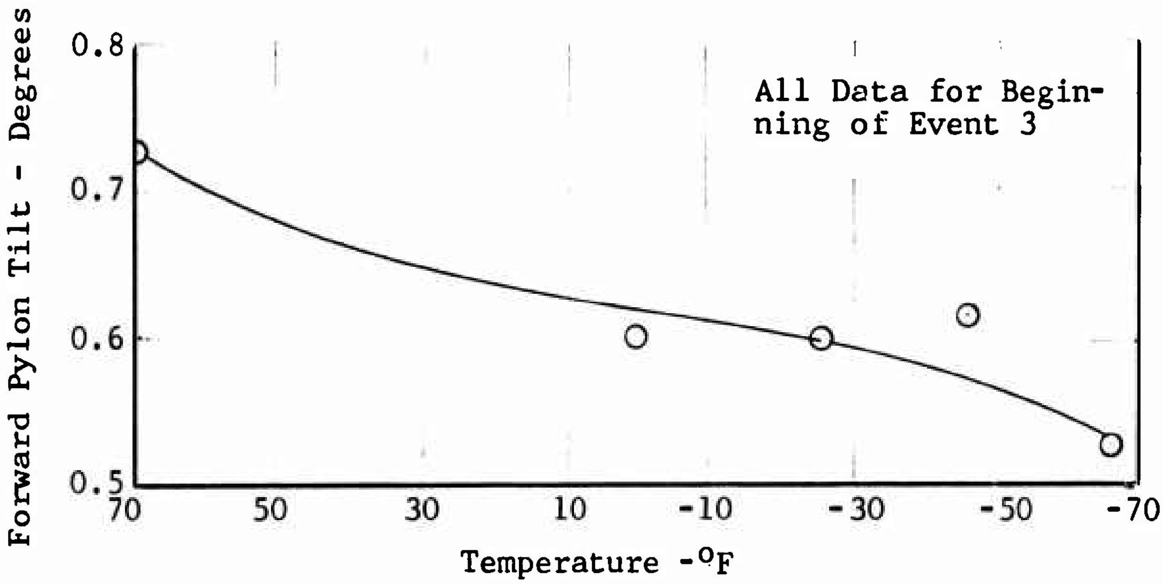


Figure 10. Pylon Tilt Versus Test Temperature.

This problem of excessive pylon tilt is a phenomenon associated with the tied-down condition in which the helicopter was operating in the hangar, and has no relevance to actual flight of the AH-1G. In forward flight, the relative wind causes the rotor to flap aft, and the fuselage is tilted forward. Both of these actions decrease pylon tilt with respect to the mast.

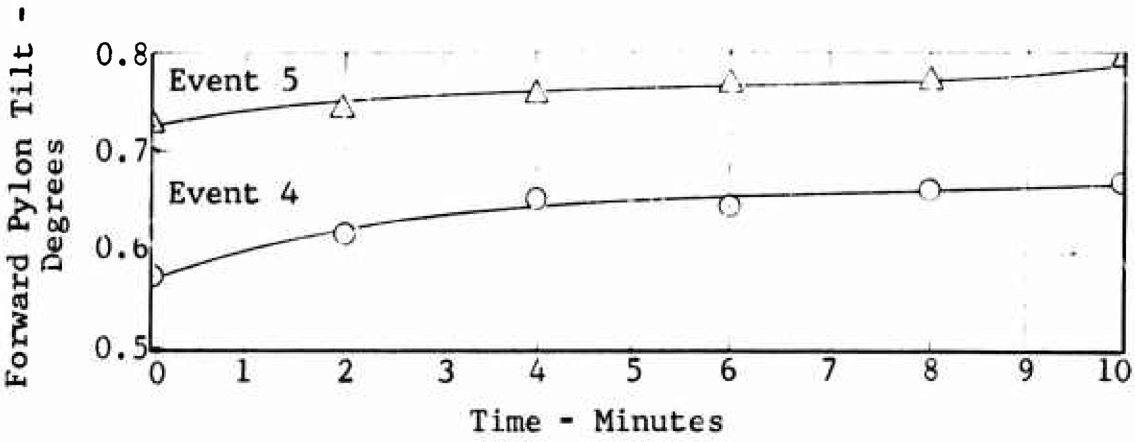


Figure 11. Pylon Tilt Versus Time During Test at -65°F.

Other than this minor problem with excessive pylon tilt, the test of the standard 540 rotor was uneventful. There was not a significant variation of control or blade loads between +70°F and -65°F. The behavior of the oscillatory pitch link loads midway through event 5 (V_H cruise) with temperature decrease is typical of control system load behavior, and is shown in Figure 12. The difference in loads can probably be attributed principally to data scatter.

Stiffening of the tail rotor control was noted during the -65°F run. This problem was investigated further after installing the EB rotor.

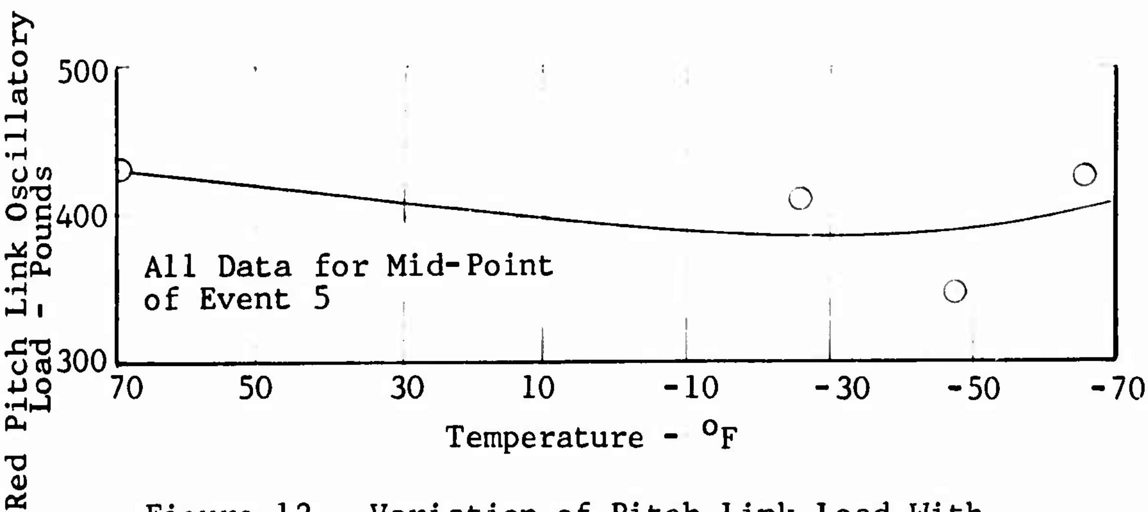


Figure 12. Variation of Pitch Link Load With Temperature for Standard 540 Hub.

Elastomeric Hub

The all-elastomeric hub was tested at +70°F, 0°F, -25°F, -45°F, -55°F, and -65°F. The -55°F test was not scheduled, but was conducted after difficulties were encountered at -65°F.

The tests at temperatures down to and including -45°F were uneventful insofar as the elastomeric pitch-change bearings are concerned. The increase in control loads with temperature decrease was moderate. No warmup procedure was required, even at -45°F, where 5 degrees of cyclic blade pitch applied immediately after start produced control loads well below the endurance limits.

Even though these tests over the temperature range of +70°F to -45°F were uneventful, they did provide some interesting observations.

- Tail Rotor Control: A stiffening of the tail rotor control system was noted at -25°F with No. 1 hydraulic system inoperative (manual operation of the tail rotor control). An increase in stiffening was noted at -45°F, but the control was still movable.

