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The Application of Elastomeric Products on the V-22 Tiltrotor Aircraft

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ABSTRACT

The U.S. Navy's V-22 Osprey Tiltrotor aircraft program has stringent requirements regarding Reliability and Maintenance (R & M). An important step in meeting the R & M requirements of the V-22 is the elimination of conventional mechanical bearings and blade retention devices (ie., tie bars) which inherently require significant maintenance. Elastomeric bearings, dampers and springs have been well established as a key ingredient in improving the R & M criteria established over the past several years for various worldwide helicopter programs, such as the UH/SH-60, CH-53D, OH-58D, AH-1, AH-64, EH-101, AS-332, A-129, BO-108, S-76, B-222, B-412, H-269 and H-500. Virtually maintenance free, on-condition inspection service lives up to 5000 hours have been demonstrated. The V-22 Osprey's proprotors contain 54 elastomeric assemblies functioning as bearings and springs as well as the proprotor to mast drive coupling. Some unique design and materials innovations were necessary to meet the stringent space, weight and life requirements. The uniqueness of the V-22's elastomeric products, particularly the hub spring and proprotor drive link coupling are presented.

I. Introduction

The V-22 Osprey's predecessor was the experimental Bell Helicopter - NASA XV-15 tiltrotor which was first flown in 1977 - twelve years ago! The XV-15's proprotors employed an elastomeric mast moment spring (to provide flapping stiffness to the proprotor). Elastomeric bearings were not designed into the proprotor in order to reduce the design lead time and initial costs. (Elastomeric bearings cost more than conventional metallic bearings initially, but demonstrate their benefits using a life cycle cost analysis). In addition, other elastomeric bearing material developments were necessary to make them candidates for the unique operating requirements of the tiltrotor. Large bearing motions associated with the airplane mode of flight could not be designed/manufactured and fit within the very restrictive space constraints.

The time frame between XV-15 development and initiation of the V-22 program saw widespread worldwide acceptance of elastomeric bearing technology to help solve the rotor R & M requirements, development of new special performance elastomers for use in elastomeric bearings, improved analysis techniques (finite element) for predicting bearing life, new cost effective manufacturing processes and the continuous improvement of manufacturing and quality control to demonstrate the high reliability required of elastomeric bearings. Although the first production elastomeric bearing was introduced by Bell Helicopter and Lord in the collective idler link assembly of the AH-1, the "true" worldwide acceptance of the elastomeric bearing as a viable technology to improve helicopter R & M, did not appear until the production go-ahead of the UH-60 Blackhawk by the U.S. Army. The very positive results of the Blackhawk's main and tail rotor elastomeric bearing life, set the stage for all new helicopter programs to include elastomeric bearings.

At about this time frame, a new, larger tiltrotor was being discussed and ultimately the V-22 Program was launched which built upon the experience gained from the XV-15. One of the V-22 proprotor objectives included the use of non-lubricated bearings and elimination of conventional helicopter blade retention devices such as tension-torsion straps or strap packs - a natural for elastomeric bearings.

It is not the intention of this paper to discuss the elastomeric bearing principle since it is assumed the reader is already familiar with this technology and several papers (References 1-14) have been published covering the subject.

II. V-22 Proprotor Configuration

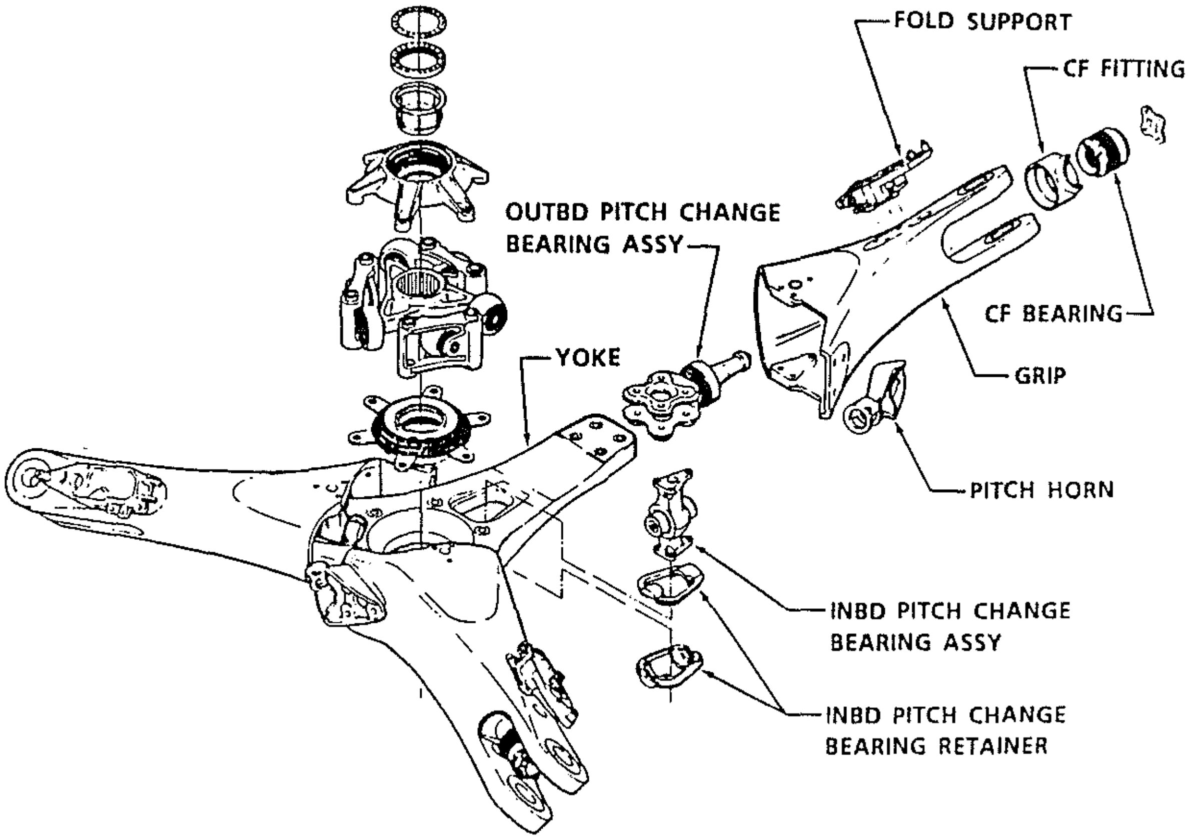
The Osprey's full scale development (FSD) proprotors (including control systems) each contain 27 elastomeric products noted in Table I.

Figure 1 illustrates the V-22's FSD proprotor showing an exploded view of the yoke, grip and the relative positioning of the elastomeric products (minus the Lower Pitch Link and Gimbal bearings). Total weight of all the V-22 elastomeric products shown in Table I is 248.45 pounds.

Table I. Elastomeric Products for Each V-22 Proprotor

No.	Description	Basic Function(s)
3	Inboard Beam Bearing	React Moments/Allow Feathering-Flap-Lag
6	Inboard Feathering Bearing	Axial Blade Motions. Two (2) each used in conjunction with Inboard Beam Bearing (with same function).
3	Centrifugal Force Bearing	React Centrifugal Force/Allow Feathering-Flapping Motions.
3	Outboard Feathering Bearing	React Moments/Allow Feathering and Small Flapping Motions.
3	Drive Links	Coupling-Transmit Torque/Allow Flapping.
1	Upper Hub Spring	React Thrust/Centering of Proprotor (to mast)/ Allow Flapping.
1	Lower Hub Spring	React Thrust/Centering of Proprotor (to mast)/ Allow Flapping.
3	Lower Pitch Link Bearing	Transmit Swashplate Loads and Motions.
4	Gimbal Bearing	Allow Stationary Swashplate Motions and React Loads.
27		

Figure 1. V-22 FSD Proprotor.



III V-22 Proprotor Bearing Requirements

The V-22 employs two (2) thirty-eight feet (38') diameter proprotors each with three (3) blades. A high percentage of the proprotor hub and blades are composite materials to reduce weight while improving reliability and service life. In components where composite materials are not feasible such as in most of the elastomeric components the use of 13-8 PH stainless steel, 10-2-3 titanium or 7075-T 73 aluminum was specified.

The elastomeric products specified for the V-22 proprotors meet the following basic requirements:

1. Provide functionality during a temperature range of -65°F to +130°F.
2. Provide adequate environmental resistance to the typical exposures encountered during helicopter and airplane flight conditions, including sunlight, ozone, fungus, lightning strikes accidental exposure to; jet fuel, hydraulic and lubricating fluids, and storage conditions (land and shipboard).
3. Provide ballistic tolerance.
4. Require no lubrication and only visual on-condition inspection.
5. Use materials and construction which minimize weight and size, while retaining cost effectiveness.
6. Provide a service life of 2500 hours, minimum, under a specified 70% airplane/30% helicopter flight spectrum in addition to ground-air-ground (G-A-G) cycling of 3 per hour.
7. Operation for 2500 hours, minimum, without; loss of elastomer-to-metal bond, fatigue failure of metal components (ie., shims or metal "separators" between layers of elastomer), column instability due to buckling of the elastomer-shim portion-under any of the specified flight or ground conditions, or a change (exceeding 20%) in the primary spring rate (stiffness) of the elastomeric component.

IV. **General Design Approach**

The use of finite element analyses (FEA) to properly analyze the elastomer as well as the metal stresses (shims & major metal parts) was mandatory to determine the detailed stress distribution, which in conjunction with fatigue (S-N) curves for the particular elastomer formulation and the metallic material utilized, provided a calculated test life under the load and motion spectrums. The elastomer fatigue data was obtained in over two million (2×10^6) hours of specimen testing at various conditions of stress & strain (compression and shear) and frequency on a variety of elastomer formulations. The specimen testing was solely supported by Lord internal development funding. A photograph of a typical Lord fatigue test machine for establishing elastomer fatigue (S-N) curves is shown in Figure 2, with a schematic of the test specimen shown in Figure 3. The machine shown in Figure 2 is capable of testing four specimens simultaneously with a range of static and dynamic axial compression and torsional shear inputs.

Figure 2. Lord Designed Elastomer Fatigue Test Machine.

