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Operational Evaluation of a Health and Usage Monitoring System (HUMS)

J. Cronkhite, B. Dickson, W. Martin, and G. Collingwood
Bell Helicopter Textron Inc., Fort Worth, Texas

April 1998

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ABSTRACT

This report describes the results of a research program to evaluate structural usage monitoring and damage tolerance methodology using data collected concurrently during a helicopter flight program. The helicopter (a Bell Model 412 equipped with a Health and Usage Monitoring System (HUMS) and data recorder) was operated by Petroleum Helicopters Inc. (PHI) during the 1996 Summer Olympic Games in Atlanta, Georgia, under the FAA's Project HeliSTAR. The mission was referred to as the Atlanta Short Haul Mission (ASHM) and involved many short flights to provide pick up and delivery service at the Olympics. The usage data collected for the ASHM was used to perform fatigue life calculations and damage tolerance evaluations on selected rotor system components known as Principal Structural Elements (PSE's). The usage data from the ASHM were compared to certification data and to data from a previous study for a mission called the Gulf Coast Mission (GCM) which involved primarily long cruise flights. Although the usage was more severe for the ASHM than the GCM, the results of the comparison showed that usage monitoring would provide benefits in extending retirement times or inspection intervals, compared to certification, especially if high/low altitude effects were considered. In addition to usage monitoring evaluations, guidelines for HUMS certification are discussed along with potential economic benefits and simplified "mini-HUMS" approaches to provide low cost systems with high paybacks.

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1. Introduction

This report describes the results of a research program to evaluate structural usage monitoring and damage tolerance methodology using data collected concurrently during a helicopter flight program. The helicopter (a Bell Model 412 equipped with a Health and Usage Monitoring System (HUMS) and data recorder) was operated by Petroleum Helicopters Inc. (PHI) during the 1996 Summer Olympic Games in Atlanta, Georgia, as a part of Project HeliSTAR. This effort was conducted by Bell Helicopter Textron Inc. (BHTI) under the cognizance of the Federal Aviation Agency (FAA), the U.S. Army, and NASA. The helicopter was flown in what is referred to as the Atlanta Short Haul Mission (ASHM). This mission involved numerous short flights to pick up and deliver packages and freight. Data recorded during the period together with pilot flight records and maintenance records were furnished by PHI to BHTI for analysis. The results of the analysis of the ASHM were compared to results from a different type of mission, the offshore oil support Gulf Coast Mission (GCM) analyzed under a previous program (Reference 1) which involved longer level flights at cruise airspeed.

The purpose of the program was to acquire usage data for the ASHM and perform component fatigue life calculations and damage tolerance evaluations for selected critical dynamic components referred to as Principal Structural Elements (PSE's). The ASHM data analysis flow is shown in Figure 1.1. The lives and inspection intervals determined for purposes of this study should not be used to draw any conclusions concerning certification or continued airworthiness of the Model 412 helicopter.

The results of the project are described in the following sections:

- Section 2 describes the ASHM, which is a series of short, high maneuver flights at low altitude and moderate gross weight.
- Section 3 describes the four PSE's that were selected for analysis and includes the service history, e.g., failures, redesigns, configuration changes, process changes, Bulletins, Airworthiness Directives (AD's), reports and other design and manufacturing actions.
- Section 4 discusses the results of the fatigue life analysis of the selected PSE's with comparisons drawn between the ASHM, the GCM, and the certification data.
- Section 5 describes the results of the damage tolerance analysis performed on the selected PSE's.
- Section 6 presents a comparison of the ASHM and GCM spectra applied to the certification load level survey data, and the measured loads data (control boost tube loads) from the ASHM.
- Section 7 discusses the results of investigations to identify improvements to usage monitoring sensors and equipment for enhancements to future usage monitoring systems.
- Section 8 discusses suggested guidelines for certification and qualification of future systems.
- Section 9 addresses the economic impact results of usage monitoring for the ASHM versus the GCM.
- Section 10 proposes reduced complexity alternatives that might be applied to smaller rotorcraft.