- Collective Control: At temperatures of -25°F and colder, if the collective control is placed at "full down" and the emergency collective accumulator turned "on" after shutdown, the accumulator will hold the collective control down long enough for the bearing elastomer to stiffen. Then, even though the accumulator will slowly lose its pressure, the collective control will remain near the "full down" position for the next start. However, the position of the collective control at start does not appear to be a low-temperature problem, since adequate hydraulic pressure was available to move the collective control after only one-third of a rotor revolution at temperatures of -25°F or colder.

  The range of boost-off collective control available immediately after start was 4-18 percent, regardless of the ambient air temperature.

  The emergency collective hydraulic accumulator was inoperative for the +70°F and -45°F tests, because hydraulic fluid had leaked past the seal into the nitrogen side of the cylinder. The failure noted at +70°F undoubtedly occurred after engine shutdown at -65°F during the test of the standard hub. The inference is that this problem may occur at temperatures of -45°F or below.

- Flapping Bearings: During preflight for the -45°F test, the flapping bearings were found to be quite stiff. They were exercised for approximately 15 minutes by pulling vertically on alternate blade tips, after which time they could be flapped much more easily. The blades were then positioned square to the mast for start.

Extrapolation of control loads and vibration levels measured during the tests between +70°F and -45°F indicated that acceptable operation would be obtained at -65°F. Therefore, the decision was made to move directly into the -65°F test.

During preflight for the first -65°F test (ground run 55) (GR 55), the flapping bearings were exercised as at -45°F. The cyclic control was moved to neutral after one-third of a revolution. The start was uneventful.

When the pilot attempted to introduce a small cyclic control input, a very large increase in control loads and fuselage vibrations was noted, and the rotor was out-of-track approximately 6 inches. The situation was unexpected, and the test proceeded with caution. Steady cyclic inputs were avoided for several minutes, while the pilot qualitatively assessed the extent of the vibration problem. Later, steady cyclic inputs were held, and the bearings began to warm. After approximately thirteen minutes, the out-of-track condition disappeared and control loads decreased below the endurance limit. Five degrees of forward cyclic control was obtained about three minutes later. After obtaining 5 degrees of forward cyclic, loads exceeded those of -45°F only slightly throughout the remainder of the mission.

In addition to the problem with the main rotor, it was noted that the tail rotor control was not movable without hydraulic boost. Boost-off collective control range was still 4 to 18 percent. The emergency collective accumulator again failed to hold its nitrogen charge.

After shutdown, the cyclic control was placed at 50 percent lateral and longitudinal cyclic, to reduce the contribution of offset soaking to the rotor out-of-track condition.

Bearing warmup in the second test at -65°F (GR 56) was conducted at flight idle (240 rpm), rather than the standard 324 rpm, to see if this lower rotational speed would produce faster bearing warming. Cyclic control inputs were held steady.

When the cyclic control was moved forward to 62.5 percent to start bearing warmup, an out-of-track condition and large cockpit vibrations were again evident, although the severity of both phenomena was reduced slightly from GR 55. After approximately three minutes of warmup, pitch link loads began to rapidly decline, the out-of-track condition ceased, and cockpit vibration was greatly reduced. Five degrees of cyclic was obtained after 5 minutes of warmup, and the mission was completed with loads similar to the previous test at this temperature.

Data analysis of GR 56 showed large differences in oscillatory pitch link loads during the warmup period, with the higher loads in the white pitch link. Oscillatory loads well above the pitch link endurance limit of 1460 pounds were noted. The large difference in oscillatory pitch link loads could not be immediately explained, but was thought to be the result of differential torsional stiffness of the pitch-change bearings, caused by inadvertent application of unequal heat to the red and white grips while warming the transmission input shaft coupling seals during preflight. It was decided to repeat the warmup portion of this test to ascertain the cause of the large differential oscillatory pitch link loads.

The magnitude of vibration at the pilot's station during the bearing warmup periods of GR 55 and 56 was great enough to cause him to conclude that they would have been intolerable had the aircraft not been tied down. This opinion was sustained throughout the remainder of testing at -65°F.

Immediately after GR 56 shutdown, the cyclic control was placed at 48 percent forward and 54 percent lateral, which was the position which had given zero blade feathering during the run. This was done to eliminate any effects which could be attributed to cold soaking the bearings at an offset cyclic position. However, during preflight for the third test at -65°F (GR 57), it was noted that the cyclic control was at 52 percent longitudinal cyclic and 54 percent lateral cyclic. The reason for motion of the longitudinal cyclic control is not known.

Warmup for GR 57 was begun at flight idle rpm. The out-of-track condition and large fuselage vibrations were again present, even though generally lower control loads were maintained throughout the warmup. As before, once the bearing warmup progressed to the point of rapidly decreasing pitch link loads, the out-of-track condition and large fuselage vibrations ceased.

Examination of the data from GR 57 again disclosed the presence of large differences in oscillatory cyclic pitch link loads. Figure 13 illustrates the behavior of pitch link loads during bearing warmup (event 2) of GR 57. At one point the white pitch link oscillatory load is almost three times that of the red pitch link. After white pitch load declines, large cyclic inputs are possible.