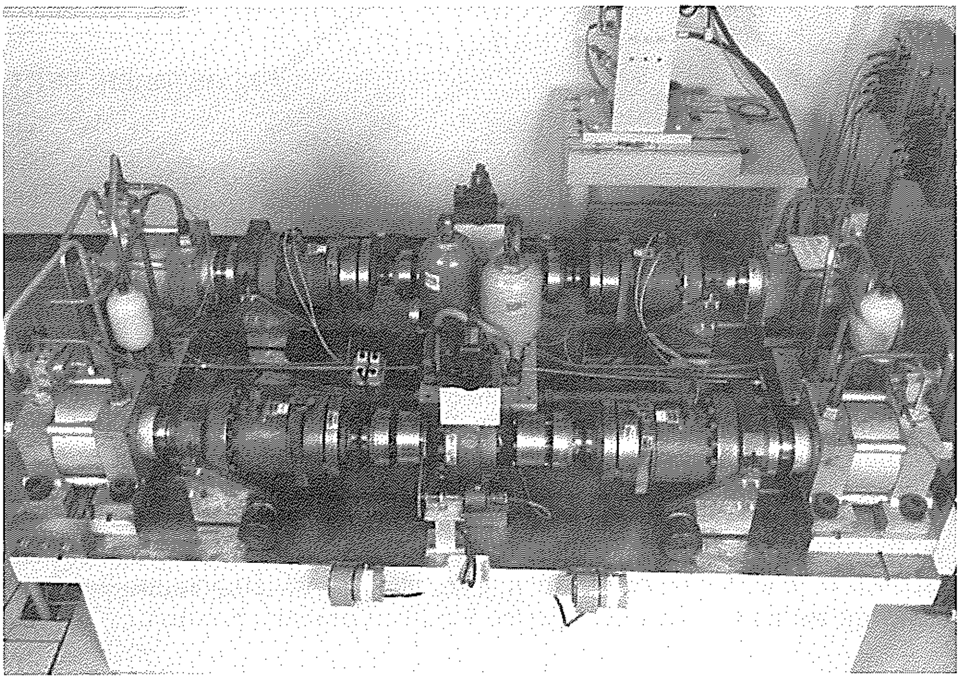
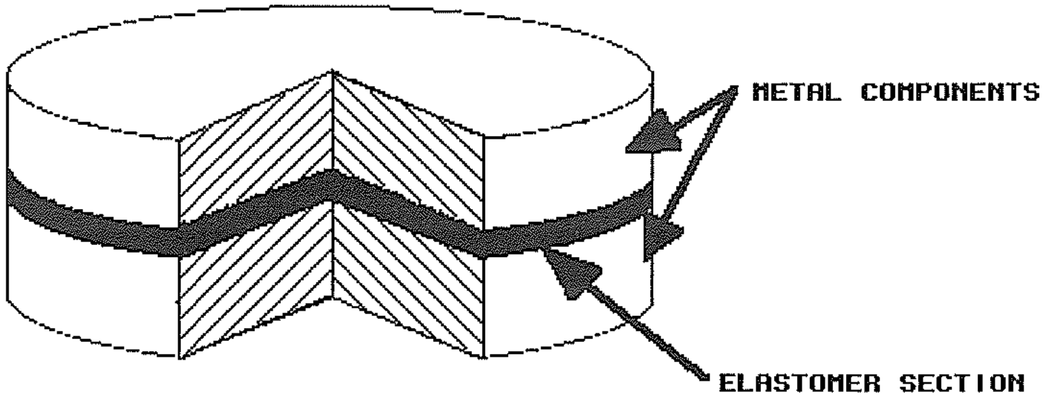


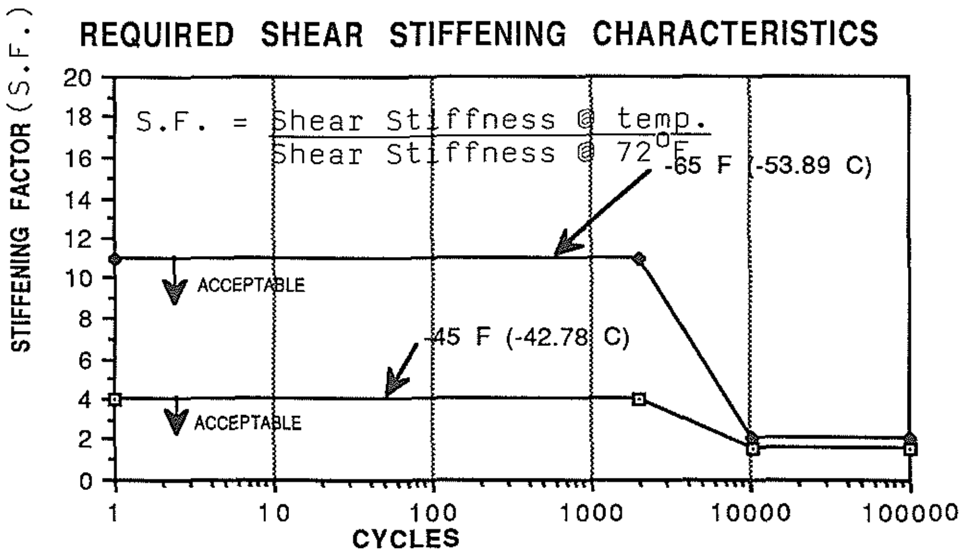
Figure 3. Schematic of Lord Elastomeric Bearing Fatigue Test Specimen.



Using the specimen shown in Figure 3, two (2) types of elastomer strain are quantified. Typically, the strains imposed on an elastomeric part can be reduced to two types of elastomer strain; **direct**, caused by static and/or dynamic "shearing" of the elastomer under motion (ie., torsional) and; **indirect**, caused by bulging of the elastomer due to static and/or dynamic compression loading. Actual product test Life is predicted using test specimen data, FEA and properly combined loading conditions. Phase relationships and frequencies become important when combining loading conditions and must be properly analyzed. Finite element analysis is also used, where appropriate, to analyze the internal temperature buildup (caused by hysterisis damping within the elastomer) in the actual elastomeric product.

In addition to the stress-strain analyses, proper selection of the V-22 elastomeric materials was necessary to insure adequate life while minimizing hysterisis heating (due to internal elastomer damping) during flight. Low temperature stiffening must also be controlled in order to minimize the resulting increased stiffnesses, particularly during proprotor startup at low temperature and structural loading during the airplane flight mode where the oscillatory loading is substantially reduced compared to helicopter flight. (The reduced oscillatory motions (i.e., feathering) during airplane flight minimize hysterisis heating which in turn contributes to increasing the elastomer stiffness at low temperature operation.) Figure 4 shows the response specification of the elastomeric products to low temperature exposure.

Figure 4. Typical Low Temperature Requirements for V-22 Elastomeric Products.



V. Elastomeric Blade Retention Bearings

The blade retention bearings, which are all elastomeric, consist of the Inboard Beam, Inboard Feathering, Centrifugal Force and Outboard Feathering Bearings. The normal flight loads (chordwise and beamwise moments and Centrifugal Force) and motions (collective and cyclic feathering, flapping and lag-due to chordwise loading) are summarized in Table II. The exact spectrums are not detailed since these are proprietary to Bell-Boeing.

Table II. V-22 Blade Retention Bearing Spectrum

Condition	%	Chordwise Moment In-Lbs	Beamwise Moment In-Lbs	CF lbs	Torsional Motion Degrees	Flapping Motion Degrees	Lag Motion Degrees
Airplane	70%	72.8K ± 20.3K	24.7K ± 3.1K	97.9K±0	24.15 ± 1.6°	<± 1/2°	<± 1/2°
Helicopter (Max.)	30%	56K ± 192K	84K ± 22.4K	140K±0	2 ± 15°	<± 1/2°	<± 1/2°
Helicopter (Min.)		29.7K ± 36.8K	48.3K ± 2.5K	140K±0	8° ± 4°	<± 1/2°	<± 1/2°

The major design challenges for the blade retention bearings are summarized below.

With the aid of finite element analyses, all of the design challenges were met.

- Accommodate large feathering motions without exceeding the allowable space envelope
- Maintain low/acceptable feathering stiffness while achieving the appropriately high chordwise/beamwise radial stiffness (to meet proprotor natural frequencies)
- Provide acceptable service life by properly establishing elastomer and metal component stress levels

V.A. Centrifugal Force (C.F.) Bearing

The C.F. bearing supplied by Lord contains 49 layers of elastomer (48 shims) bonded and vulcanized between the two major end metal components. Forty-six layers are conical transitioning to three spherical layers. This bearing is shown in Photo 1 and is used to react the centrifugal force (C.F.) while permitting feathering motions of the blade and accommodating cocking (misalignment) motion caused by flapping or lag. Figure 5 shows a cross section of the bearing taken from the F.E.A. plot.

Photo 1. V-22 Centrifugal Force Bearing.

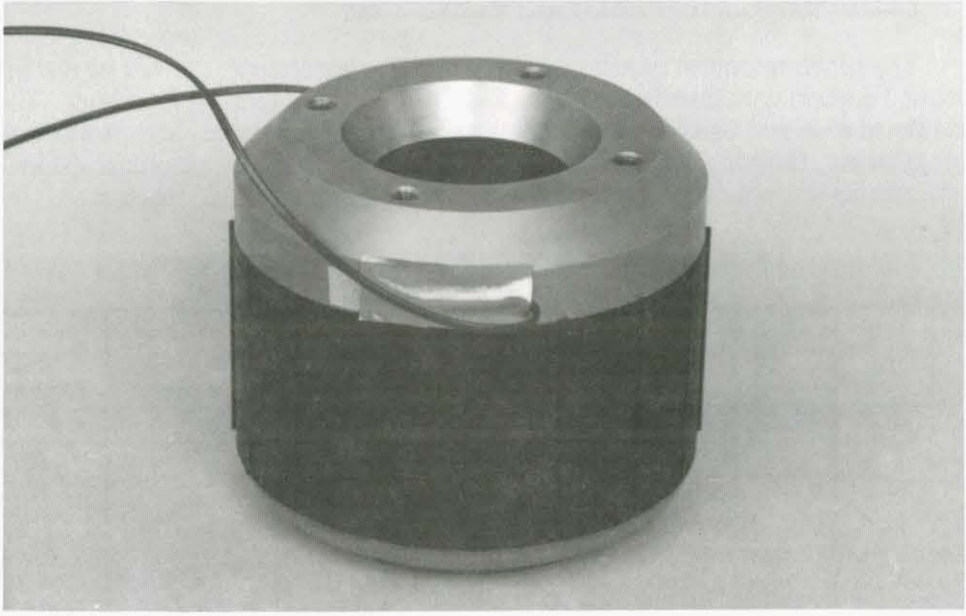
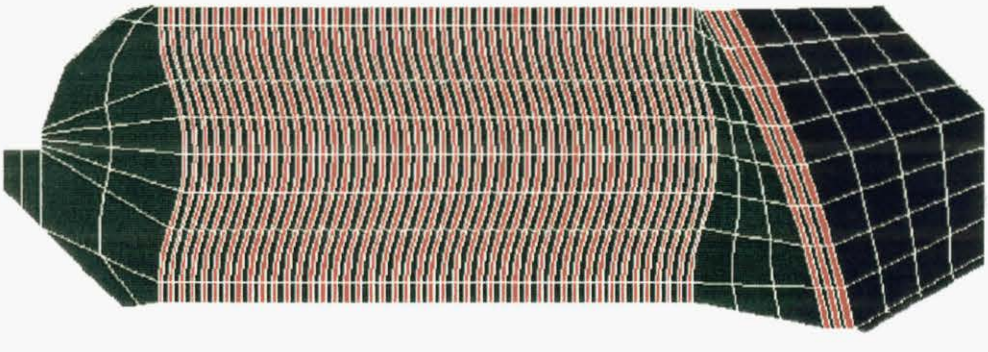
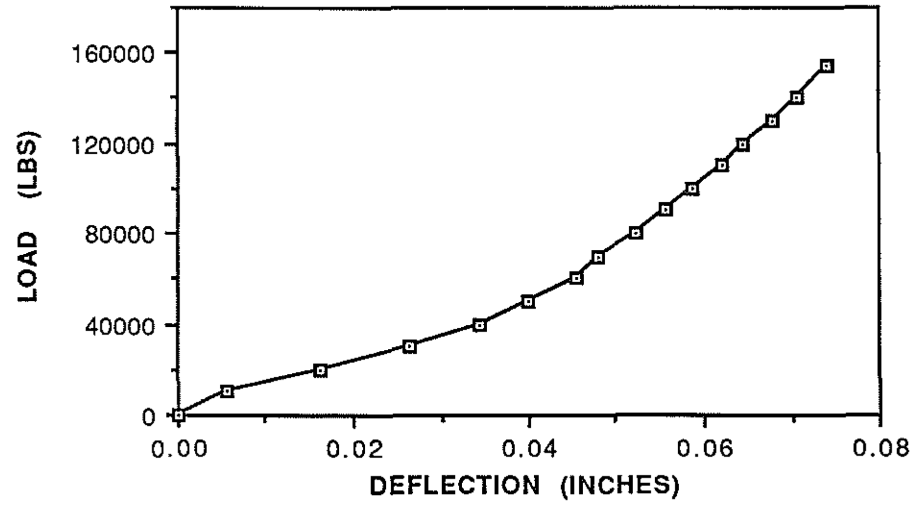


Figure 5. Cross Section Schematic of V-22 Centrifugal Force Bearing.