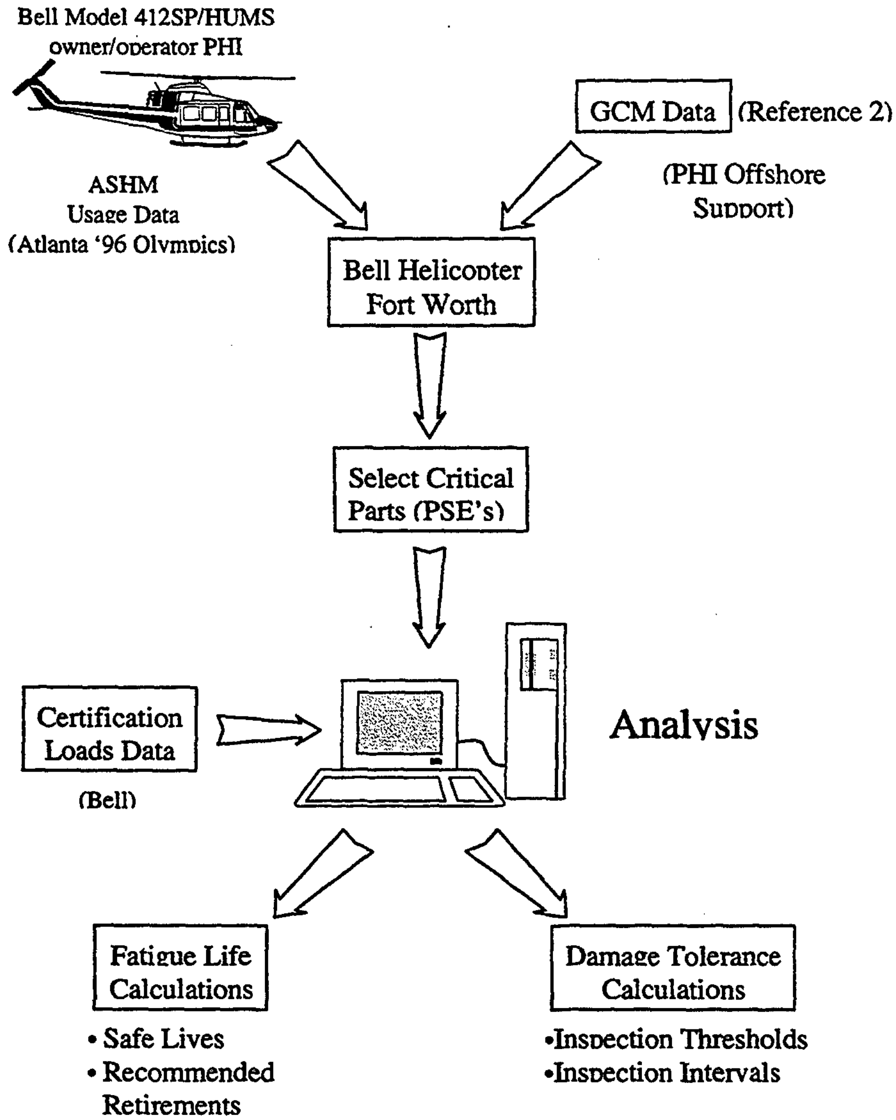

Figure 1.1 Data Collection and Analysis Flow

2. Atlanta Short Haul Mission Description

HUMS data recorded during project HeliSTAR covered the period from 19 July 1996, through 1 August 1996, and contained a total of nine flying days. It should be noted that the data sample for the ASHM is limited (approximately 17 hours of flight data) compared to the approximately 450 hours of flight data processed from the GCM. Because of the limited amount of data, care should be exercised regarding the mission characteristics presented and any analysis resulting from the use of the ASHM data.

The ASHM consisted mainly of flights that were of short duration, with a large number of maneuvers. The broad mission statistics are presented in Table 2.1. The mission spectrum detailing time at condition broken out by gross weight is tabulated in Table 2.2. It should be noted that Autorotation is defined, for the purpose of mission spectrum, as less than 10% combined engine torque whilst in flight. A comparison between the Certification spectrum, GCM spectrum, and the ASHM spectrum is presented in Table 2.3. The ASHM consists of a significantly higher percentage time in low to moderate speeds (0.8 and $0.9V_h$) and in turning maneuvers (conditions 34 through 37) than either of the other spectra. The Gulf Coast mission consisted primarily of high-speed level flight. Both the ASHM and GCM indicate more time spent at 324 rpm than at 314 rpm while the certification spectrum assumes more time at 314 rpm. The time at condition comparison is emphasized in Figure 2.1 which presents the data sorted by descending time at condition for the ASHM.

The correlation of Pilot recorded Flight duration vs. HUMS recorded Flight duration is presented in Figure 2.2. It should be noted that pilots record takeoff and landing times to the nearest minute whereas HUMS recorder has a resolution of 0.5 seconds. Consequently, a large apparent scatter in the short flight duration region may occur. The cumulative difference between the pilot-reported and the HUMS-recorded flight duration is presented in Figure 2.3. The difference does not appear to settle down to a steady value, indicating the data sample may not be large enough to be statistically viable.

Ground running time is not included in the time-at-condition spectrum, but is calculated separately so that damage can be related to flight time. The certification process similarly assumes the time spent in ground running and then sums that damage into the 100 hour spectrum damage before calculating a life.

A detailed flight by flight comparison between the pilot logbook data and the HUMS recorded data is presented in Table 2.4. Flight data were not recorded during the afternoon on two of the mission days, resulting in the loss of approximately 10 hours of flight data. An investigation indicated that the recorder was not operating during the missing 10 hours but did not reveal a reason for the data loss. The Quick Access data Recorder (QAR) used for the ASHM was separate from the HUMS and not representative of an integrated data recorder as would be used in a production system. Statistical methods need to be developed to account for unrecorded or corrupted data.

Table 2.1 Mission Statistics

Period of Mission		7/19/96 Thru 8/1/96 inclusive
Airframe Log Book Hours	start	8298:45
	end	8325:50
Maintenance Log Flight Hours		27:05
Pilot recorded Flight Hours		26:10
Pilot recorded Flights		160
Hums recorded Flight Hours		17:13
Hums recorded Flights		95
Hums recorded Ground Time		14:06
Average Flight duration		10 Minutes
Gross Weight Breakdown	Light	0%
	Medium	57%
	Heavy	43%
Altitude Breakdown	<3k ft	94%
	3k-6k ft	6%
	>6k ft	0%
Correlation of Flight Time		-5% Average
		14% Std Dev
Correlation of Gross Weight		-1% Average
		5% Std Dev
Correlation of CG		2.8" Average
		2.7" Std Dev

Table 2.2 ASHM Spectrum

No.	Flight Condition	Percent Time at Gross Weight (LB)			
		<8000	8000 to 10000	10000 to 12500	Total
1	Rotor Start	0	0	0	0
2	Ground Time (rpm 250-324)	0	0	0	0
3	Normal Shutdown with Collective	0	0	0	0
4	IGE Steady Hover at 314 r.p.m.	0	1.0280	0.5741	1.6022
5	IGE Steady Hover at 324 r.p.m.	0	2.0872	1.1657	3.2529
6	IGE 90o Right Hover Turn	0	0.6913	0.2508	0.9421
7	IGE 90o Left Hover Turn	0	0.7437	0.5278	1.2715
8	IGE Longitudinal Control Reversal	0	0.0214	0.0365	0.0579
9	IGE Lateral Control Reversal	0	0.0206	0.0683	0.0889
10	IGE Rudder Control Reversal	0	0.0389	0.0095	0.0484
11	IGE Right Sideward Flight	0	0.0151	0	0.0151
12	IGE Left Sideward Flight	0	0.1191	0.0556	0.1746
13	IGE Rearward Flight	0	0	0	0
14	Normal Takeoff & Acceleration to Climb Airspeed	0	3.6859	2.5724	6.2583
15	Twin Engine Normal Approach & Landing	0	0.0730	0.0532	0.1262
16	Single Engine Normal Approach & Landing	0	0	0	0
17	0.4 Vh Level Flight at 314 r.p.m.	0	0.3415	0.2897	0.6312
18	0.4 Vh Level Flight at 324 r.p.m.	0	1.3658	1.1588	2.5246
19	0.6 Vh Level Flight at 314 r.p.m.	0	0.6053	0.5038	1.1091
20	0.6 Vh Level Flight at 324 r.p.m.	0	2.4211	2.0154	4.4365
21	0.8 Vh Level Flight at 314 r.p.m.	0	3.2802	3.1597	6.4399
22	0.8 Vh Level Flight at 324 r.p.m.	0	13.1208	12.6389	25.7597
23	0.9 Vh Level Flight at 314 r.p.m.	0	2.1725	1.2442	3.4167
24	0.9 Vh Level Flight at 324 r.p.m.	0	8.6901	4.9768	13.6669
25	1.0 Vh Level Flight at 314 r.p.m.	0	0.8648	0.4278	1.2926
26	1.0 Vh Level Flight at 324 r.p.m.	0	3.4593	1.7112	5.1705
27	Vne at 314 r.p.m.	0	0	0	0
28	Vne at 324 r.p.m.	0	0	0	0
29	Twin Engine Full Power Climb	0	1.5310	1.3080	2.8391
30	Single Engine Full Power Climb	0	0	0	0
31	0.6 Vh Cyclic Pullup	0	0.3961	0.2691	0.6651
32	0.9 Vh Cyclic Pullup	0	0.0151	0.0143	0.0294
33	Norm. Accel. from Climb A/S - 0.9 Vh	0	0	0	0
34	0.6 Vh Right Turn	0	2.6922	2.0724	4.7646
35	0.9 Vh Right Turn	0	1.9977	2.0462	4.0439
36	0.6 Vh Left Turn	0	1.3739	1.4509	2.8248
37	0.9 Vh Left Turn	0	2.6319	1.7406	4.3725
38	0.9 Vh Longitudinal Control Reversal	0	0	0	0
39	0.9 Vh Lateral Control Reversal	0	0	0	0
40	0.9 Vh Rudder Control Reversal	0	0	0	0
41	Deceleration from 0.9 Vh to Descent A/S	0	0	0	0
42	Twin Engine Partial Power Descent	0	1.3961	0.6953	2.0914