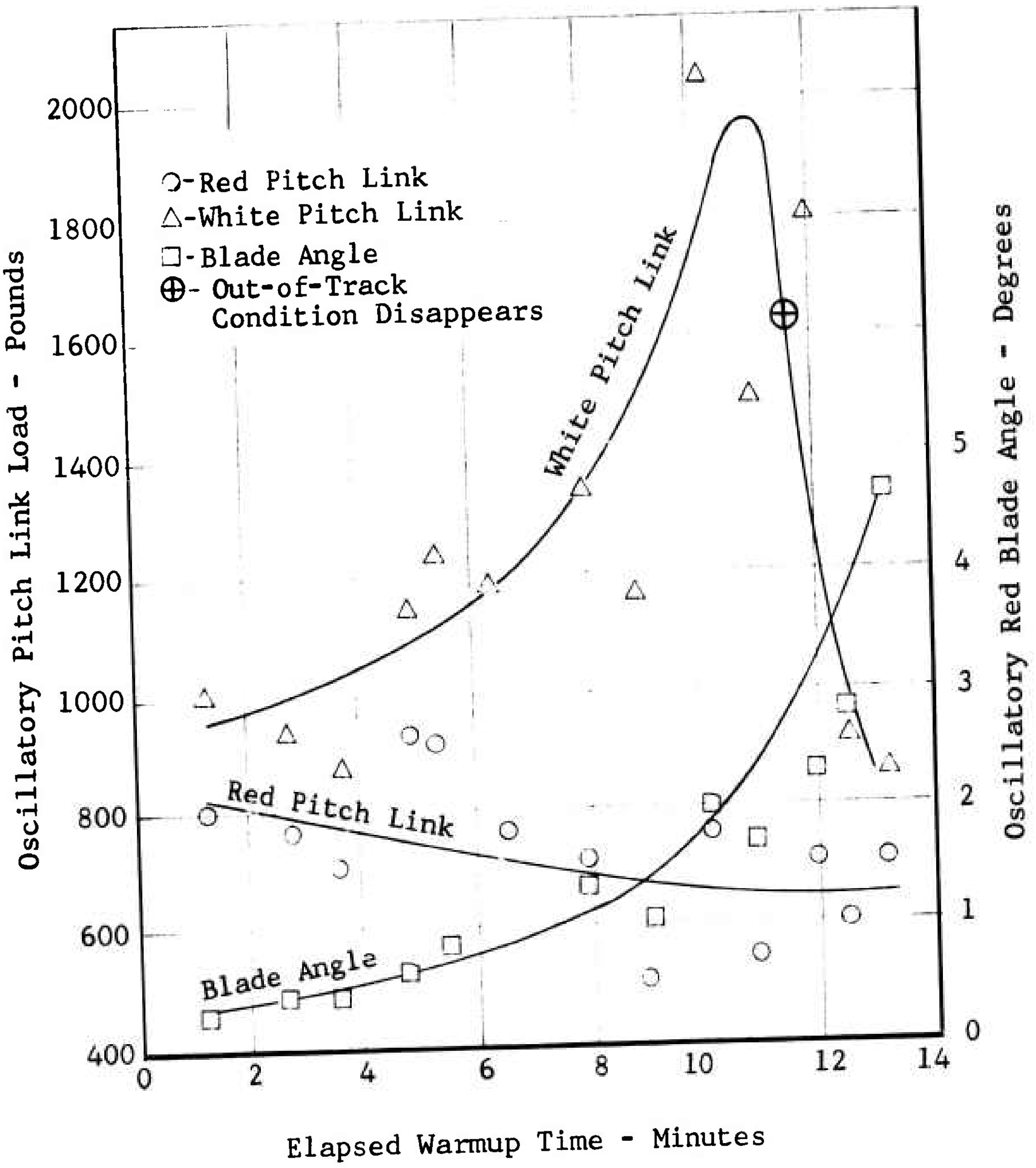


Figure 13. Rotor Behavior During Warmup at -65°F (GR 57).

An attempt was made, during the warmup of the transmission input shaft seals prior to engine start for GR 57, to observe the flow of heat as it rose from the transmission bay. It could be easily seen that the right side of the helicopter was favored by the greatest heat flow. The suspicion of warming of the elastomeric bearings on the red hub to a higher level than the white hub was apparently correct.

The fuselage vibrations incurred during these three tests at -65°F were large enough to cause pilot discomfort. Had the helicopter not been rigidly anchored, it is possible that the vibration would have been large enough to cause an abort.

Since satisfactory operation had been obtained at -45°F, it was decided to perform a test at -55°F to determine more nearly the temperature region in which problems appear.

Prior to the test at -55°F (GR 58) it was noted that the cyclic control had moved by about 1 percent laterally and longitudinally (0.25 degree) from the position in which it had been left the previous day. The cyclic control was still at a position which gave essentially zero cyclic blade pitch.

Just prior to applying heat to the transmission input shaft seals, the rotor was rotated 180 degrees, so that the prestart environments of the red and white hubs could be reversed. The instrumented bearing, which was positioned atop the white grip, indicated a temperature rise in the elastomer interior of about 13°F during warming of the transmission shaft seals. The corresponding temperature rise for the preceding three runs at -65°F was 3° to 5°F. The inference was that elastomeric bearings in the red grip, which was positioned on the right side of the aircraft prior to start during GR 55, 56, and 57, were about 10°F warmer than those in the white grip at the time of engine start. This is a logical explanation of the difference in torsional stiffness of the two sides of the hub, and explains the out-of-track condition and fuselage vibrations.

Only a slight out-of-track condition was noted during bearing warmup in the -55°F test, and it soon disappeared. Fuselage vibrations were considered to be within acceptable levels. An initial cyclic blade angle of 1 degree produced only 1400 pounds of axial force in the red pitch link, and 5 degrees was obtained very quickly.

It was noted that unequal oscillatory loads in the pitch links were again present, but the red pitch link loads were about twice as large as the white pitch link loads, confirming the theory that unequal heating of the bearings during warmup caused unequal torsional bearing stiffness and the resulting out-of-track condition and large fuselage vibration levels.

The remainder of the test at -55°F was uneventful. All loads were well below the endurance limit. Boost-off collective range was again 4-18 percent. The cyclic control was left at 62.5 percent (longitudinal and lateral) to provide an adverse soaking condition for the next test.

The next test at -65°F (GR 59) was to determine if the bearings could be satisfactorily warmed by rising warm air during the heating of the transmission input shaft coupling seals, avoiding the requirement to exercise them with cyclic inputs after engine start.

To provide heat to the bearings, the canopy cover was removed during preflight and draped over the main rotor hub. An elastomeric bearing, incorporating thermocouples in its elastomer, was first placed atop each grip. The parachute which had been stuffed in the annular space between the main rotor mast and the upper cowling was removed to allow the heat to rise freely. Heat was applied to the transmission shaft coupling seals for about 25 minutes.

The temperature of the elastomeric bearings atop the hub rose from -65°F to -14°F during preheat of the transmission shaft coupling seals. Five degrees of cyclic control was applied immediately after the engine start sequence was completed, with a resulting maximum oscillatory load in the pitch links of only 650 pounds. The out-of-track condition and large fuselage vibration levels noted during previous tests at -65°F were absent.

The simulated takeoff (event 3) was conducted, and loads and vibrations were determined to be lower than in previous tests at -65°F, so the mission was terminated.

GR 59 completed the Climatic Hangar testing of the Model 540 all-elastomeric-bearing main rotor hub.

Variation of Loads With Ambient Temperature After Bearing Warmup

Figure 14 depicts the variation of red pitch link oscillatory load with temperature for events 5 and 7 (120-knot cruise and V_H cruise) and event 6 (hover with zero cyclic blade pitch).

As should be expected, oscillatory loads are lower for zero cyclic pitch, and the oscillatory load for zero cyclic pitch does not increase so rapidly with temperature decrease. Events 5 and 7 both required the maximum cyclic pitch of 6 degrees, and a rise of oscillatory pitch link load with temperature decrease is apparent. However, all loads are significantly below the endurance level of 1460 pounds.

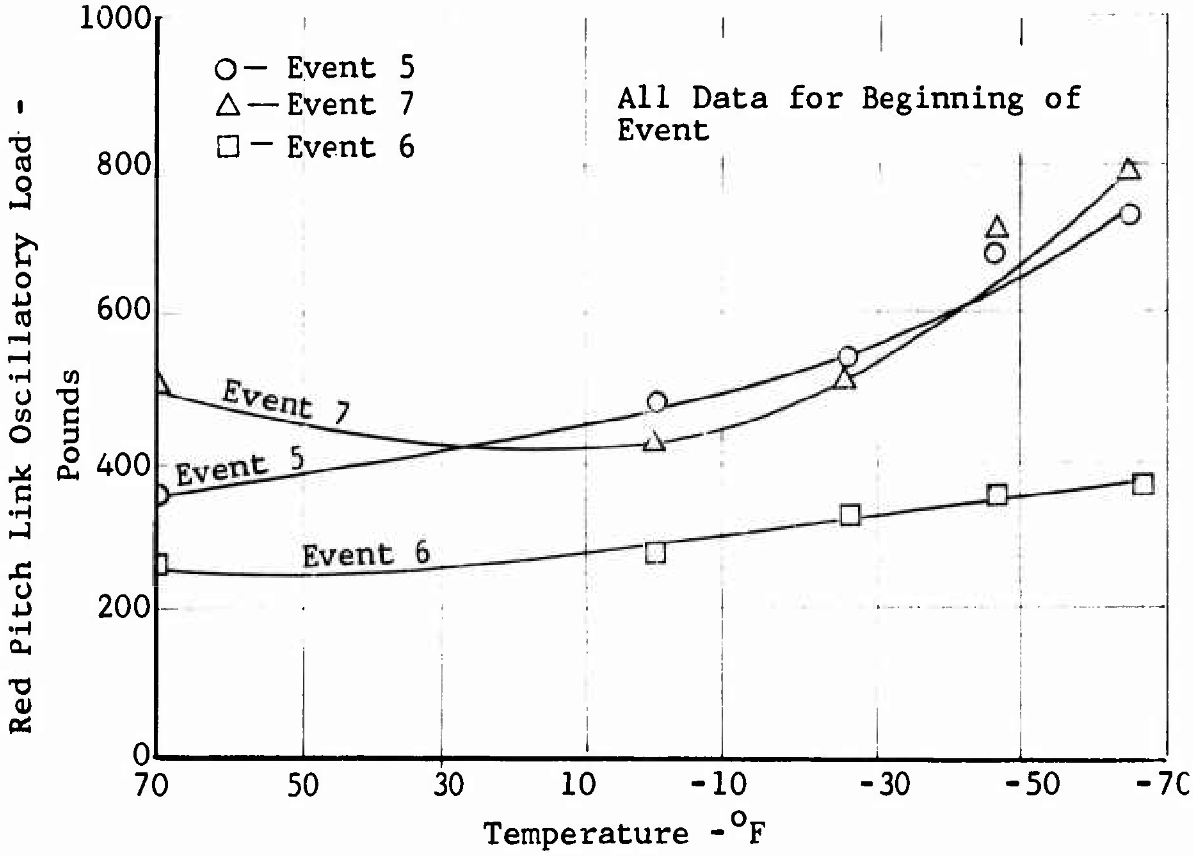


Figure 14. Red Pitch Link Load Versus Temperature.