The bearing contains titanium shims which have a slightly conical shape to improve column stability and properly distribute the direct and indirect stresses and strains in the elastomer, shims and end plates. The measured buckling load was in excess of 400,000 pounds (test machine limitation), which provides a more than adequate margin of safety, even for a service life deteriorated bearing. The result of the axial (C.F. load carrying direction) load vs. deflection test is shown in Curve 1. Other static and/or dynamic stiffness testing was conducted to verify that the torsional (with and without C.F. loading), cocking (flapping or lag) and radial spring rates met the specification requirements. In addition to the stiffness and endurance (qualification) testing performed, 100,000 G-A-G (ground-air-ground) cycles, simulating 100,000 flights, were completed without deterioration of the bearing. This test is very severe, since the number of G-A-G cycles is well in excess of the V-22 requirements (7500 per 2500 hours), but provides a "quick" check on the design relative to elastomer and metal stresses.

Curve 1. Static Axial Stiffness of C.F. Bearing



V.B. <u>Outboard Feathering Bearing (O.B.F.)</u>

The Lord O.B.F. bearing shown in Photo 2 is used to permit feathering motions of the blade while reacting chordwise and beamwise radial loads. (This bearing in conjunction with the Inboard Beam and Feathering Bearings react the chordwise and beamwise bending moments caused by torque, thrust and aerodynamic loading.) It must also accommodate some cocking or misalignment caused by these moments and allow for static axial motion of the Centrifugal Force Bearing and structural deflections. F.E. Analysis was utilized in the design optimization of this bearing and the final configuration is shown in Figure 6. In order to minimize weight, the shims along with the outer member are titanium while the inner member "spindle" is made from a stainless steel forging. The radial stiffness is of primary importance in contributing to the proprotor natural frequencies and the typical result is noted in Curve 2. Upon verification that the radial, axial, torsional and cocking spring rates were in compliance with specification, low cycle radial loading was performed for 100,000 cycles to the most severe radial loading expected in flight to provide a good check on the acceptability of the design prior to endurance (spectrum) testing. No detectable bearing damage was noted, providing a good indication of bearing capability under the "accelerated" test.

Photo 2. V-22 Outboard Feathering Bearing

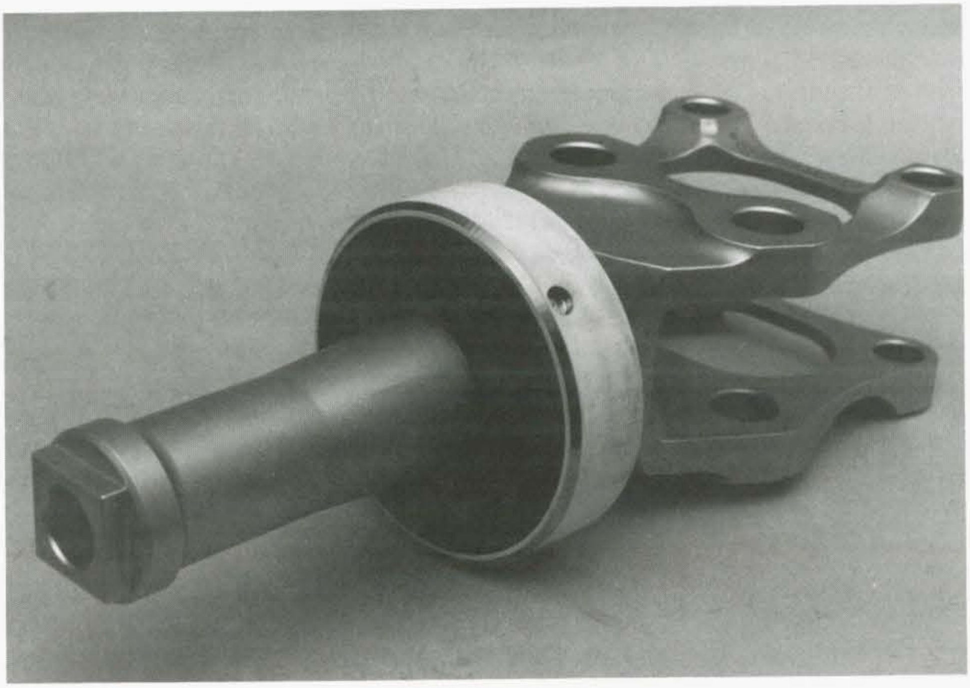
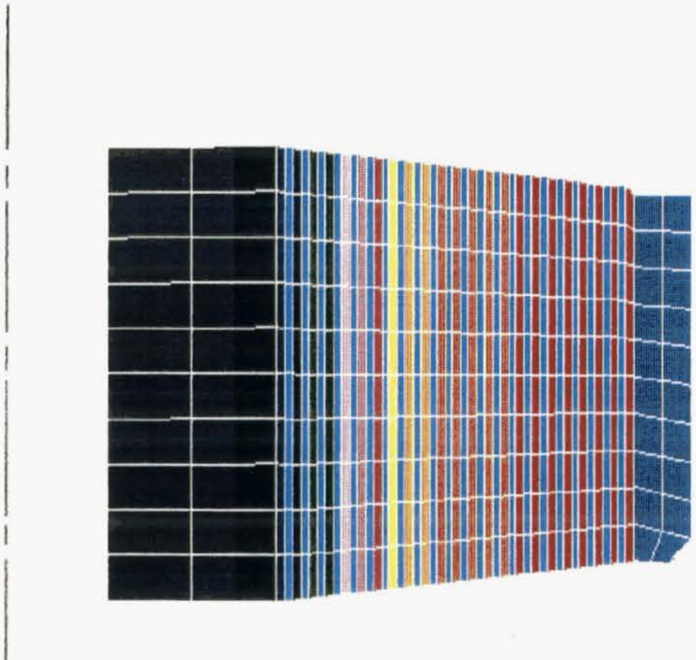
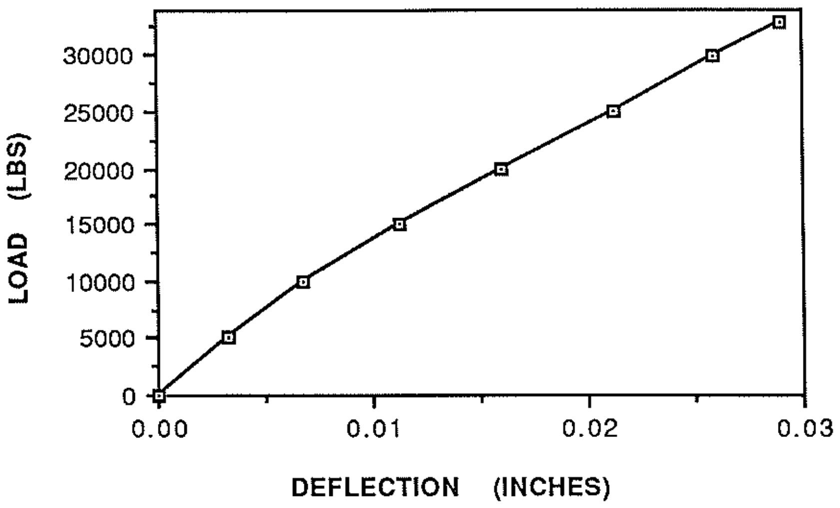


Figure 6. Cross Section Schematic of V-22 Outboard Feathering Bearing



Curve 2. Static Radial Stiffness of Outboard Feathering Bearing



V.C. Inboard Beam (I.B.) - Feathering (I.F.) Bearings

The Lord I.B. and I.F. Bearings are shown in Photo 3. Two (2) Feathering Bearings are used in conjunction with each Inboard Beam Bearing in order to accommodate the large (primarily airplane mode) feathering motions in a much smaller (approximately 47%) diameter than the Outboard Feathering Bearing. This also reduces the torsional (feathering) stiffness at the expense of a more complicated configuration.

The two (2) I.F. Bearings in series with the I.B. Bearing, accommodate; the feathering in torsional shear flexing of the elastomer, radial loading (due to bending moments), cocking or misalignment/bending and axial displacement of the Centrifugal Force Bearing & structural deflection along the axis of the blade. To accommodate structural bending, particularly in the flapping (beamwise) direction, some spherical elastomer-shim sections in the Inboard Beam Bearing were deemed desirable from a life standpoint.

The Inboard Feathering Bearings are constructed using eight (8) concentric cylindrical elastomer sections with titanium shims, while the Inboard Beam Bearing contains five (5) concentric cylindrical elastomer sections, transitioning to six (6) spherical (rod end type) elastomer sections, again using titanium shims. The I.B. outer member ("beam") is made from forged titanium and the inner member is made from stainless steel, while the I.F. inner member is stainless steel and the outer member is aluminum.

Photo 3. V-22 Inboard Beam and Feathering Bearings

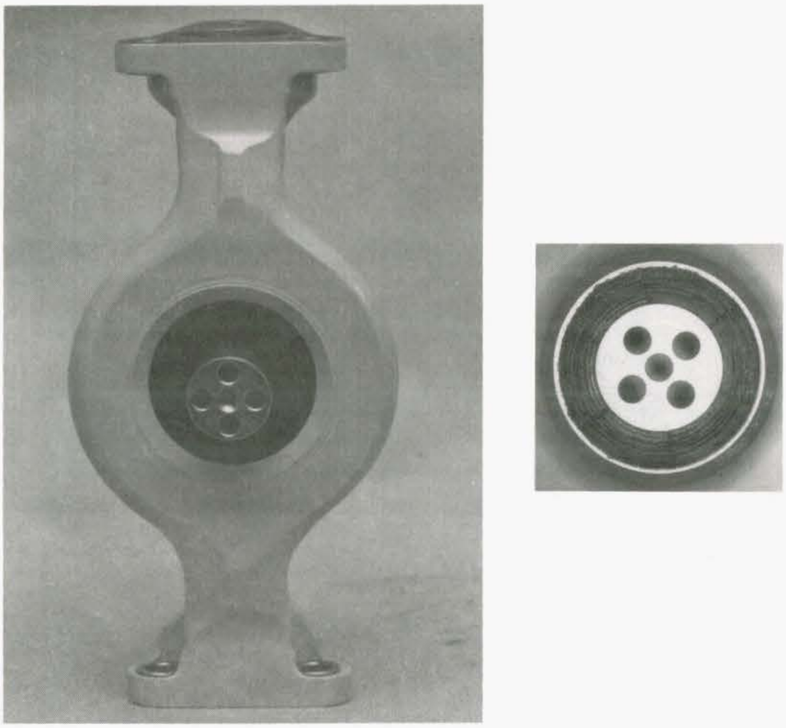
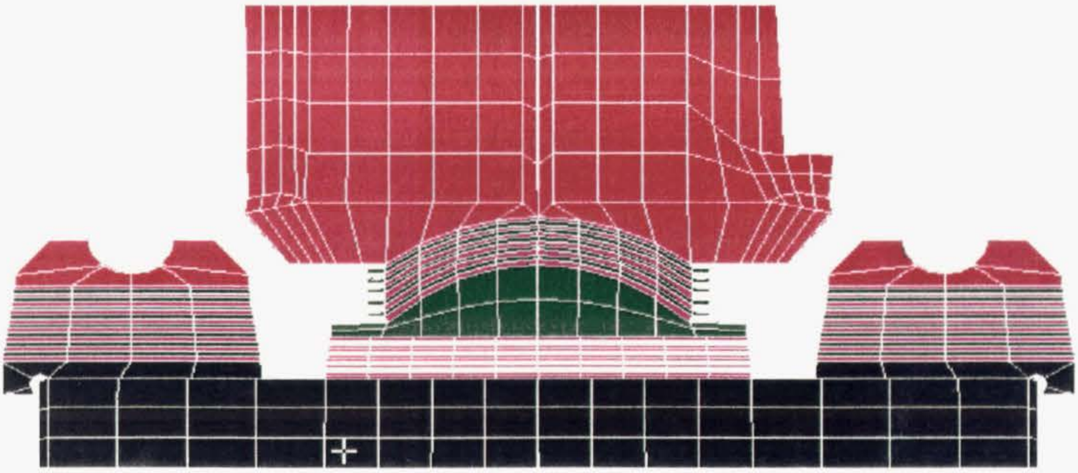
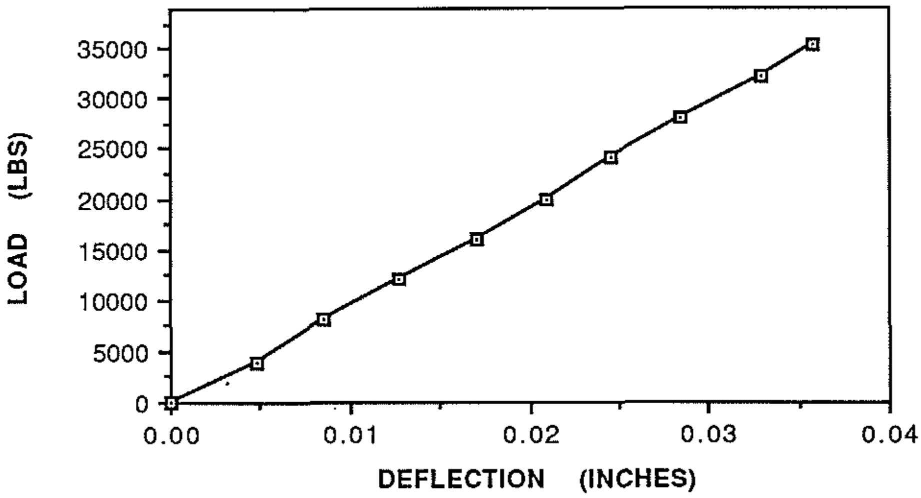