Table 2.2 ASHM Spectrum

No.	Flight Condition	Percent Time at Gross Weight (LB)			
		<8000	8000 to 10000	10000 to 12500	Total
43	Single Engine Partial Power Descent	0	0	0	0
44	Twin to Single Engine in Full Power Climb	0	0	0	0
45	Twin to Single Engine at 0.9 Vh	0	0	0	0
46	Single to Twin Engine in Power Descent	0	0	0	0
47	Twin Engine to Autorotation[1] at 0.6 Vh	0	0.0024	0.0008	0.0032
48	Twin Engine to Autorotation[1] at 0.9 Vh	0	0.0016	0.0016	0.0032
49	Stabilized Autorotation[1] to Twin Engine	0	0	0	0
50	Autorotation[1] at Vne and Minimum r.p.m.	0	0	0	0
51	Autorotation[1] at Vne and Maximum r.p.m.	0	0	0	0
52	Autorotation[1] Right Turn	0	0.0167	0.0183	0.0349
53	Autorotation[1] Left Turn	0	0	0	0
54	Unrecognized	0	0.0246	0.0175	0.0421
		0	56.9250	43.0750	100.0000

Note:

1) Autorotation recorded when combined engine power less than 10%

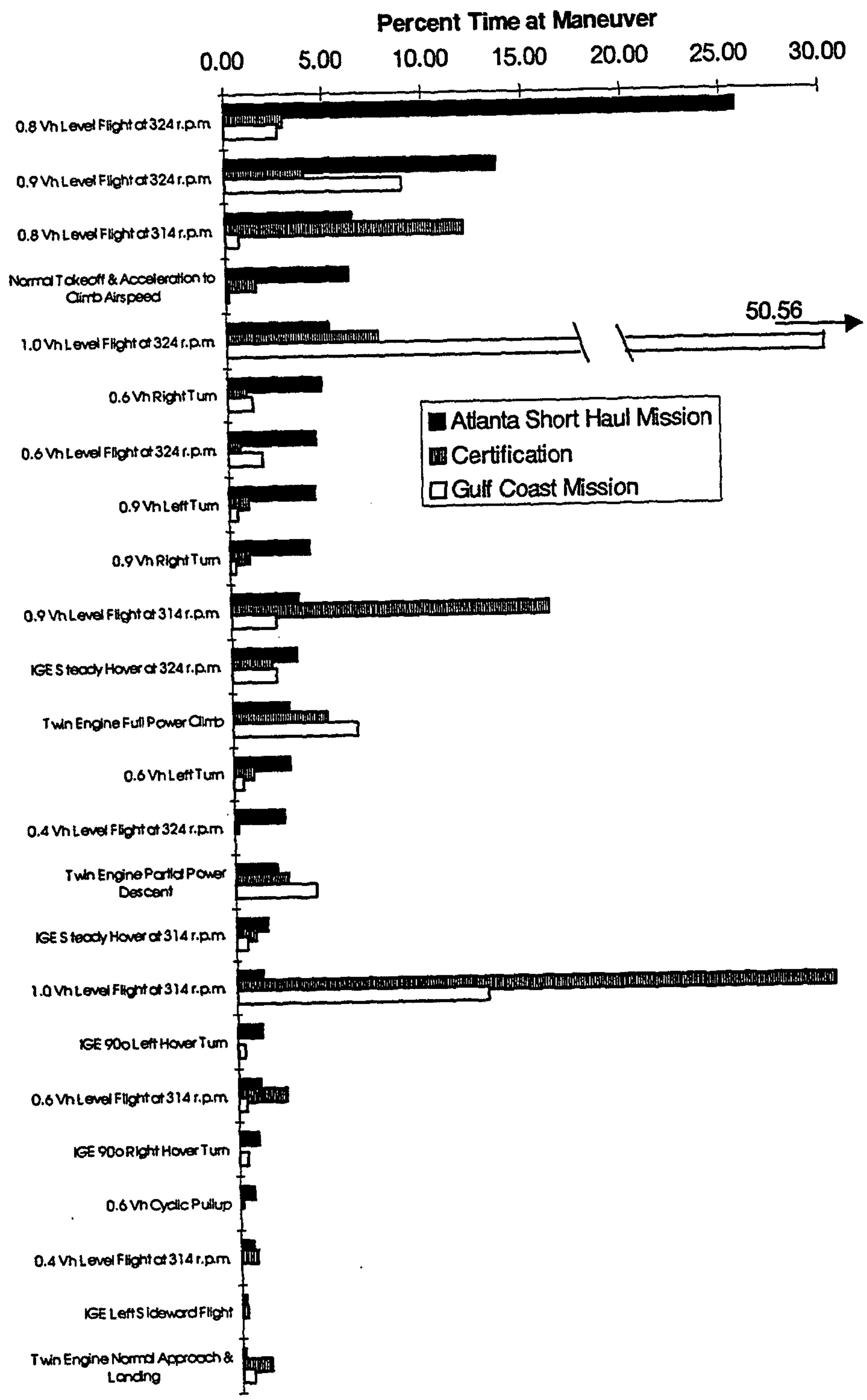

Figure 2.1 Spectra Comparison

Table 2.3 Spectra Comparison

No.	Certification Spectrum Condition	Certification %	Atlanta Short Haul %	Gulf Coast %
1	Rotor Start[1]	0.5000	0	0
2	Ground Time (rpm 250-324)[2]	1.0000	0	0
3	Normal Shutdown with Collective[1]	0.5000	0	0
4	IGE Steady Hover at 314 r.p.m.	1.0000	1.6022	0.5501
5	IGE Steady Hover at 324 r.p.m.	2.0000	3.2529	2.2003
6	IGE 90o Right Hover Turn	0.0700	0.9421	0.4330
7	IGE 90o Left Hover Turn	0.0700	1.2715	0.3809
8	IGE Longitudinal Control Reversal	0.0100	0.0579	0.0331
9	IGE Lateral Control Reversal	0.0100	0.0889	0.0359
10	IGE Rudder Control Reversal	0.0100	0.0484	0.0968
11	IGE Right Sideward Flight	0.2500	0.0151	0.0379
12	IGE Left Sideward Flight	0.2500	0.1746	0.0976
13	IGE Rearward Flight	0.1000	0	0
14	Normal Takeoff & Acceleration to Climb Airspeed	1.5000	6.2583	0.1323
15	Twin Engine Normal Approach & Landing	1.4300	0.1262	0.5461
16	Single Engine Normal Approach & Landing	0.0300	0	0.0084
17	0.4 Vh Level Flight at 314 r.p.m.[3]	0.8000	0.6312	0
18	0.4 Vh Level Flight at 324 r.p.m.[3]	0.2000	2.5246	0
19	0.6 Vh Level Flight at 314 r.p.m.	2.4000	1.1091	0.4379
20	0.6 Vh Level Flight at 324 r.p.m.	0.6000	4.4365	1.7514
21	0.8 Vh Level Flight at 314 r.p.m.	12.0000	6.4399	0.6736
22	0.8 Vh Level Flight at 324 r.p.m.	3.0000	25.7597	2.6945
23	0.9 Vh Level Flight at 314 r.p.m.	16.0000	3.4167	2.2297
24	0.9 Vh Level Flight at 324 r.p.m.	4.0000	13.6669	8.9187
25	1.0 Vh Level Flight at 314 r.p.m.	30.4000	1.2926	12.6411
26	1.0 Vh Level Flight at 324 r.p.m.	7.6000	5.1705	50.5644
27	Vne at 314 r.p.m.	0.8000	0	0.4511
28	Vne at 324 r.p.m.	0.2000	0	1.8046
29	Twin Engine Full Power Climb	4.7500	2.8391	6.3150
30	Single Engine Full Power Climb	0.1200	0	0.0013
31	0.6 Vh Cyclic Pullup	0.1500	0.6651	0.0862
32	0.9 Vh Cyclic Pullup	0.0500	0.0294	0.0182
33	Norm. Accel. from Climb A/S - 0.9 Vh	1.0000	0	0
34	0.6 Vh Right Turn	1.0000	4.7646	1.2422
35	0.9 Vh Right Turn	1.0000	4.0439	0.2726
36	0.6 Vh Left Turn	1.0000	2.8248	0.4894
37	0.9 Vh Left Turn	1.0000	4.3725	0.3962
38	0.9 Vh Longitudinal Control Reversal	0.0500	0	0
39	0.9 Vh Lateral Control Reversal	0.0500	0	0
40	0.9 Vh Rudder Control Reversal	0.0500	0	0
41	Deceleration from 0.9 Vh to Descent A/S	0.1800	0	0
42	Twin Engine Partial Power Descent	2.6440	2.0914	4.1055

Table 2.3 Spectra Comparison

No.	Certification Spectrum Condition	Certification %	Atlanta Short Haul %	Gulf Coast %
43	Single Engine Partial Power Descent	0.1300	0	0.0323
44	Twin to Single Engine in Full Power Climb	0.0100	0	0.0003
45	Twin to Single Engine at 0.9 Vh	0.0100	0	0.0065
46	Single to Twin Engine in Power Descent	0.0100	0	0.0051
47	Twin Engine to Autorotation[4] at 0.6 Vh	0.0050	0.0032	0.0003
48	Twin Engine to Autorotation[4] at 0.9 Vh	0.0050	0.0032	0.0001
49	Stabilized Autorotation[4] to Twin Engine	0.0100	0	0
50	Autorotation[4] at Vne and Minimum r.p.m.	0.0200	0	0
51	Autorotation[4] at Vne and Maximum r.p.m.	0.0200	0	0
52	Autorotation[4] Right Turn	0.0030	0.0349	0.0128
53	Autorotation[4] Left Turn	0.0030	0	0.0071
54	Unrecognized	0	0.0421	.2895[5]
		100.0000	100.0000	100.0000

Note:

1) Rotor starts and shutdowns are considered as events. Main Rotor Yoke is the only affected component out of the four selected components.
2) Ground time was added after spectrum analysis, therefore is excluded from the spectrum.
3) 0.4Vh data missing from gulf coast data.
4) Autorotation recorded when combined engine power is less than 10%
5) Unrecognized data reduced to 0.05% for component fatigue life calculations.