Figure 15 shows the variation of main rotor mast parallel bending with temperature, plotted again for events 5, 6, and 7. This plot provides essentially the same evidence as the preceding figure, although the increase in loads for events 5 and 7 with lowering temperatures is not so significant.

The largest mast stress resulting from combined loading was obtained during the first elastomeric bearing test at -65°F, and was 32,000 psi. The endurance level for the mast is 36,700 psi. The largest stress obtained with the

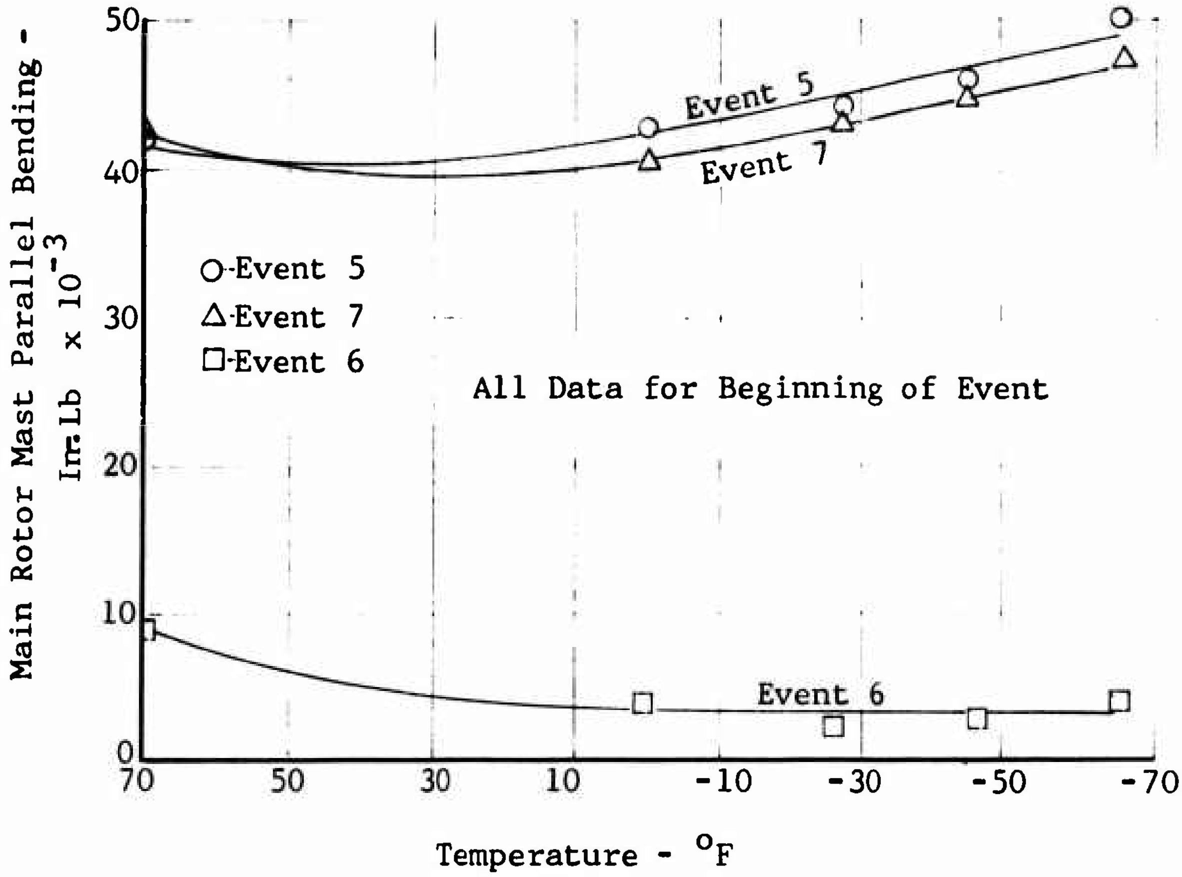


Figure 15. Main Rotor Mast Parallel Bending Versus Temperature.

standard hub was 29,500 psi, so while the elastomeric hub does provide increased mast stress, that stress is still relatively low.

Figures 16 and 17 illustrate the behavior of longitudinal and lateral cyclic boost tube load with decreasing temperature. Both plots convey essentially the same information. The rise in oscillatory load with temperature decrease is moderate, and the maximum load is well below the endurance limit of 1260 pounds.

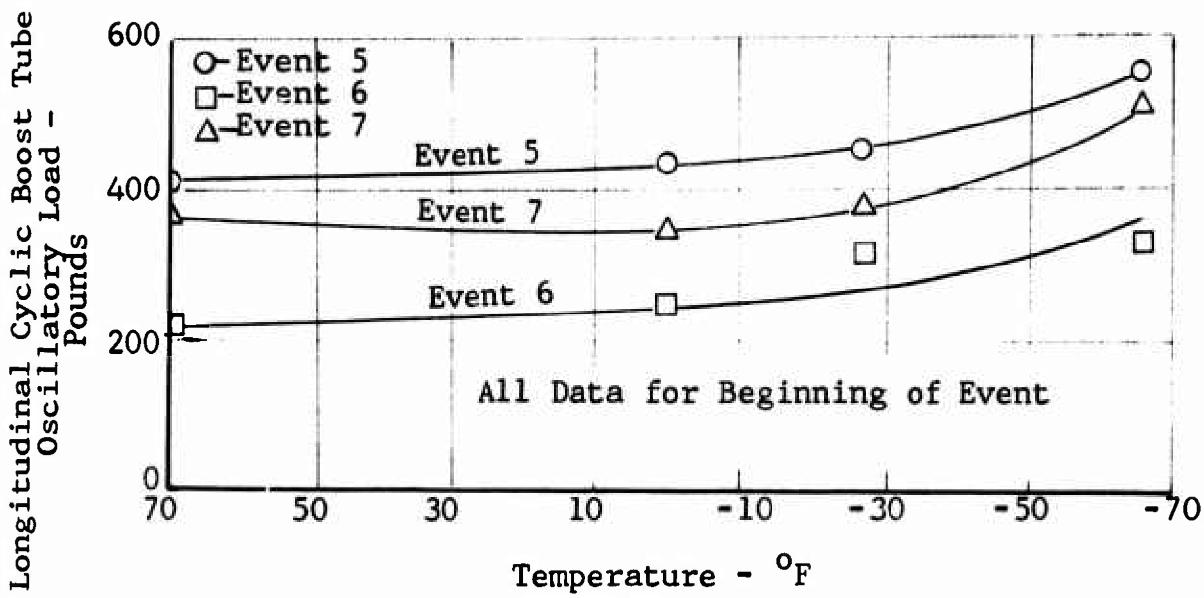


Figure 16. Longitudinal Cyclic Boost Tube Oscillatory Load Versus Temperature.