Figure 7 depicts the F.E.A. grid of the combined Inboard Beam and Feathering Bearing assembly. As was performed on the Outboard Feathering Bearing, a "quick", "accelerated" test of the I.B. - I.F. Bearing assembly, was performed for 300,000 cycles to the most severe, radial loading condition expected in flight without any adverse effects. This again provided confidence in the design configuration prior to qualification testing. The radial stiffness test results typical to the I.B. - I.F. Bearing assembly is shown in Curve 3.

Figure 7. Cross Section Schematic of V-22 Inboard Beam Feathering Bearing.



Curve 3. Static Radial Stiffness of Inboard Beam Feathering Bearing Assembly.



V.D. Blade Retention Bearings - Summary

Photos 1 thru 3 depict the Lord elastomeric bearings used in the V-22 blade retention system. In all cases the elimination of highly loaded mechanical joints has been eliminated where possible by bonding/vulcanizing the elastomeric bearings directly to primary structural members. This approach:

- Eliminates fasteners (ie., bolts).
- Reduces tight tolerances on two mating surfaces.
- Reduces overall size via elimination of separate bearing "races".
- Eliminates a potential source of fretting/brinnelling.
- Reduces overall cost through a reduction in parts.
- Reduces the number of parts (simplicity) in proprotor.
- Reduces the weight via elimination of extra bearing "races".

While initially this design approach adds cost compared to the purchase of a conventional separate elastomeric bearing "cartridge", the above benefits, coupled with the fact that re-conditioning/refurbishment of the assembly is possible, far outweigh the additional initial expense.

VI. Proprotor Control System Bearings

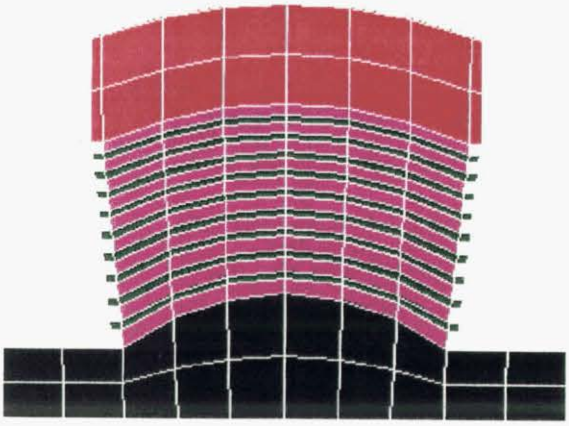
The V-22 proprotor control system employs elastomeric bearings at the Lower Pitch Link attachment to the rotating swashplate and the Gimbal Bearings used in the non-rotating swashplate.

The Lower Pitch Link (L.P.L.) Bearing, shown in Photo 4, is used to react the control system collective and cyclic loads from each blade, while accommodating the typical misalignment motions (torsion and cocking) caused by feathering, flapping and lag. Photo 4 was taken after the lower pitch link bearing had completed 200 hours of helicopter endurance testing.

Photo 4. V-22 Lower Pitch Link Bearing.

The L.P.L. Bearing is composed of ten (10) concentric spherical (rod end type) elastomeric elements. The outer and inner members are made from stainless steel while the shims are alloy steel. The elastomer and shim sections are vulcanized and bonded simultaneously to the stainless steel outer member (rod end) to gain the benefits as discussed previously in Section V.D. Figure 8 shows the basic configuration of the L.P.L. Bearing.

Figure 8. Cross Section Schematic of V-22 Lower Pitch Link Bearing.



VIB. Upper Pitch Link Rod End Bearing

The original design of the V-22 included the use of elastomeric bearings at the proprotor pitch horn position but as a result of further design studies it was realized that removal for maintenance and/or replacement (with the proprotor blades folded and the V-22 wing in a stowed position) would not be possible without special tools or procedures which were not acceptable per the V-22 overall specifications related to maintenance. Consequently a conventional rod end bearing was utilized. Certainly where the maintenance requirements/blade fold-wing stowage do not prohibit their use, the application of elastomeric rod ends (similar to those used at the lower end of the pitch link) are ideally suited to improve service life.

VIC. Swashplate Gimbal Bearing

The swashplate Gimbal Bearings, shown in Photo 5, are installed in the non-rotating portion of the proprotor control system to allow gimballing ("tilting") of the swashplate as input from the hydraulic boost actuators/flight control system while reacting loads generated by reactions from blade feathering and the torque reactions from the rotating portion of the swashplate.

Photo 5. V-22 Swashplate Gimbal Bearing.

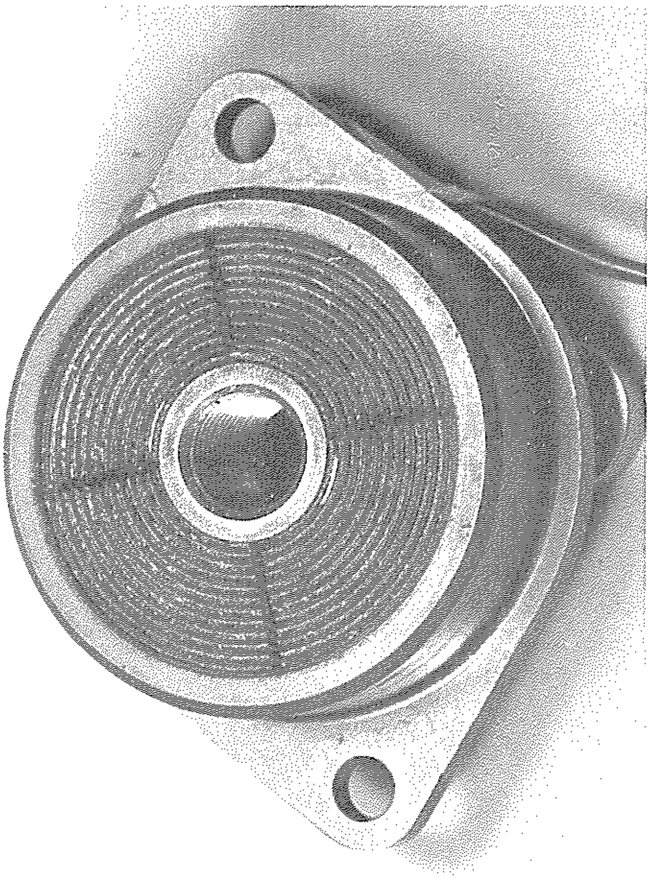


Figure 9. Cross Section Schematic of V-22 Gimbal Bearing.

The Gimbal Bearings (four per proprotor control system) are the simplest of the V-22 elastomeric bearings, being comprised of twelve (12) concentric conical shaped elastomeric elements which are simultaneously vulcanized and bonded to the titanium shims and outer member as well as to the stainless steel inner member. Figure 9 displays the basic configuration cross section.

VII. **Proprotor Hub Spring (H.S.) Assembly**

The proprotor Hub Spring, consists of an upper and lower element as shown in Photo 6. The lower H.S. outer member is "cradled" in the proprotor yoke, while the upper H.S. outer member is attached to the proprotor yoke through the Drive Link Coupling's "pillowblocks" which connect one end of each Drive Link to the yoke as depicted in Figure 1. The inner structural members of both the upper and lower Hub Spring are attached through splines to the transmission mast. These two (2) parts provide for; centering of the proprotor relative to the mast, a thrust reaction bearing and flapping with a controlled auxiliary "spring" restraint. The configuration of the H.S. Assembly consists of concentric spherical (domes of different spheres with a common center) elastomeric layers in both the upper and lower parts as depicted in the F.E.A. grid of Figure 10. The elastomeric layers are vulcanized and bonded to the stainless steel shims and to the aluminum outer major structural members of each Hub Spring.

Photo 6. V-22 Proprotor Hub Spring Assembly.

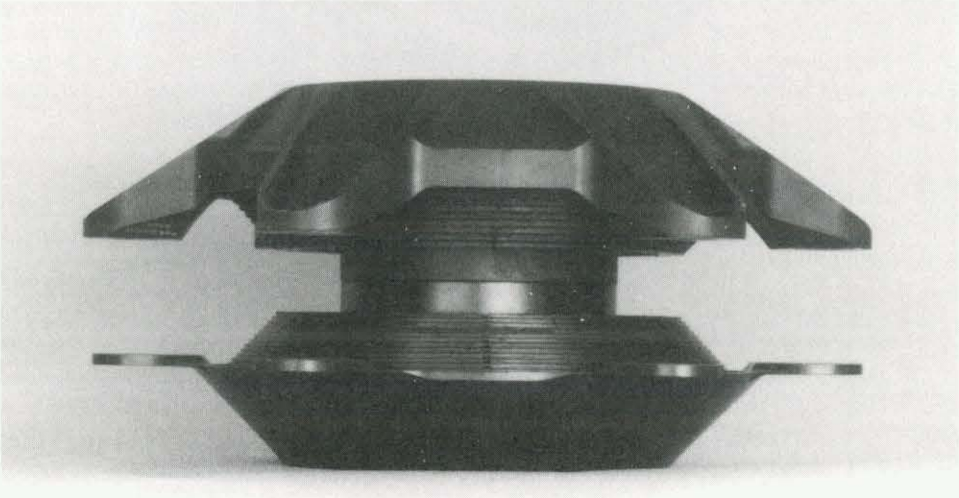
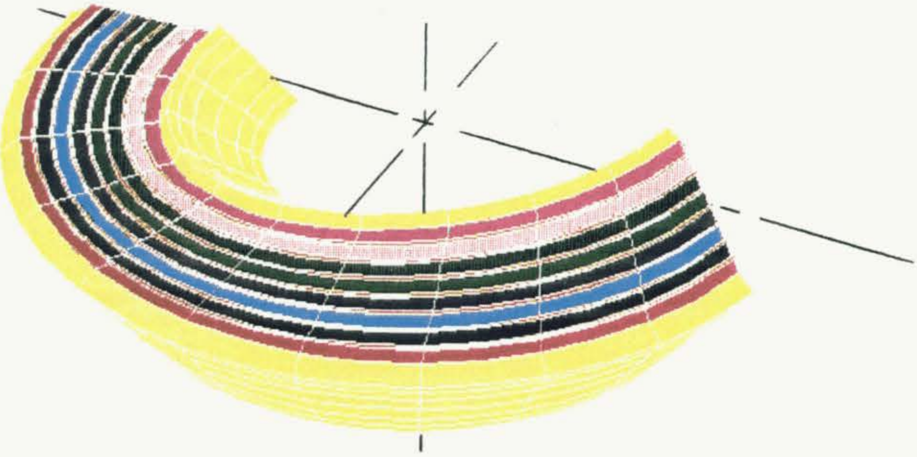