Table 2.4 Detail Flight Record Comparison

Pilot Record				HUMS Record				Difference		
Flight Start	GW LB	CG IN.	Time Min.	Flight Start	GW LB	CG IN.	Time Min.	GW LB	CG IN.	Time
07/19/96 05:41	9767	140.8	14	07/19/96 05:43	9725	141.0	14.2	0%	-0.2	-1%
07/19/96 06:32	9842	139.2	12	07/19/96 06:33	9663	142.1	11.9	2%	-2.9	1%
07/19/96 06:49	9337	139.4	16	07/19/96 06:50	9018	142.2	15.6	4%	-2.8	3%
07/19/96 07:20	9652	138.6	14	07/19/96 07:20	10357	133.1	13.6	-7%	5.5	3%
07/19/96 07:40	8947	139.9	7	07/19/96 07:40	9588	134.9	6.3	-7%	5.0	11%
07/19/96 09:31	10067	140.0	6	07/19/96 09:31	9805	142.7	6.1	3%	-2.7	-2%
07/19/96 09:42	10007	140.1	4	07/19/96 09:41	10263	135.8	4.5	-2%	4.3	-11%
07/19/96 09:52	9927	140.3	3	07/19/96 09:52	10569	136.6	3.4	-6%	3.7	-12%
07/19/96 10:03	9847	140.5	6	07/19/96 10:04	10324	138.6	5.7	-5%	1.9	5%
07/19/96 10:15	9717	140.9	17	07/19/96 10:15	9978	134.6	20.6	-3%	6.3	-17%
07/19/96 10:40	9542	139.6	13	07/19/96 10:41	9581	137.9	12.3	0%	1.7	6%
07/19/96 10:58	9382	139.0	8	07/19/96 10:58	9440	138.1	7.5	-1%	0.9	7%
07/19/96 11:14	9184	139.4	9							
07/19/96 11:25	9047	140.1	7							
07/20/96 08:00			25	07/20/96 07:58	10076	138.7	28.4			-12%
07/22/96 21:45	10190	140.5	4	07/22/96 21:47	10412	140.6	5.7	-2%	-0.1	-30%
07/22/96 22:00	10065	140.4	17	07/22/96 22:01	10334	140.7	17.6	-3%	-0.3	-3%
07/22/96 22:24	10078	139.5	9	07/22/96 22:26	9968	139.2	9.6	1%	0.3	-6%
07/22/96 22:42	9620	141.1	16	07/22/96 22:44	9945	140.4	11.9	-3%	0.7	34%
07/23/96 05:15	9941	140.5	6	07/23/96 05:15	9985	140.5	7.3	0%	0.0	-18%
07/23/96 05:38	10751	136.6	16	07/23/96 05:39	11679	131.1	16.6	-8%	5.5	-4%
07/23/96 06:15	9893	140.1	6	07/23/96 06:16	10124	143.2	6.0	-2%	-3.1	0%
07/23/96 06:26	9531	140.5	5	07/23/96 06:28	9943	139.5	5.5	-4%	1.0	-9%
07/23/96 06:40	9788	137.9	7	07/23/96 06:41	9309	140.1	7.9	5%	-2.2	-11%
07/23/96 06:52	9201	139.4	13	07/23/96 06:54	9736	140.1	12.6	-5%	-0.7	3%
07/23/96 07:08	11083	136.3	12	07/23/96 07:09	9309	135.7	11.9	19%	0.6	1%
07/23/96 07:45	8965	139.5	9	07/23/96 07:48	10980	138.5	8.5	-18%	1.0	6%
07/23/96 08:14	8781	139.6	6	07/23/96 08:15	9373	136.5	6.1	-6%	3.1	-2%
07/23/96 08:22			8	07/23/96 08:23	9571	138.0	6.5			23%
07/23/96 09:29	9961	140.4	5	07/23/96 09:30	9882	141.6	6.7	1%	-1.2	-25%
07/23/96 09:42	9871	140.7	7	07/23/96 09:44	10005	137.7	7.3	-1%	3.0	-4%
07/23/96 09:54	9731	141.0	7	07/23/96 09:56	9958	138.1	7.6	-2%	2.9	-8%
07/23/96 10:15	9541	140.6	19	07/23/96 10:16	10004	135.9	20.0	-5%	4.7	-5%
07/23/96 10:41	9430	139.1	12	07/23/96 10:43	9915	133.9	13.2	-5%	5.2	-9%
07/23/96 10:58	9270	139.0	6	07/23/96 10:59	8994	139.8	7.3	3%	-0.8	-18%
07/23/96 11:10	9150	139.6	10	07/23/96 11:12	9138	140.5	10.2	0%	-0.9	-2%
07/23/96 11:27	9030	139.5	5	07/23/96 11:29	9675	133.9	6.0	-7%	5.6	-17%
07/23/96 12:15	10360	132.6	5	Missing	Hums	Data				
07/23/96 12:27	10300	132.5	7	"	"	"				
07/23/96 12:47	10051	132.1	6	"	"	"				
07/23/96 13:00	9851	131.7	18	"	"	"				
07/23/96 13:26	9571	131.3	10	"	"	"				
07/23/96 13:43	9411	131.0	6	"	"	"				
07/23/96 13:55	9271	130.8	9	"	"	"				
07/23/96 14:12			9	"	"	"				
07/23/96 15:02	10411	139.1	6	"	"	"				
07/23/96 15:12	10271	138.6	5	"	"	"				

Table 2.4 Detail Flight Record Comparison

Pilot Record				HUMS Record				Difference		
Flight Start	GW LB	CG IN.	Time Min.	Flight Start	GW LB	CG IN.	Time Min.	GW LB	CG IN.	Time
07/23/96 15:24	10236	138.5	6	"	"	"				
07/23/96 15:37	10136	138.8	20	"	"	"				
07/23/96 16:03	9811	139.0	12	"	"	"				
07/23/96 16:21	9641	138.4	7	"	"	"				
07/23/96 16:33	9551	138.0	10	"	"	"				
07/23/96 16:47	9381	137.8	10	"	"	"				
07/23/96 17:04	9271	138.4	9	"	"	"				
07/23/96 17:45	10461	138.8	5	"	"	"				
07/23/96 17:57	10416	138.9	6	"	"	"				
07/23/96 18:09	10306	138.4	4	"	"	"				
07/23/96 18:22	10166	138.7	20	"	"	"				
07/23/96 18:48	9771	139.1	11	"	"	"				
07/23/96 19:05	9621	138.1	6	"	"	"				
07/23/96 19:18	9511	138.2	10	"	"	"				
07/23/96 19:32	9361	137.8	9	"	"	"				
07/23/96 19:49	9241	138.4	3	"	"	"				
07/23/96 21:45	10321	139.0	5	"	"	"				
07/23/96 22:00	10221	138.6	15	"	"	"				
07/23/96 22:24	10093	139.0	9	"	"	"				
07/23/96 22:42	9851	139.5	13	Missing	Hums	Data				
07/24/96 05:55	10111	140.8	12	07/24/96 05:57	9837	141.2	12.5	3%	-0.4	-4%
07/24/96 06:26	10262	138.8	12	07/24/96 06:28	10291	137.3	12.8	0%	1.5	-6%
07/24/96 06:42	9691	141.3	15	07/24/96 06:44	10090	136.0	14.4	-4%	5.3	4%
07/24/96 07:10	9901	138.4	18	07/24/96 07:11	9662	135.5	18.4	2%	2.9	-2%
07/24/96 07:38	9221	139.8	5	07/24/96 07:40	9144	133.5	4.9	1%	6.3	2%
07/24/96 09:30	10081	140.7	5	07/24/96 09:30	9983	139.3	6.9	1%	1.4	-28%
07/24/96 09:42	9961	140.6	4	07/24/96 09:44	10202	136.2	4.5	-2%	4.4	-11%
07/24/96 09:53	9901	140.8	2	07/24/96 09:55	10393	139.9	2.6	-5%	0.9	-23%
07/24/96 10:02	9831	141.0	6	07/24/96 10:04	10117	136.7	6.5	-3%	4.3	-8%
07/24/96 10:15	9701	141.3	19	07/24/96 10:17	9592	139.5	18.9	1%	1.8	1%
07/24/96 10:41	9549	140.2	10	07/24/96 10:43	10018	133.4	11.5	-5%	6.8	-13%
07/24/96 10:58	9375	139.6	6	07/24/96 11:00	9237	136.7	7.2	1%	2.9	-17%
07/24/96 11:10	9255	139.2	10	07/24/96 11:11	9147	135.8	10.1	1%	3.4	-1%
07/24/96 11:27	9135	139.8	4	07/24/96 11:28	9840	132.7	5.0	-7%	7.1	-20%
07/24/96 12:15	9945	140.7	5	Missing	Hums	Data				
07/24/96 12:27	9825	141.0	3	"	"	"				
07/24/96 12:37	9745	140.9	3	"	"	"				
07/24/96 12:47	9636	140.6	6	"	"	"				
07/24/96 13:00	9467	140.4	19	"	"	"				
07/24/96 13:26	9151	139.5	10	"	"	"				
07/24/96 13:43	9011	140.6	7	"	"	"				
07/24/96 13:55	8881	140.5	9	"	"	"				
07/24/96 14:12	8741	139.9	4	"	"	"				
07/24/96 15:00	10216	138.8	6	"	"	"				
07/24/96 15:12	10146	139.0	4	"	"	"				
07/24/96 15:24	10046	139.3	5	"	"	"				
07/24/96 15:37	9866	139.7	19	"	"	"				
07/24/96 16:03	9586	138.8	11	"	"	"				