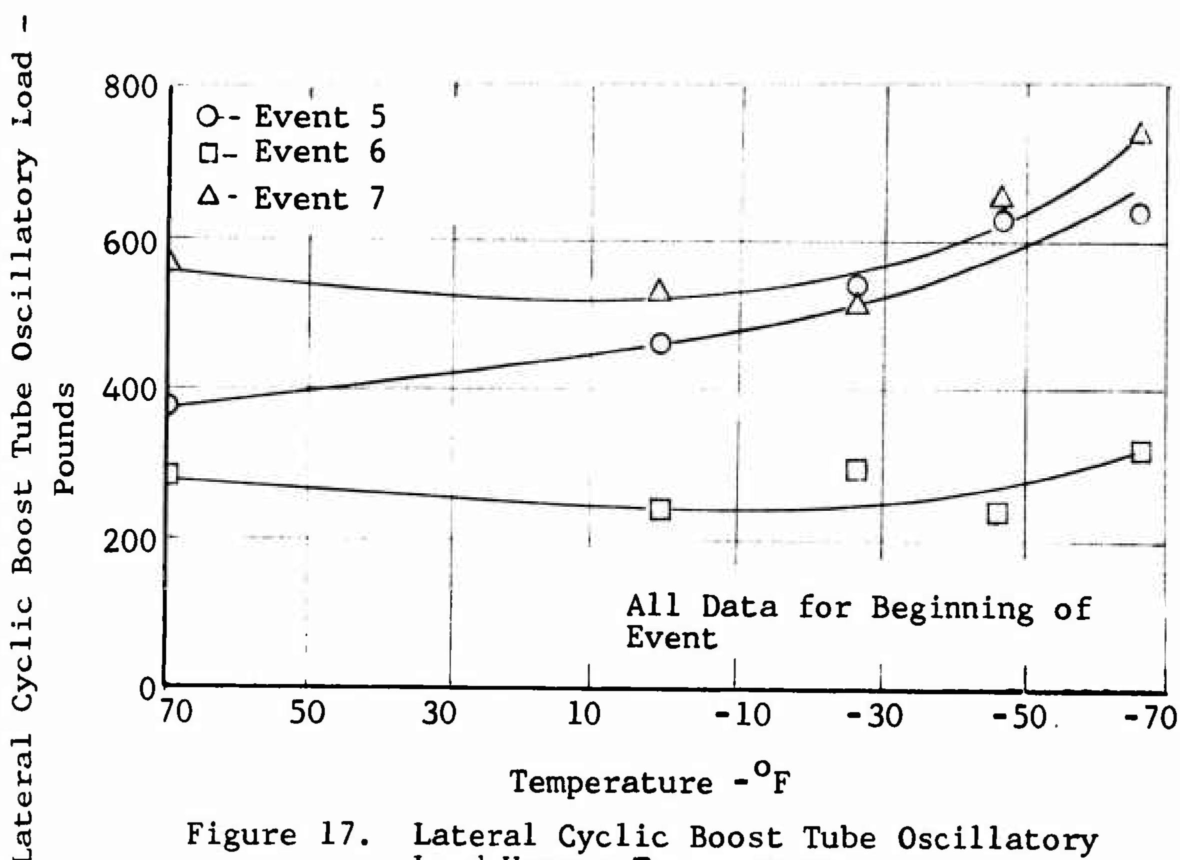


Figure 17. Lateral Cyclic Boost Tube Oscillatory Load Versus Temperature.

Figure 18 depicts the behavior of main rotor yoke chord and beam bending with temperature variation for both the standard and elastomeric rotors. The purpose of the plot is to show that rotor loads are not substantially different for the two hubs, and that loads are well below the endurance limits.

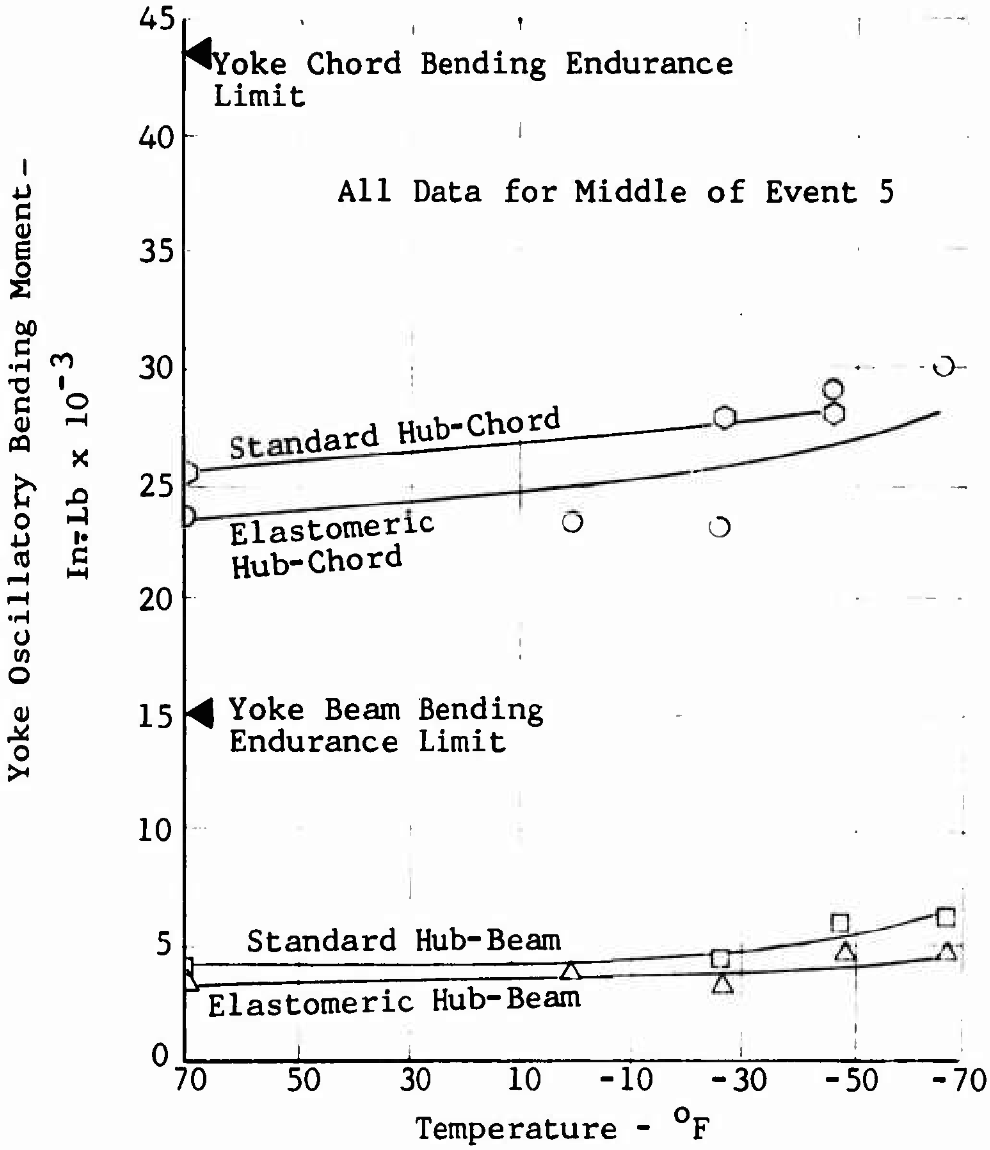


Figure 18. Main Rotor Yoke Bending Versus Temperature.

Pitch-Change Bearing Warmup at $-65^{o}F$

As seen from the above discussion, operation of the rotor after the elastomeric pitch-change bearings have warmed may be accomplished at tolerable control load levels at any temperature tested. The only significant bearing warmup problem was encountered at $-65^{o}F$. This portion of the discussion will treat that problem.