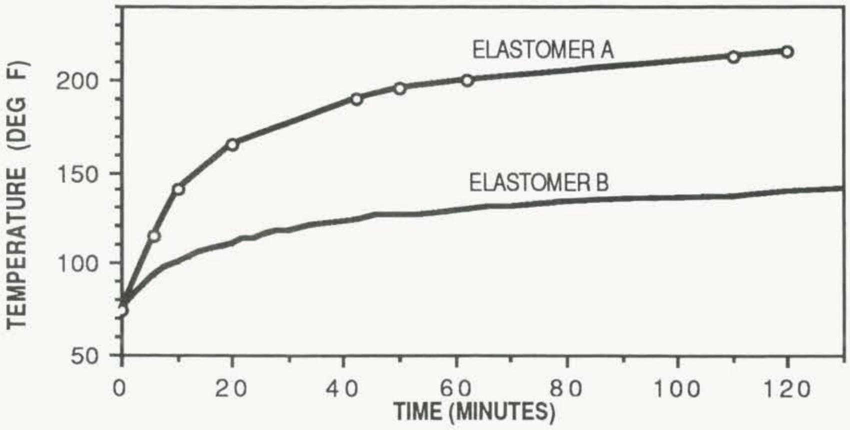
Figure 10. Cross Section Schematic of V-22 Upper Hub Springs.



The Hub Spring Assembly is, along with the "Links" of the Drive Coupling, one of the most demanding elastomeric products used in the V-22 proprotor. This is due to the large and continuous flapping motions coupled with high loads which must be accommodated, particularly during the helicopter portion of the aircraft's duty cycle.

As a result of the large and continuous nature of the proprotor flapping inputs, during helicopter flight, the H.S. assembly can generate a significant amount of internal hysterisis heating (due to inherent damping in the elastomer), which if not properly analyzed and accounted for in the elastomer selection, can lead to very early degradation in service. A significant amount of elastomer formulation development coupled with H.S. model testing resulted in a satisfactory configuration which would not overheat due to hysterisis damping nor be overly stiff during low temperature flight, particularly during the airplane duty cycle, where the cyclic motions are substantially less than during helicopter flight. Curve 4 shows the difference in the temperatures of two different elastomers initially evaluated during developmental testing (Prior to the FSD phase). These tests along with the evaluation of other elastomers (with varying amounts of damping), determined the final elastomer selection in conjunction with the configuration.

Curve 4. V-22 Hub Spring Elastomer Temperature Test Results.



VIII. Proprotor Coupling

The performance requirements of the V-22 proprotor coupling are extremely challenging due to the high torque and misalignment requirements. The coupling which transmits power (with rotor breaking capability) from the proprotor gearbox to the rotor must also accommodate angular misalignment created by proprotor flapping. The XV-15 tiltrotor aircraft utilized a Hooke's or Universal Joint for the proprotor coupling. This type of coupling is undesirable for the V-22 due to the non-constant velocity nature of the coupling, weight and the need for maintenance. During preliminary design of the V-22 several drive coupling concepts were studied, some of which were laboratory tested.

Lord had been studying various coupling concepts which would be capable of:

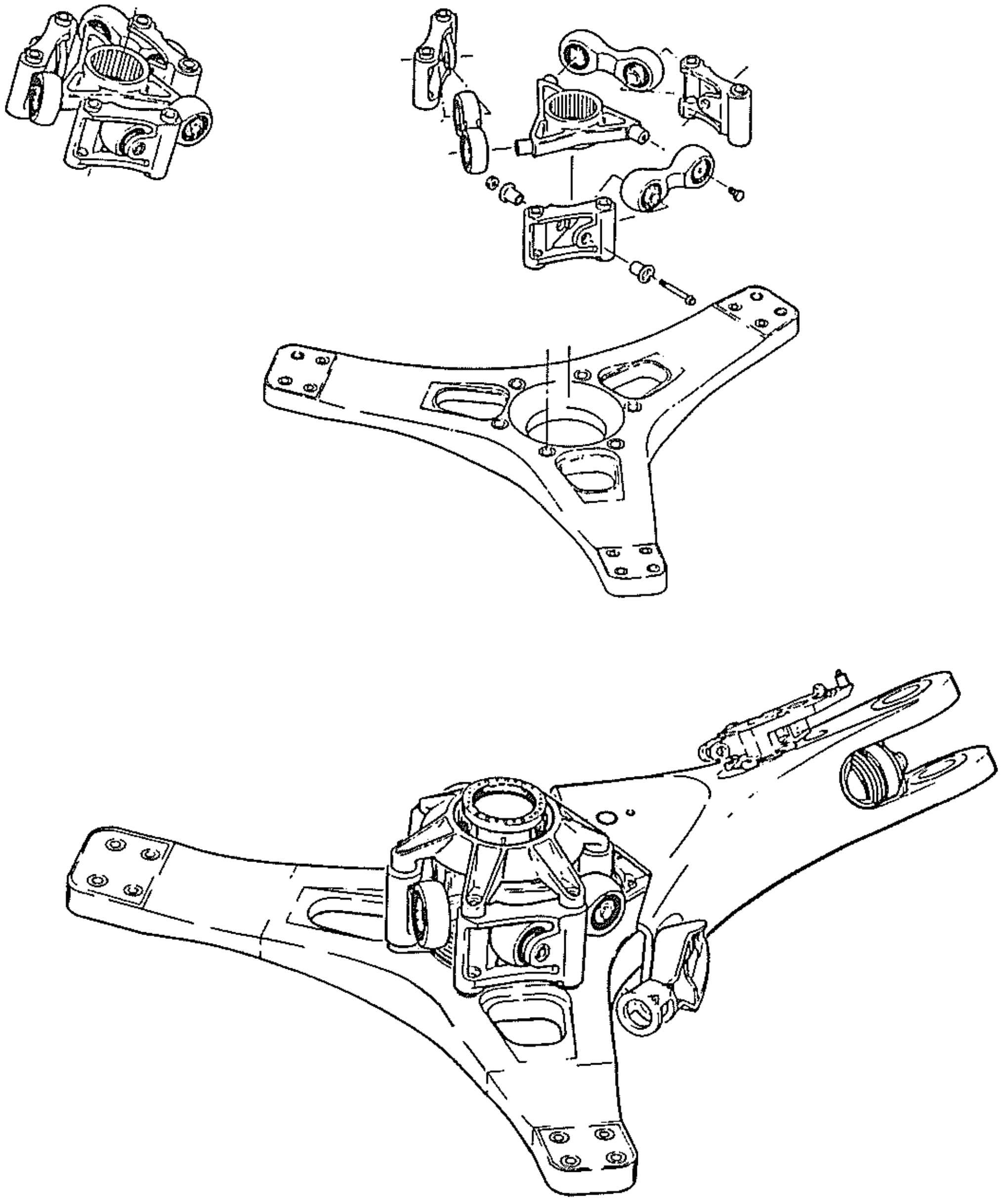
- Transmitting high torque in two (2) directions;
- Accommodating large angular misalignment;
- Operating as a constant velocity coupling; and
- Requiring no lubrication.

Scale models were built to verify the constant velocity requirement. The most promising coupling was a concept which came to be known as the Drive Link Coupling and is covered by a United States patent (No.4804352).

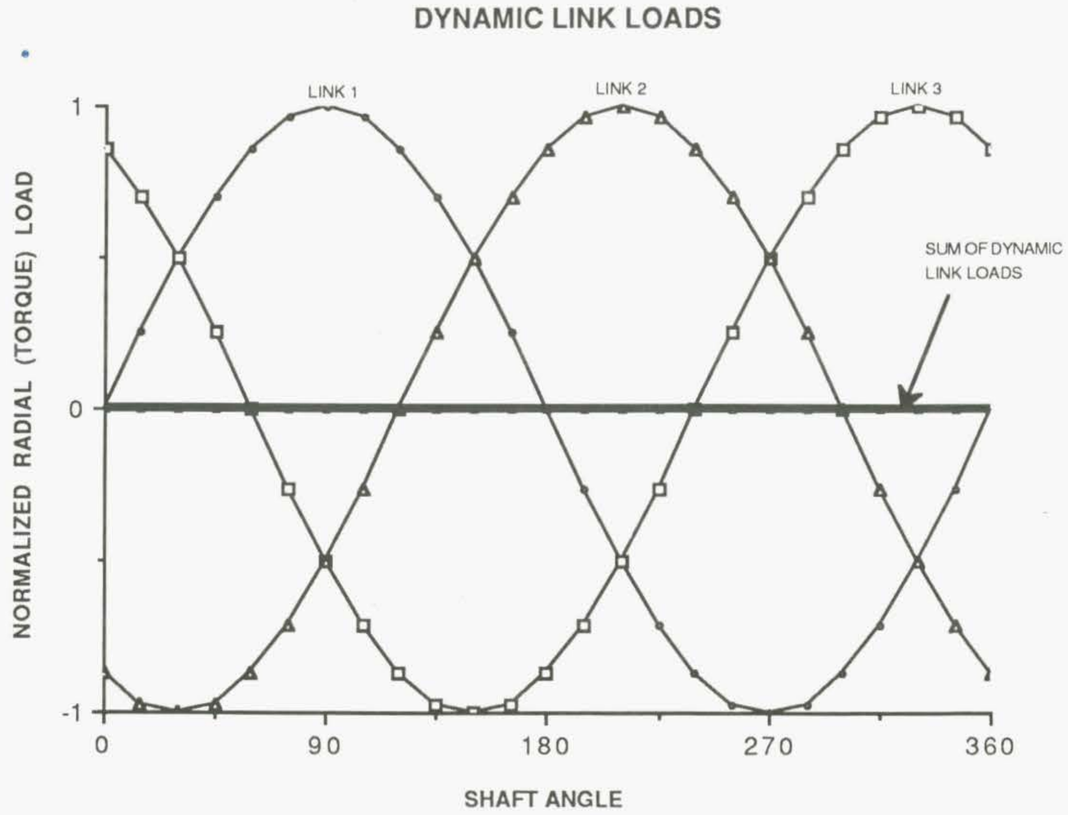
VIIIA. Drive Link Coupling

The Lord developed Drive Link Coupling was selected by the Bell-Boeing team for use in the V-22. The coupling concept consists of three (3) links, centrally and equally spaced around the transmission mast with one end of each link connected to the mast through a "drive plate" while the opposite end of each link is connected to the proprotor yoke at "pillowblocks" as shown in Figure 11. Each link end contains an elastomeric rod end configuration bearing to accommodate the misalignment and transmit torque in two (2) directions at essentially constant velocity. Curve 5 demonstrates the constant velocity of the coupling. The oscillatory dynamic torque due to angular misalignment is accommodated through flexing of the elastomeric bearings. The oscillatory torque is cancelled out in the Link Coupling assembly and no oscillatory dynamic torque is transmitted to the proprotor which could cause undesirable vibration. The coupling, being kinematically non-linear, accommodates the oscillatory torque as well as the static torque through compression loading of the elastomeric bearings, while misalignment is provided for through shear flexing of the elastomer.