Table 2.4 Detail Flight Record Comparison

Pilot Record				HUMS Record				Difference		
Flight Start	GW LB	CG IN.	Time Min.	Flight Start	GW LB	CG IN.	Time Min.	GW LB	CG IN.	Time
07/24/96 16:20	9436	138.2	7	"	"	"				
07/24/96 16:29	9316	138.1	11	"	"	"				
07/24/96 16:47	9206	138.7	10	"	"	"				
07/24/96 17:04	9056	138.6	9	"	"	"				
07/24/96 17:45	10326	139.0	5	"	"	"				
07/24/96 17:57	10236	138.8	5	"	"	"				
07/24/96 18:09	10126	139.0	6	"	"	"				
07/24/96 18:22	9966	139.4	19	"	"	"				
07/24/96 18:48	9706	139.2	11	"	"	"				
07/24/96 19:05	9546	138.6	7	"	"	"				
07/24/96 19:14	9446	138.2	11	"	"	"				
07/24/96 19:32	9296	138.2	9	"	"	"				
07/24/96 19:49	9166	138.9	5	"	"	"				
07/24/96 20:35	10286	139.2	5	"	"	"				
07/24/96 20:47	10166	138.9	5	"	"	"				
07/24/96 21:08	10026	139.3	6	"	"	"				
07/24/96 21:22	9916	139.5	19	"	"	"				
07/24/96 21:47	9636	139.0	11	"	"	"				
07/24/96 22:29	9436	138.2	11	Missing	Hums	Data				
07/25/96 05:55	10111	140.8	13	07/25/96 05:57	10049	140.0	14.5	1%	0.8	-10%
07/25/96 06:22	10280	140.4	15	07/25/96 06:26	10448	134.9	13.9	-2%	5.5	8%
07/25/96 06:42	9651	141.4	15	07/25/96 06:44	9979	137.5	15.2	-3%	3.9	-1%
07/25/96 07:10	10131	141.9	16	07/25/96 07:12	10053	139.8	16.5	1%	2.1	-3%
07/25/96 07:38	9161	139.8	4	07/25/96 07:39	9572	134.7	5.3	-4%	5.1	-25%
07/25/96 09:30	9911	140.7	5	07/25/96 09:31	10163	135.9	6.6	-2%	4.8	-24%
07/25/96 09:45	9711	141.3	3	07/25/96 09:47	10096	137.3	4.1	-4%	4.0	-27%
07/25/96 09:56	9611	141.2	2	07/25/96 09:58	9784	139.3	3.3	-2%	1.9	-39%
07/25/96 10:05	9521	140.9	7	07/25/96 10:05	10019	135.9	8.2	-5%	5.0	-15%
07/25/96 20:35	10266	139.1	5	07/25/96 20:36	10119	140.5	5.9	1%	-1.4	-15%
07/25/96 20:47	10156	138.9	13	07/25/96 20:49	10825	133.9	12.1	-6%	5.0	7%
07/25/96 21:22	9836	139.7	19	07/25/96 21:24	10161	135.8	18.8	-3%	3.9	1%
07/25/96 21:46	9636	139.0	22	07/25/96 21:48	9630	137.0	21.8	0%	2.0	1%
07/26/96 20:35	10286	139.2	5	07/26/96 20:38	10632	133.2	5.1	-3%	6.0	-2%
07/26/96 20:47	10186	138.9	5	07/26/96 20:49	10103	136.9	4.7	1%	2.0	6%
07/26/96 21:08	10086	139.1	6	07/26/96 21:10	10164	137.5	5.7	-1%	1.6	5%
07/26/96 21:22	9936	139.5	19	07/26/96 21:24	9700	139.6	18.6	2%	-0.1	2%
07/26/96 21:47	9686	139.2	10	07/26/96 21:49	9529	138.4	10.1	2%	0.8	-1%
07/26/96 21:58	9566	138.7	14	07/26/96 22:01	9710	134.5	13.1	-1%	4.2	7%
07/27/96 05:10	10031	140.5	5	07/27/96 05:09	10074	137.9	6.9	0%	2.6	-28%
07/27/96 05:33	10738	136.6	17	07/27/96 05:35	10259	133.6	17.3	5%	3.0	-2%
07/27/96 06:51	9671	141.4	16	07/27/96 06:54	9676	135.3	16.1	0%	6.1	-1%
07/27/96 12:51	10106	139.1	22	07/27/96 12:54	9721	139.7	22.1	4%	-0.6	0%
07/27/96 13:26	9816	139.7	10	07/27/96 13:29	9691	134.4	8.5	1%	5.3	18%
07/30/96 05:15	10240	140.2	4	07/30/96 05:16	9781	140.1	4.9	5%	0.1	-18%
07/30/96 05:38	10583	138.8	18	07/30/96 05:41	10744	137.0	16.8	-2%	1.8	7%
07/30/96 06:22	10092	139.0	5	07/30/96 06:24	10901	133.3	4.4	-7%	5.7	14%
07/30/96 06:29	9892	140.3	6	07/30/96 06:31	10752	133.6	5.8	-8%	6.7	3%
07/30/96 08:19	9845	140.2	6	07/30/96 08:22	10307	133.1	6.1	-4%	7.1	-2%