Figure 19 is a plot of pitch link oscillatory load and red blade cyclic pitch versus time during a bearing warm-up at $-65^{o}F$ (GR 56). This test produced larger pitch link loads than others because the warmup was made in a shorter time. The time axis zero marks the beginning of deliberate warmup. Points to the left of zero were obtained during routine inspection of the transmission area by the crew chief after the start sequence was completed. The crew chief's inspection required about 80 seconds.

The large magnitudes of oscillatory pitch link load, and the large disparity between the red and white pitch link oscillatory loads, are evident. In the worst case, the white pitch link oscillatory load is over twice that of the red pitch link.

The initial cyclic inputs (prior to time zero) produced large oscillatory loads in the pitch links. Since the difference in oscillatory loads was caused by differential bearing spring rates, the difference in loading would have increased had control inputs been larger.

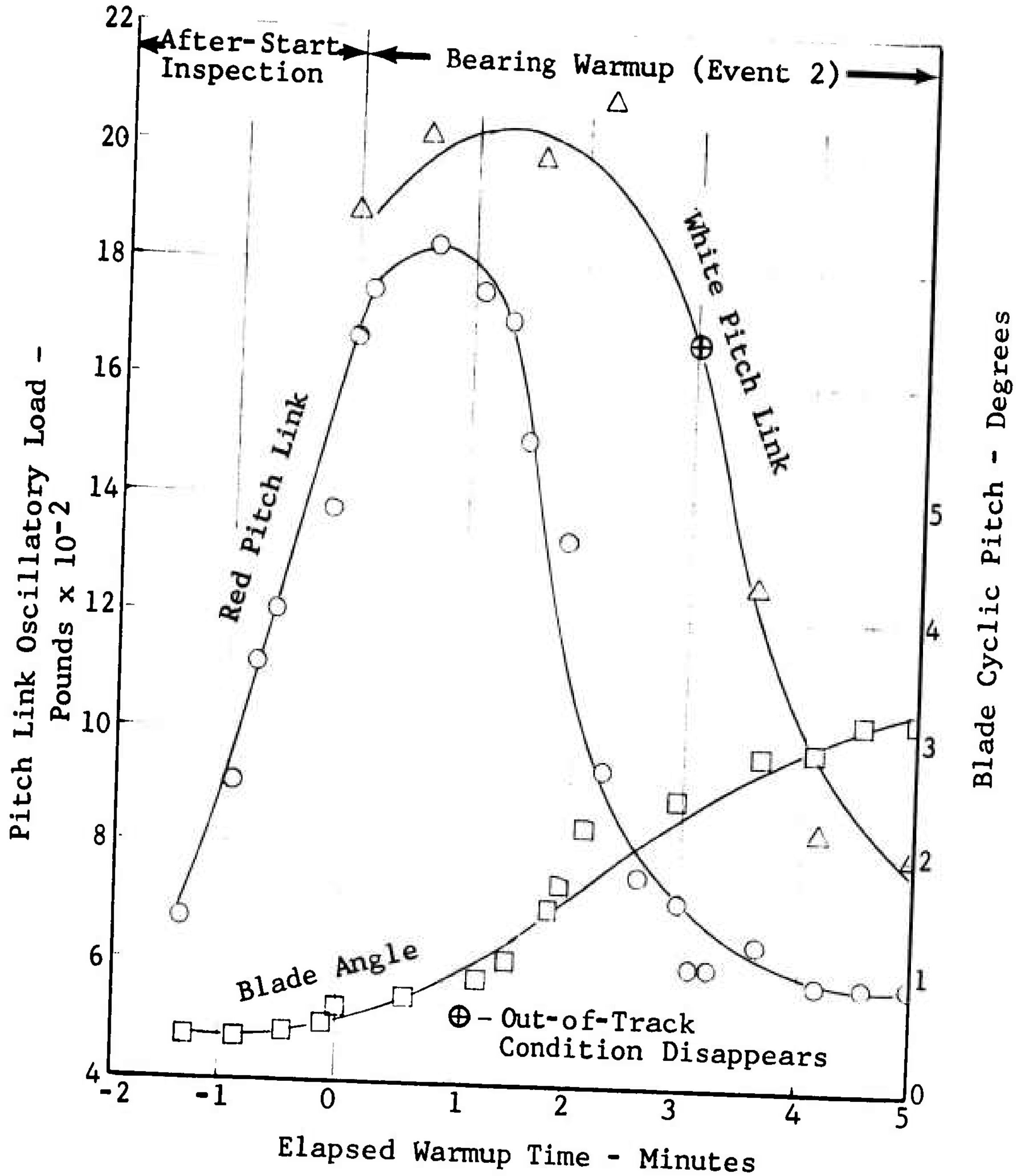


Figure 19. Rotor Behavior During Warmup at -65°F (GR 56).

Figure 20 is a plot of red pitch link load/red blade grip angle versus time for the warmup period of GR 56. This is a cross plot of data contained in Figure 19. This is not strictly a plot of bearing spring rates, since the spring rate of the control system is also involved in the "effective" spring rate.