Figure 11. V-22 Proprotar Drive Coupling

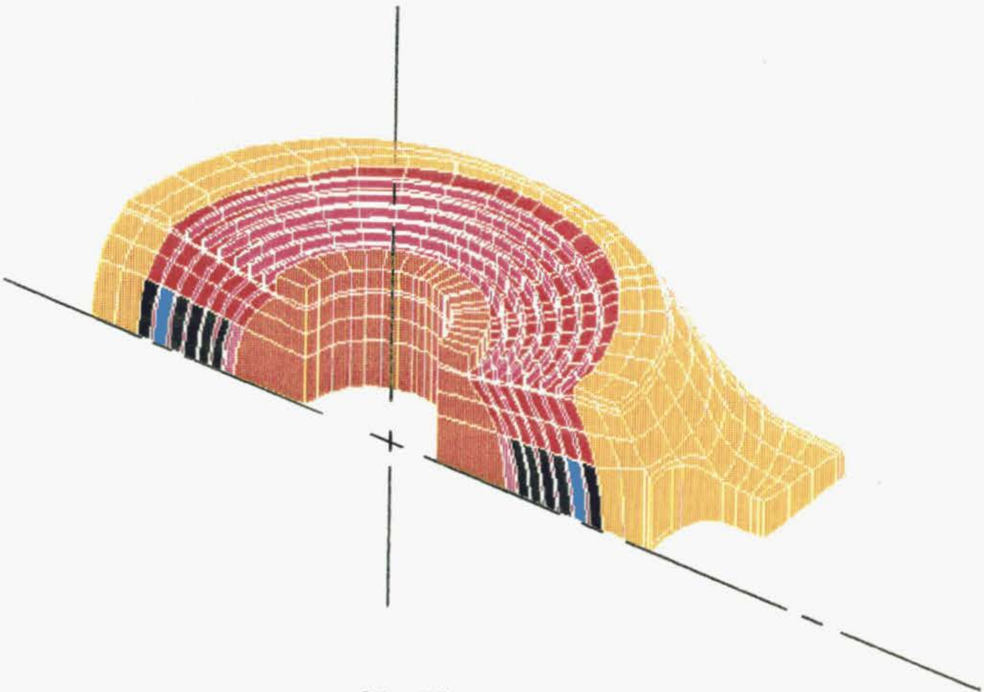


Curve 5. V-22 Drive Link Coupling Constant Velocity Verification



The outer member ("link") is machined from a titanium forging while the metallic shims are also of titanium and the inner members are manufactured from stainless steel. This provides a minimum size/weight coupling, which meets the stringent reliability and maintainability demands of the V-22 program. The internal geometry of the Drive Link is shown in Figure 12 from the F. E. A. plot.

Figure 12. Cross Section Schematic of V-22 Drive Link



IX. Qualification Testing

IXA. Design Verification

Static and some dynamic testing of each of the V-22 proprotor elastomeric products was conducted to establish that:

- All static and dynamic stiffnesses met the specification criteria.
- All products were capable of meeting the limit and ultimate load or deflection specification requirements.
- The elastomer-shim quality (uniformity of spacing) was met.
- The ultimate strength of the elastomer-to-metal (shims & major metal parts) bonds was acceptable and consistent from test parts to production quantities.
- All products met the dimensional, weight requirements and workmanship specifications.

Only after these tests/inspections were satisfactorily completed, were shipments to the customer and subsequent Endurance Testing permitted.

All parts, except for the Hub Spring Assembly, due to equipment availability limitations, were tested under low cycle fatigue using the G-A-G inputs or to the most severe flight conditions to establish additional confidence in the designs prior to manufacture of bearings for shipment or for endurance testing. The results of these tests have been discussed previously for each part.

IXB. Endurance Testing

In order to verify that the V-22 elastomeric products used in the proprotor met the design objectives, laboratory endurance testing of the nine (9) parts was conduced using a simulated flight spectrum coupled with the ground-air-ground (GAG) cycles.

Ultimately it was decided to conduct the endurance testing using the helicopter only load and motion inputs since a high percentage of the fatigue damage is consumed for this portion of the V-22's flight duty cycle. Airplane spectrum inputs were imposed minimally, to prevent excessive overheating of the elastomer due to the inherent hysterisis damping of the elastomer. The potential for overheating exists since the endurance tests are performed 24 hours per day where as only 30% of the V-22's duty cycle is at the more severe helicopter inputs. The spectrums for each part were established such that the airplane inputs (for "cooling") were imposed no less than after thirty (30) minutes of continuous simulated helicopter flight inputs. All testing to date has been conducted with the temperature surrounding the test specimens at room temperature (ie., 72°F ± 10°F). Additionally, to date, only one specimen of each part (except for the Inboard Feathering Bearing) has been endurance tested.

Since the Service Life objective for the elastomeric products is 2500 hours, minimum, the initial endurance testing was limited to 750 hours (30% of the 2500 hours is assumed to be helicopter flight). This testing is severe and provides the evidence of the various product's adequacy for at least initial flight testing. Additional testing is anticipated to establish through laboratory spectrum testing the "product's" test life under airplane plus helicopter inputs while developing inspection and replacement criteria for use in Maintenance Manuals.

The Lord Endurance test machines were designed in-house using servo-hydraulic systems to apply the appropriate loads and/or motions with the proper phase angles. All loads and motions were controlled or measured using load cells and linear or rotary variable differential transducers (LVDT or RVDT) while infra-red pyrometers, thermocouples and strain gages were also used to monitor other important parameters throughout the testing. Test inputs and data acquisition were controlled by mini-computers.

Many of the machines were active up to four degrees of freedom to simulate the loads and motions imposed by the V-22 proprotor during flight and G-A-G cycles.

A total of seven (7) different test machines were designed and built. Photos 7 through 18 show the various Endurance Test machines. The Inboard Beam and two Inboard Feathering bearings as well as the Upper and Lower Hub Springs were tested as they would be installed in the proprotor, thus only seven machines were needed for the nine parts. Table III summarizes the various test machines and their capabilities.

Table III. V-22 Endurance Test Machine Capabilities

Machine	Bearings Tested	Machine Capabilities	See Photo Number
1.	(1) Inboard Beam Brg. & (2) Inboard Feathering Brg.	Static & Dynamic Feathering Motion Static & Dynamic Chordwise Loading Static & Dynamic Beamwise Loading Static Cocking Motion (Rotor Coning) Static Axial Motion (Along Blade Axis)	7
2.	(1) Outboard Feathering Brg.	Static & Dynamic Feathering Motion Static & Dynamic Chordwise Loading Static & Dynamic Beamwise Loading Static Cocking Motion (Rotor Coning) Static Axial Motion (Along Blade Axis)	16
3.	(1) Centrifugal Force Brg.	Centrifugal (axial) Force Static & Dynamic Feathering Motion Static Cocking Motion (Rotor Coning)	8 & 9
4.	(2) Lower Pitch Link Brgs.	Static & Dynamic Pitch Link Loading Dynamic Cocking (Flapping & Lag) Static & Dynamic Feathering Motion	10 & 11
5.	(2) Gimbal Bearings	Static & Dynamic Radial Loading Static & Dynamic Axial Loading Dynamic Torsion	12 & 13
6.	(1) Drive Link	Static Torque Load & Dynamic Loading due to Misalignment Dynamic Misalignment around two axes.	14 & 15
7.	(1) Upper Hub Spring & (1) Lower Hub Spring	Axial Thrust Loading (Variable) Misalignment (Cocking) Due to Flapping	17 & 18

Notes:

A. All machines were instrumented to:

1. Continuously monitor/periodically record elastomer temperature.
2. Continuously control/periodically record load and motion inputs.
3. Periodically measure static & dynamic spring rates of elastomeric products.

B. Loads and/or motions are applied in real time frequency/frequencies with proper phase angle between load(s) and motion(s).

C. All test machines also included monitoring devices such as thermocouples, vibration pickups and limit switches to automatically stop the testing in the event of a machine malfunction. This would prevent damage to Endurance Test specimens as well as the equipment.

"Failure" criteria was defined as:

- A fatigue crack in any shim or
- A complete loss of elastomer-to-metal bond or
- The inability of the bearing to react loads (ie., column instability) or
- The direct contact of adjacent metal shims or
- A 20% change in the static stiffness of the bearing along or around selected axes.

It should be noted that the 20% change in stiffness is arbitrarily established as a "failure", even though the bearing would be capable of continued service for several more flight hours.

The test machines were instrumented to periodically record loads and/or motions (which can be converted into spring rates) to obtain trends in the change of the spring rates. If the trend indicated an approach towards the 20% change, the test bearings could be removed for a more precise static stiffness measurement. Periodically (ie., every 100 to 250 hours) the test parts were removed from the machines for a thorough visual inspection, photographing and static stiffness measurements.

IXC. Qualification Test Results

As of this time all of the V-22 Lord elastomeric bearings, except for the Lower Pitch Link Bearing, achieved the 750 (helicopter only) test life objective without failure. Testing of the Lower Pitch Link Bearings was stopped after 541 hours had been completed when one of the two bearings recorded a 21% spring rate reduction in the feathering motion axis (bearing torsion). The other bearing was in good condition with only a 13.7% reduction. There is high confidence that a slight change in the test spectrum sequencing, to reduce the hysterisis heating in the elastomer, during subsequent endurance testing will increase the test life to 750+ hours. Table IV summarizes the test results.

Table IV. Endurance Test Results for V-22 Bearings

Bearing (s)	Total*/Helicopter Hours**
1. (1) Inboard Beam Brg. & (2) Inboard Feathering Brg.	1488/750
2. (1) Outboard Feathering Brg.	1488/750
3. (1) Centrifugal Force Brg.	1123/750
4. (2) Lower Pitch Link Brgs.	781/541
5. (2) Gimbal Brgs.	750/750
6. (1) Drive Link	750/750
7. (1) Upper Hub Spring & (1) Lower Hub Spring	1465/750

* "Total" hours include Helicopter plus Airplane (to minimize overheating due to elastomer hysterisis) hours.

** No "failure" at 750 hours of Helicopter except for Lower Pitch Link.

X. Conclusion

The elastomeric products for the V-22 Osprey tiltrotor aircraft, while a demanding application from a size, space and weight viewpoint, combined with the large feathering motion requirements of the blade retention system to accommodate the feathering of a helicopter plus those of an airplane has been demonstrated to be a success based on the Design Verification and laboratory Endurance Test results.

Initial flight test results provide no evidence of problems with the elastomeric bearings, springs and couplings. The team of Lord personnel and those at Bell Helicopter Textron felt a sense of accomplishment and pride when the first V-22 aircraft made its maiden flight on March 19, 1989.

Confidence is high that the elastomeric products on the V-22 and future tiltrotor aircraft can provide the high reliability and low maintenance demands sought by the customer.

Photo 7. Inboard Beam/Feathering Bearing Test Machine.