Table 2.4 Detail Flight Record Comparison

Pilot Record				HUMS Record				Difference		
Flight Start	GW LB	CG IN.	Time Min.	Flight Start	GW LB	CG IN.	Time Min.	GW LB	CG IN.	Time
07/30/96 08:26	9600	140.1	7	07/30/96 08:29	10524	134.0	6.3	-9%	6.1	11%
07/30/96 21:45	10156	140.4	6	07/30/96 21:46	10068	139.3	8.9	1%	1.1	-33%
07/30/96 22:00	10146	139.9	14	07/30/96 22:02	10219	137.0	14.9	-1%	2.9	-6%
07/30/96 22:24	10200	139.9	8	07/30/96 22:26	10441	136.3	9.4	-2%	3.6	-15%
07/30/96 22:42	9676	140.9	14	07/30/96 22:44	9721	138.7	11.6	0%	2.2	21%
07/31/96 05:55	11206	140.9	13	07/31/96 05:57	9796	140.9	14.3	14%	0.0	-9%
07/31/96 06:20	9956	140.3	17	07/31/96 06:24	11124	131.6	14.3	-10%	8.7	19%
07/31/96 06:42	9816	140.7	17	07/31/96 06:44	10239	136.3	17.5	-4%	4.4	-3%
07/31/96 07:10	10786	138.2	16	07/31/96 07:12	11417	133.9	15.8	-6%	4.3	1%
07/31/96 07:38	9336	139.2	3	07/31/96 07:40	9780	135.1	5.8	-5%	4.1	-48%
07/31/96 21:43	10161	140.3	5	07/31/96 21:43	10120	135.9	6.6	0%	4.4	-24%
07/31/96 22:00	10141	139.8	14	07/31/96 22:02	10509	134.1	14.4	-4%	5.7	-3%
07/31/96 22:24	9931	140.4	8	07/31/96 22:26	10118	136.5	10.8	-2%	3.9	-26%
07/31/96 22:38	9661	140.7	14	07/31/96 22:41	10378	135.0	12.9	-7%	5.7	9%
08/01/96 06:02	11900	140.1	14	08/01/96 05:49	10379	136.5	15.4	15%	3.6	-9%
08/01/96 06:20	11900	139.0	18	08/01/96 06:23	10709	135.0	17.7	11%	4.0	2%
08/01/96 06:42	11900	140.6	27	08/01/96 06:44	10670	135.1	25.9	12%	5.5	4%