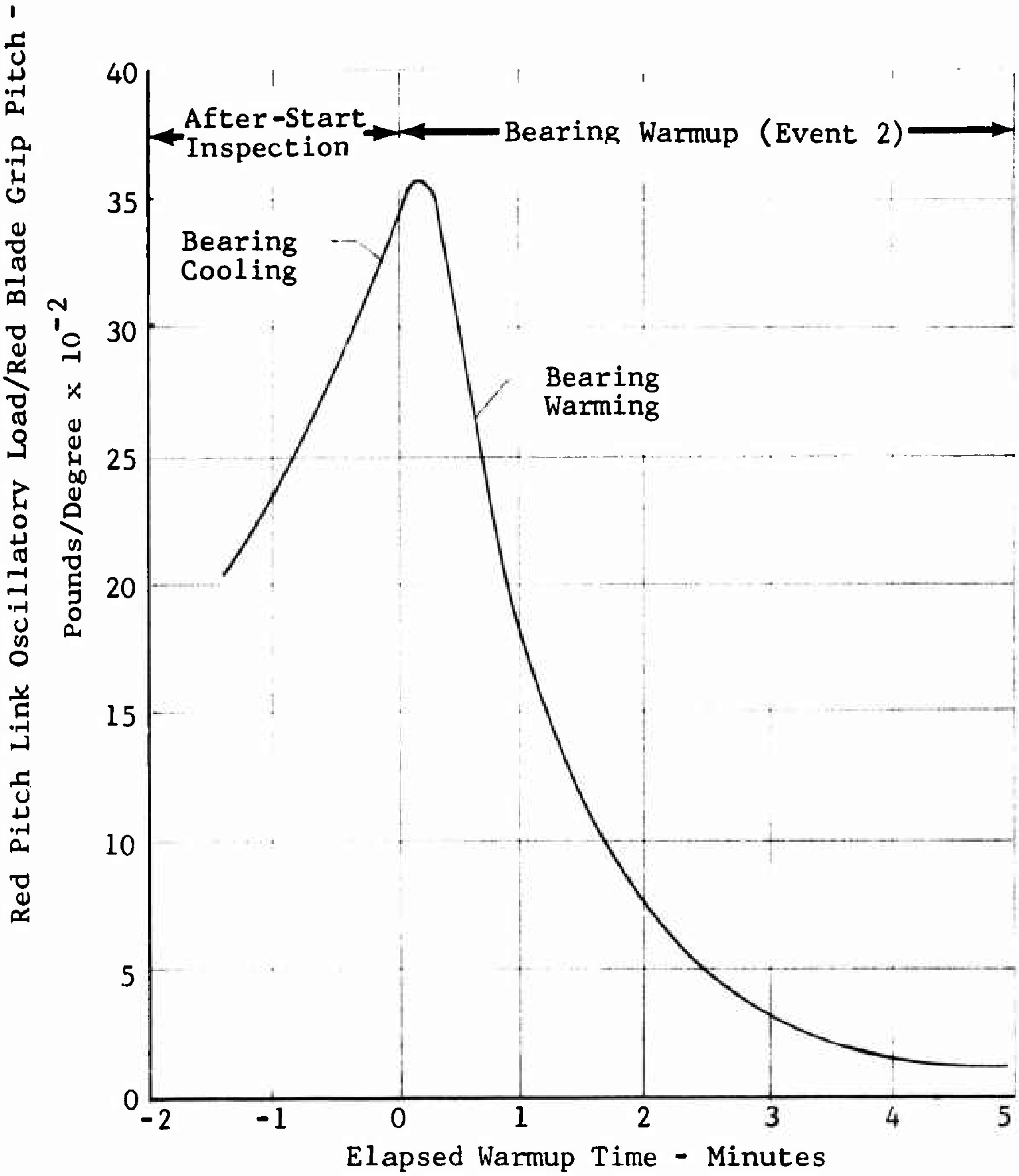


Figure 20. Pitch Change Bearing Effective Spring Rate During Bearing Warmup at $-65^{\circ}F$ (GR 56).

These figures illustrate the bearing warmup characteristics found in all three tests at -65°F (GR 55, 56, and 57) in which the elastomeric pitch-change bearings were not heated prior to engine start. Initially, the bearings are extremely stiff, and even a small cyclic control input produces large oscillatory control loads. Since the red and white sides of the hub existed in different temperature environments prior to engine start, bearing warmup was begun with different torsional spring rates for the red and white bearings. Thus, different oscillatory loads are found in the red and white pitch links. Although only a small cyclic pitch angle of about 0.3 degree was maintained prior to the beginning of the warmup event of GR 56 (during the crew chief's inspection), it is in this period that the maximum effective spring rates are found (about 3600 pounds per degree for the red grip). Spring rates for the white grip were larger, since those bearings were colder, but since white blade pitch angle was not recorded, a corresponding value is not available.

As may be seen in Figures 13 and 19, red pitch link oscillatory declined before white pitch link loads. This phenomenon was caused by differential warming of the bearings during preflight heating of the transmission input shaft coupling seals. Figure 20 shows an increase in red grip spring rates until shortly after the warmup event began. This phenomenon was probably caused by a cooling of the elastomeric bearings while rotating in the cold air after being heated prior to engine start. Figure 13 illustrates the same phenomenon for the white pitch link. Figure 13 also shows red grip spring rate to be declining when the warmup event began. This was probably caused by the elevation of the red grip temperature above the white during preflight heating of the transmission input shaft coupling seals, and the small amount of cyclic exercise imposed on the bearing during the crew chief's inspection.

Figure 21 illustrates another interesting fact: the bearing elastomer changes temperature rapidly when subjected to large differential temperatures. These data were obtained from a thermocouple inside an elastomeric bearing placed atop the hub during the "soak" period of GR 59. The bearing was brought from a warm room and placed directly in a -65°F environment. The average coefficient of temperature change of the bearing is about .02°F/minute/°F temperature differential.

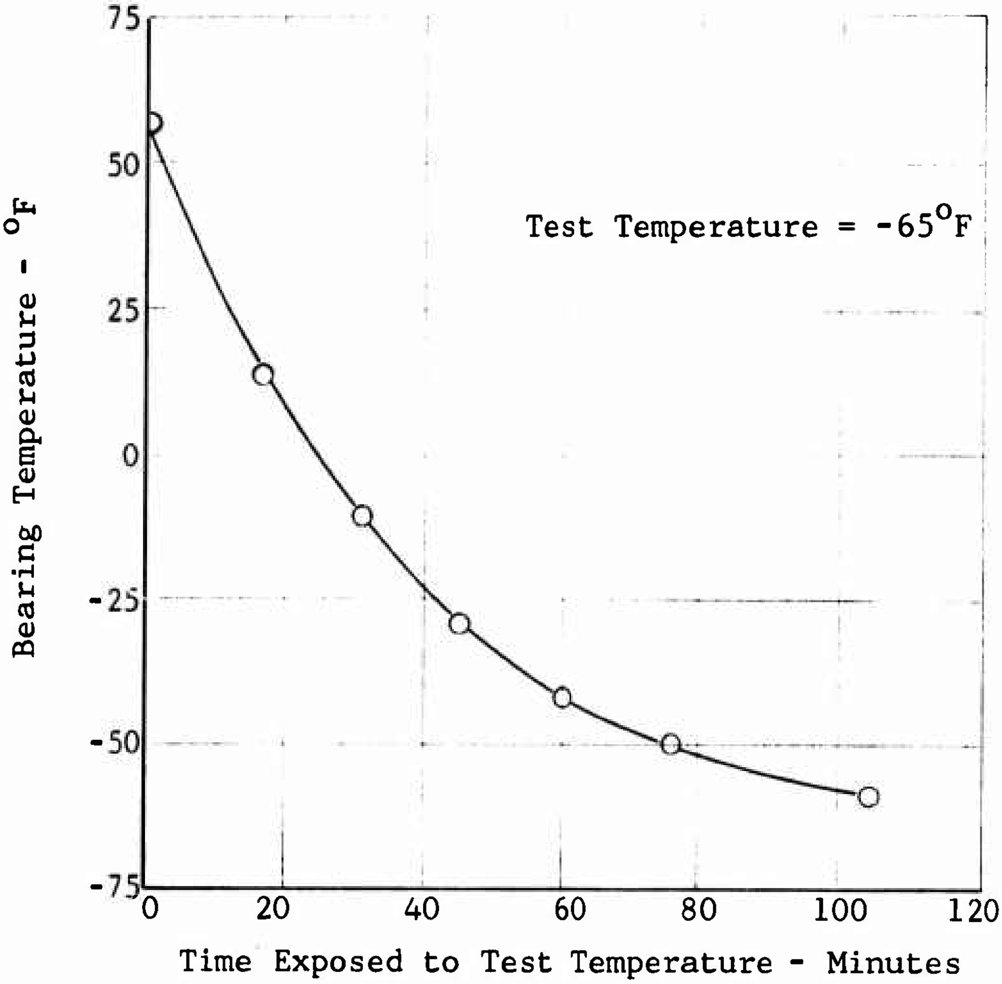


Figure 21. Pitch Change Bearing Temperature Behavior When Exposed to Temperature Differential.

A plot of elastomeric bearing temperature change during preheat of the transmission input shaft coupling seals before GR 59 (using the canopy cover) showed a rise in bearing temperature (interior elastomer) of 45°F in about 25 minutes. The elastomer temperature continued to rise for about 5 minutes after the heating was terminated, then showed a sharp decrease when the engine start was begun. A time history by these actions during GR 59 is shown in Figure 22.

It appears that the bearing elastomer changes temperature more rapidly than had been thought, thereby allowing a rapid warming of the bearings by using a simple "tent" to conduct heat from the transmission area to the hub during preflight heating of the transmission input shaft coupling seals.