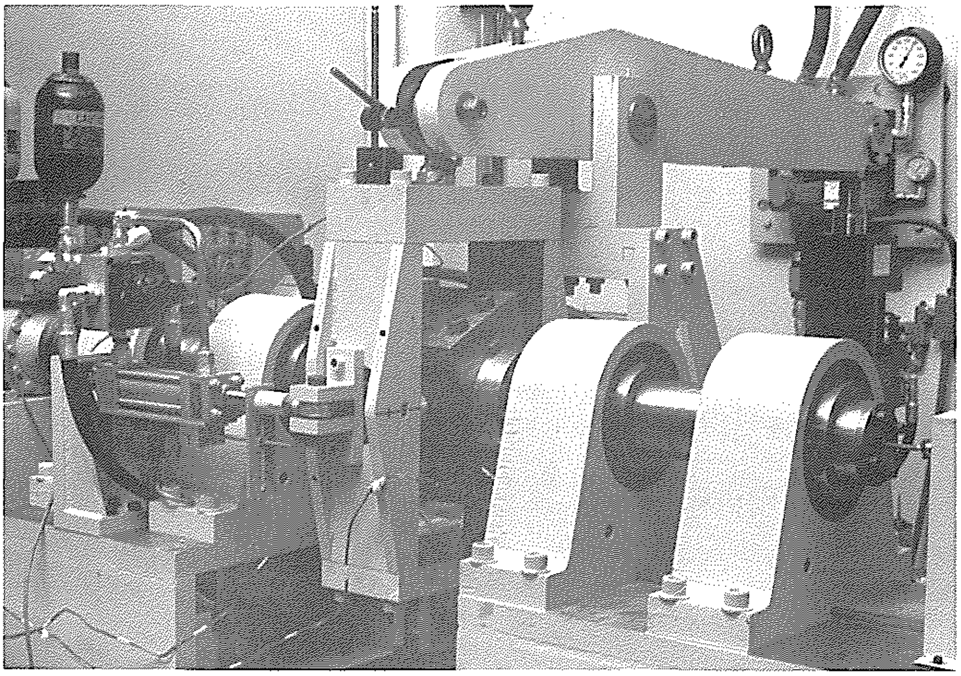


Photo 8. C.F. Bearing Test Machine.

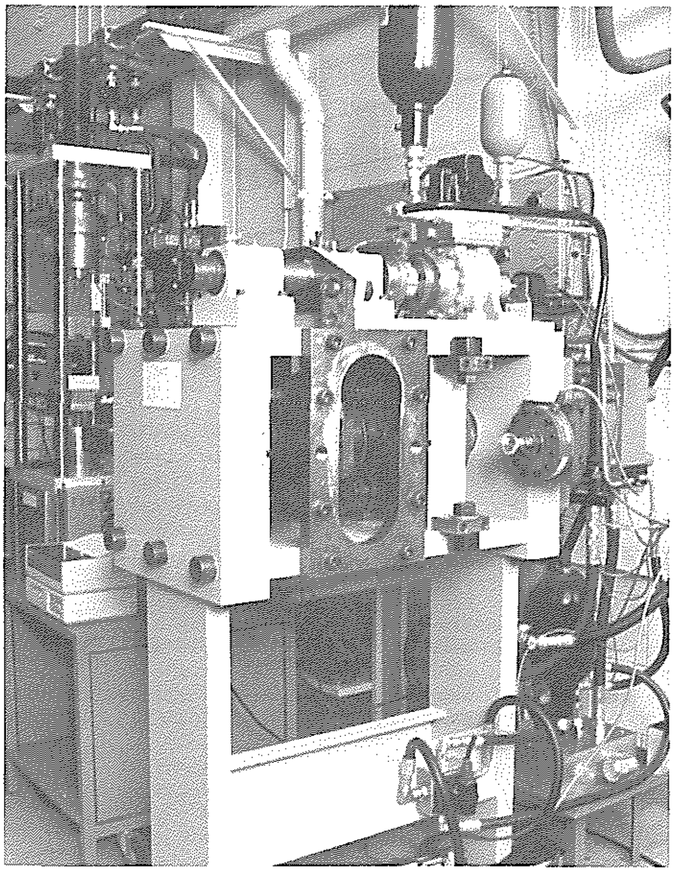


Photo 9. Close-up C.F. Bearing in Test Machine.

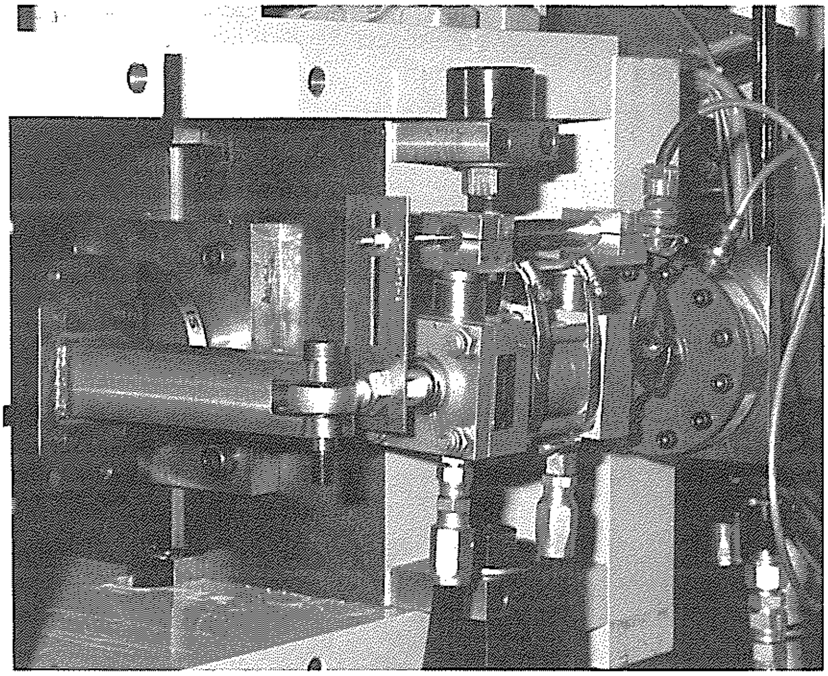


Photo 10. Lower Pitch Link Rod End Test Machine.

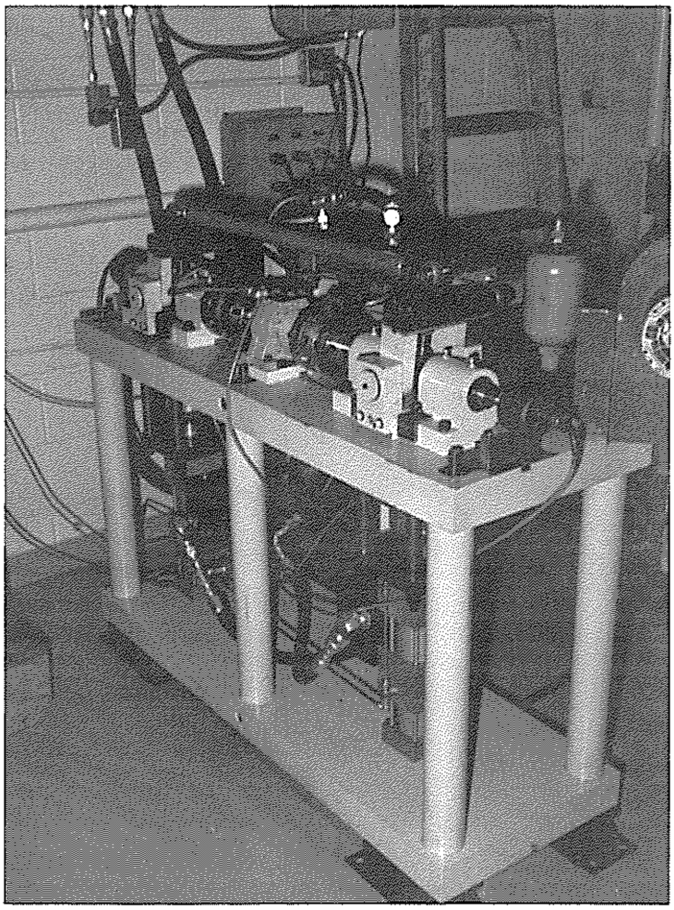


Photo 11. Lower Pitch Link Rod End Test Machine.

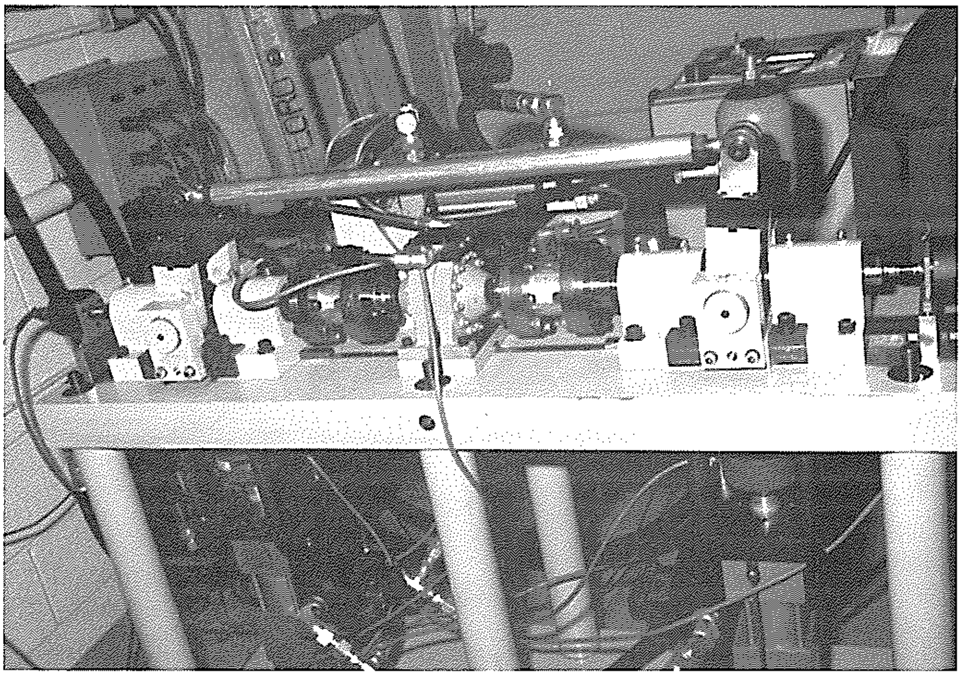


Photo 12. Gimbal Bearing Test Machine.

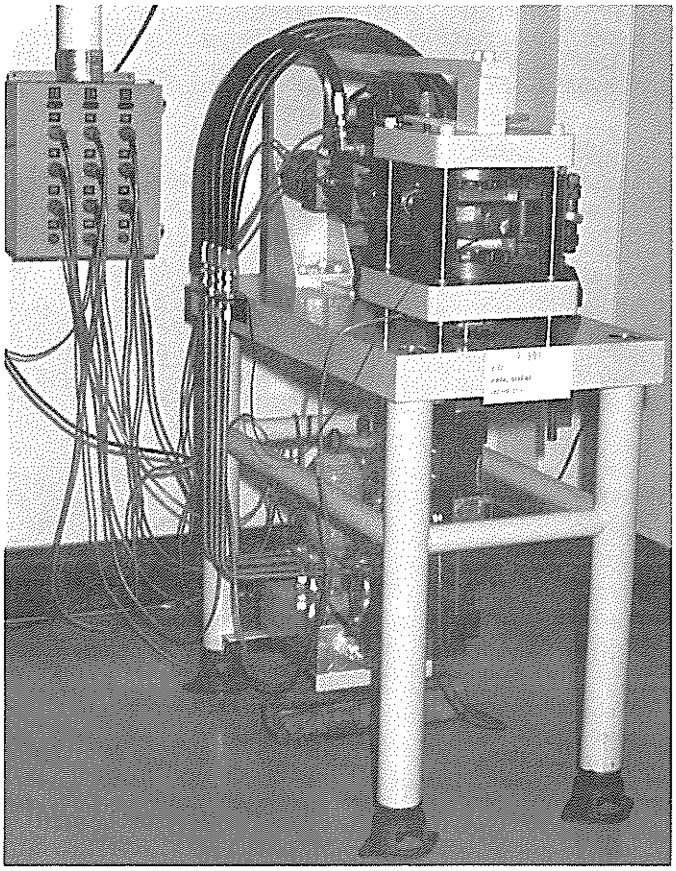


Photo 13. Gimbal Bearing Test Machine.