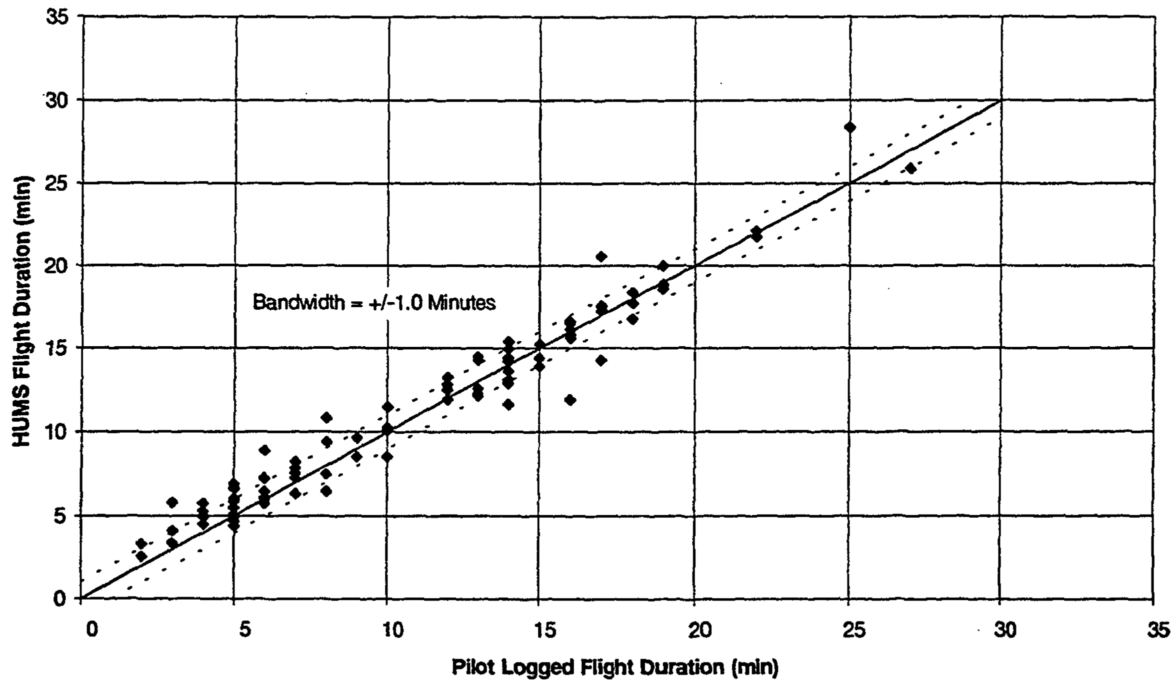

Figure 2.2 Flight Duration Correlation

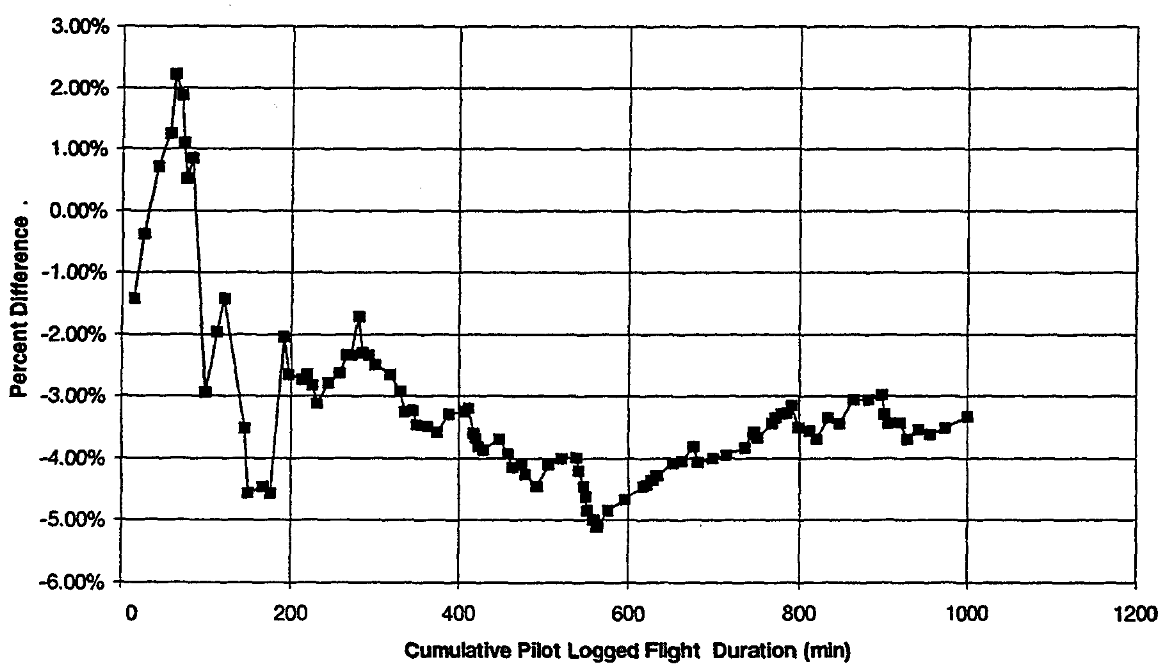

Figure 2.3 Cumulative Flight Duration

3. Selected Components

This section discusses the four PSE's that were selected for analysis. The PSE's selected comprise the following components:

1. Rephase lever (Figure 3.1)
2. Collective Lever (Figure 3.2)
3. Main Rotor Spindle (Figure 3.3)
4. Main Rotor Yoke (Figure 3.4)

The part service history of the PSE's is presented in support of the assumptions made for the initial flaw sizes used for the damage tolerance analysis and includes the service history, e.g., failures, redesigns, configuration changes, process changes, Advisory Service Bulletins (ASB's), Airworthiness Directives (AD's), reports and other design and manufacturing actions.

As part of this study, the documented service history of the four PSE's was reviewed for premature component removal. The source of the data for this study was either the customer Discrepancy and Malfunction Report (DMR) or documentation of service returned components using BHTI Field Investigation Reports for all design derivatives. In the case of DMR's, BHTI maintains a computer database that summarizes the information from the written document. A total of 877 DMR's were reviewed by this method beginning with the introduction of the Model 412 helicopter in 1981. A request was forwarded to the Field Investigation Laboratory to provide reports on any of the four study components that had been evaluated during the same period.

Table 3.1 is a summary of the findings of this inquiry. The reasons for component removal are divided into broad categories for the purposes of this study. Generally, an attempt has been made to separate and note categories involving physical discrepancies/damage to the component whether manufacturing induced or service induced. Although it was hoped that descriptive information concerning the discrepancies/damage could be gathered, in the vast majority of cases it simply was not noted on the DMR's. This suggests an improvement to the DMR reporting system might be in order. Most of the descriptions were general and not informative from a technical perspective. A sketch or drawing of the component with documented discrepancies is needed as part of the DMR reporting procedure to accurately classify the component anomalies.

The total number of DMR's reviewed may not represent all components that were removed prematurely, although all component and component design derivatives are included in this study. Generally, a DMR is written by the customer as a means of obtaining warranty credit towards a replacement part. In the case of the yoke, a large number of components were removed in response to a manufacture's bulletin or an FAA Airworthiness Directive or both. In the case of the spindle, a large number of the parts in the "other" category were removed due to premature deterioration of the elastomeric feathering bearing or replacement with an improved part.

Table 3.1 Part Service History

Topic		Rephase Lever	Collective Lever	M/R Spindle	M/R Yoke
	Removal Hours	0	0-6424	0-3159	0-4980