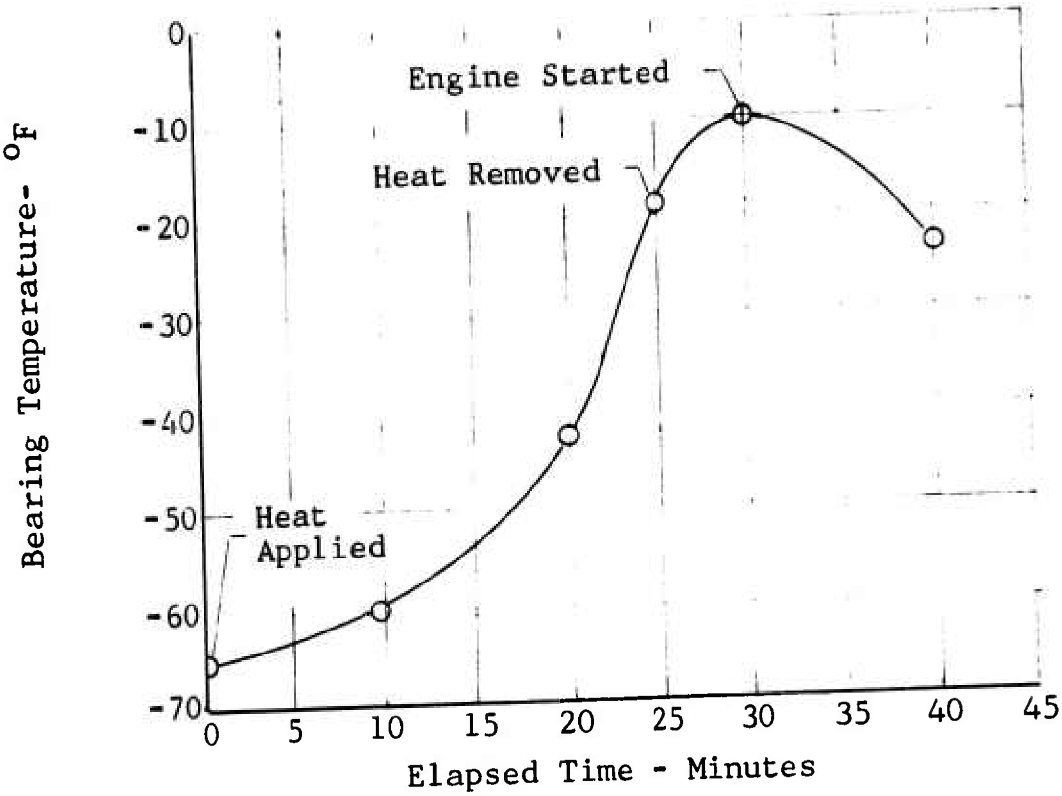


Figure 22. Bearing Warming Characteristics During Preflight at -65°F.

CONCLUSIONS

TEST RELEVANCE

Conclusions regarding low-temperature operation of the AH-1G, based on results of this testing, must be made with an understanding of the basic differences involved in flight operations and tied-down operation in the climatic laboratory.

In addition to the basic limitations to Climatic Hangar testing discussed on page 10, some other differences in test and field operation are discussed below.

Warming of the pitch-change bearings by rising warm air during preflight heating of the transmission input shaft coupling seals could be affected by operational conditions, such as nearby turning rotors, which were not present in the climatic laboratory.

The aerodynamic environment surrounding the bearings is quite different in flight and ground operation. Greater airflow is present in flight, which could lower bearing temperature.

Control loads information was monitored continually during this test, and the pilot always had the assurance that dangerous loads would be avoided. Operation in the field is without such assurance, and the operational pilot might be reluctant to apply sufficient control inputs to warm the bearings at very low temperatures in a reasonable time.

The large fuselage vibrations suffered during bearing warmup at low temperatures, while tolerable when the vehicle was rigidly tied down, would have been more alarming had the vehicle been unrestrained.

Just as one must be careful in relating these test results to operational situations, care should also be exercised in comparing these test data with those gathered during low-temperature laboratory testing in small cold chambers. Such small chambers provide reasonable assurance of the coincidence of ambient air and bearing temperatures prior to beginning bearing exercise. The ambient air temperature at the time of engine start during these tests was not the same as bearing temperature, because of localized application of heat during preflight, since heat was transferred to the bearing by convection and conduction from the heated transmission area.

PRODUCT SUITABILITY

The suitability of the all-elastomeric-bearing Model 540 hub for operation in the temperature range of +70°F to -65°F was defined as extensively as possible without actually flying the test vehicle in that environment. Cold weather flight testing will be required to completely determine bearing suitability.

Operation of the EB rotor on an AH-1G at -65°F without precautions could result in large oscillatory loads, and large differential oscillatory loads in the control system during the bearing warming period. This is caused principally by uneven warming of the pitch-change bearings during preflight heating of the transmission input shaft coupling seals. Large fuselage vibrations are present in this circumstance, and may be sufficiently large to cause an abort.

This testing did not indicate any advantage to cyclically exercising the bearings at flight idle (247 rpm) instead of 324 rpm. Although the first warmup conducted at flight idle at -65°F (GR 56) was completed in substantially less time than the previous warmup (GR 55), larger oscillatory pitch link loads were experienced in GR 56, which was the primary reason for the reduced warmup time. The third warmup at -65°F (GR 57) required nearly 12 minutes for the out-of-track condition to disappear (about the same as GR 55) even though the warmup was at flight idle. The time required for warmup was seen to be primarily a function of pilot technique, not rpm.

The principal conclusion obtained from these tests was that the use of a "boot" which will allow warming of the pitch-change bearings during preflight, even at -65°F, eliminates the problems which would otherwise be present. The use of this inexpensive aid makes very low temperature operation entirely practical, and reduces the question of unrestricted operation at -65°F to an academic one.

AH-1G SUITABILITY

The emergency collective hydraulic accumulator did not reliably hold its nitrogen charge at temperatures of -45°F and below.

The tail rotor control system becomes progressively stiffer with lowering temperatures and became inoperable without hydraulic boost at -65°F.

Preflight exercising of the flapping bearing prior to start at temperatures below -45°F, as conducted in these tests, may not be a field requirement. The spring force of the flapping bearings is small compared to that of the pitch-change bearings, and the influence of the flapping bearings on control loads is probably small. If a boot is used to warm the hub prior to start, preflight exercising of the flapping bearings is certainly unnecessary.

It is desirable to avoid tieing the rotor down at a large flapping angle when the elastomeric hub is to be used at -55^{o}F or colder without preheat, to avoid any out-of-track condition which might be caused by doing so. It is also desirable that the cyclic control be placed near the neutral position at engine shutdown for the same reason. The collective control should be placed in the "full down" position after engine shutdown, and the collective accumulator switch left in the "on" position if the next start is likely to be made in windy conditions. At temperatures of -25^{o}F or colder this is probably unnecessary, since hydraulic pressure is available after about one-third of a rotor revolution. Testing conducted at Bell Helicopter Company subsequent to the Climatic Hangar tests indicates that hydraulic pressure is obtained after two-thirds of a rotor revolution at $+70^{o}$F. A collective control hold-down device may not be required.

RECOMMENDATIONS

A low-temperature flight test of the all-elastomeric-bearing rotor on the AH-1G is necessary to accurately define the behavior of the rotor under operational conditions and to establish formal operational procedures.

The use of a boot to duct warm air from the transmission compartment to the main rotor hub is recommended whenever preflight warming of the transmission input shaft couplings is required. The use of such a boot should be a requirement at a temperature of $-55^{\circ}F$ or lower.

The requirement for a collective lever hold-down device for warm-weather operation should be investigated.

The Operator's Manual for the AH-1G incorporating elastomeric pitch-change bearings should contain a caution to tie the rotor down approximately square with the mast, and to position the cyclic control near the neutral position at engine shutdown, when the succeeding start is to be made at temperatures of $-55^{\circ}F$ or colder if the hub is not to be preheated. The rotor blade should be aligned with the fuselage.

A low-temperature test of the emergency hydraulic accumulator should be conducted to determine the cause of its repeated failures at low temperatures, and an appropriate remedy devised.