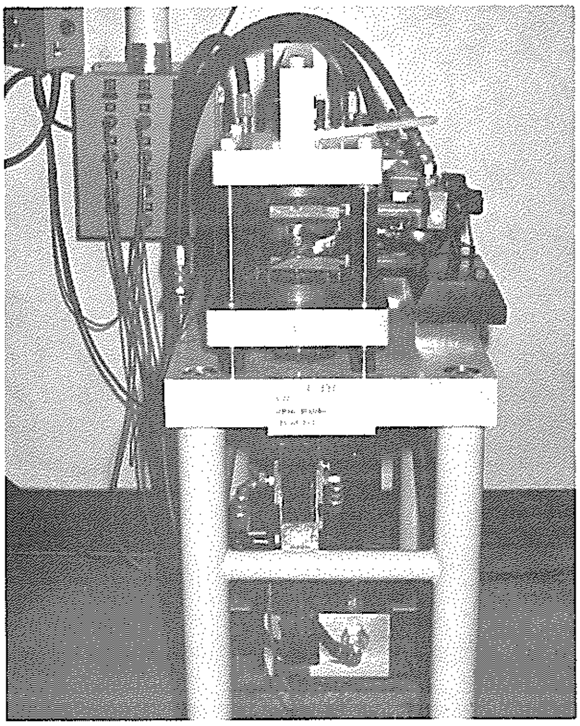


Photo 14. Drive Link Test Machine.

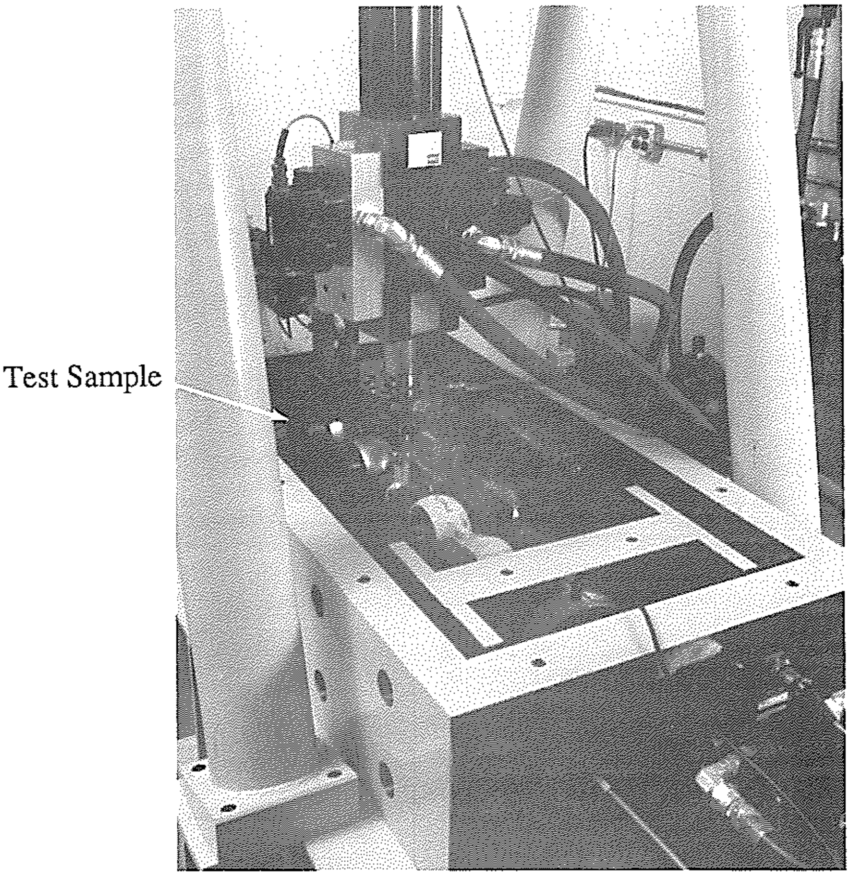


Photo 15. Drive Link Test Machine.

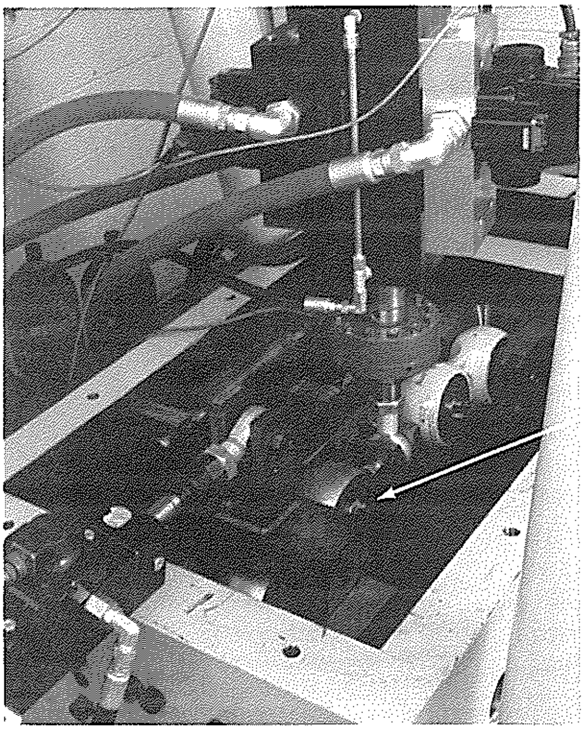


Photo 16. Outboard Feathering Bearing Test Machine.

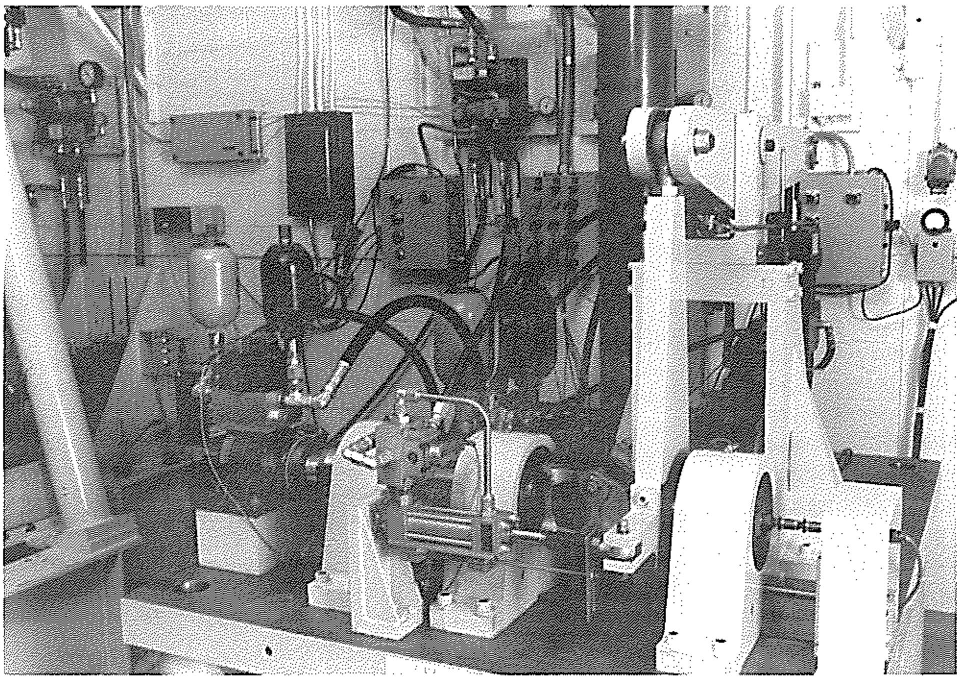


Photo 17. Hub Spring Test Machine.

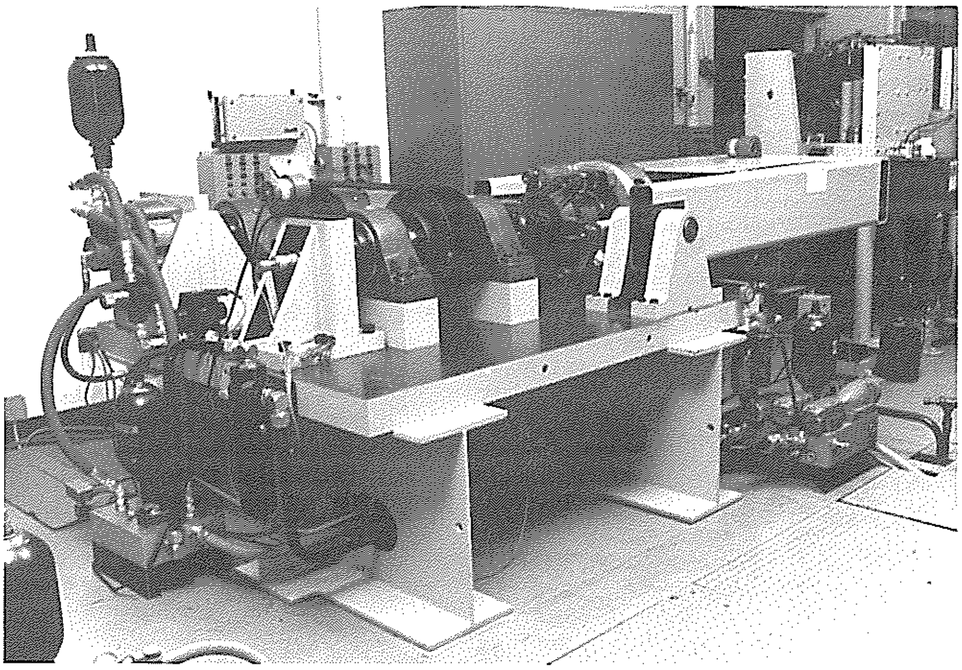
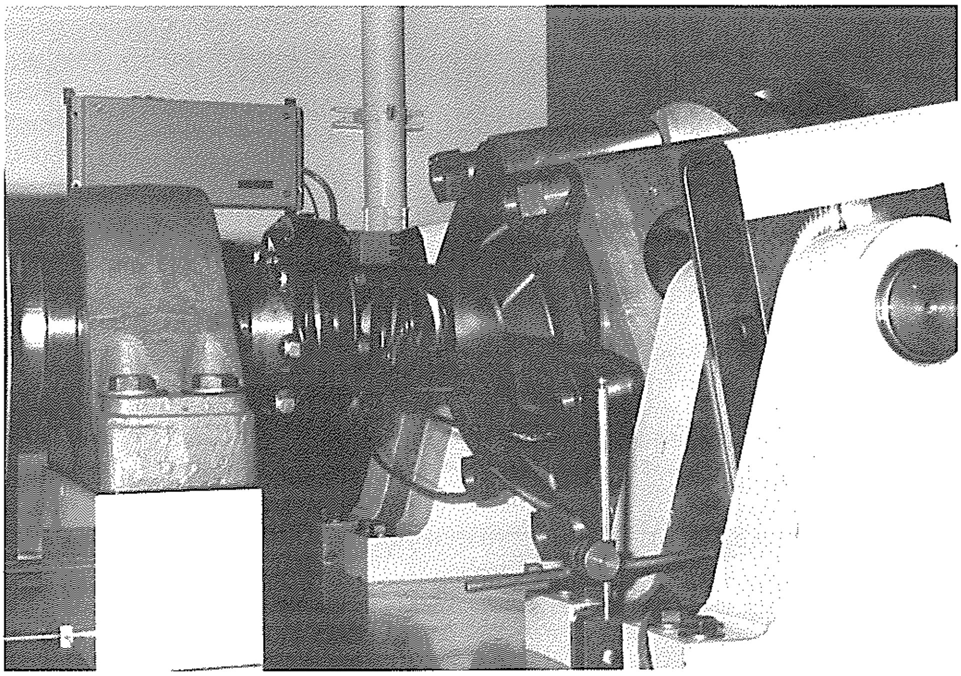


Photo 18. Close-up Hub Spring Test Machine at 8° Cocking.



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