	Manufacturing Problem	4	5	1	6
	Metal Fatigue				2
	Bulletin or AD	11			204
Mechanical Damage	Scratches				1
	Wear		7	1	1
	Corrosion			51	
	Other	0	1	582	0
	Total Parts	15	13	635	214
CR&O Limit - Inches	Scratches	0.005	0.010	0.005 to 0.010	0.005 to 0.010
	Wear	.002	-	-	0.002
	Corrosion	0.0025	0.005	0.005 to 0.010	0.005 to 0.010

The rephase lever is manufactured from a 7075-T73 aluminum forging, Figure 3.1. The rephase lever pivots on a rotating hub and provides a reindexing of pitch link to the swashplate by offsetting the attach points. Swashplate motion is imparted to the rephase lever via a tubular link or a drive link. This motion is then transferred to the rotor by the pitch link with the rephase lever as the intermediate mechanism. The majority of the DMR's for the rephase lever resulted from bulletins, which provided an improved version of the design.

The collective lever is manufactured from a 7075-T73 aluminum forging, Figure 3.2. The collective boost actuator attaches at the apex of the lever. The lever pivots about an axis common to a lug situated on the swashplate support. The ends of the legs attach to the collective sleeve to impart mean blade angle changes. The majority of the DMR's for the collective lever involved joint wear as the cause of replacement. Parts returned to manufacturer that would not install correctly due to accumulation of adverse tolerances are included in the table. No corrosion reports were received.

The original spindle design (Figure 3.3) was manufactured from SAE 4340 alloy steel and was protected from corrosion by an applied surface finish. The elastomeric feathering bearing was mechanically attached to the spindle by means of a bonded inner race. The pitch horn is splined to the end of the spindle. The spindle exhibited corrosion in the pitch horn attachment area as a result of the corrosion protection wearing away. Four of the 51 DMR's reported corrosion on the order of 0.1 mm (0.0039 inch) in the pitch horn attachment area of the spindle where no corrosion was allowed per the Component Repair and Overhaul Manual (CR&O). Mechanical or corrosion damage of 0.005 inch is allowed around the blade attachment lugs while 0.010 inch mechanical or corrosion damage is allowed elsewhere. The majority of the 582 DMR's in the "other" category resulted from a gradual deterioration of the elastomeric feathering bearing that was detected either visually or as a change in rotor vibration characteristics. Later designs of the spindle were made from 15-5PH stainless steel to eliminate the corrosion problem. The elastomeric feathering bearing is molded directly to the spindle surface allowing the elastomeric element to be increased in size to reduce strains.

In the case of the main rotor yoke (Figure 3.4), the original design was initially certificated with a 5000 hour life. In two separate incidents, the yoke sustained a partial flexure fatigue crack (non-catastrophic) after ground static compressive overloads due to high surface winds. The high loads compressively yielded the shotpeened surface of the 6AL-4V annealed titanium flexure, nullifying the benefits of the peening. A 700 hour service life was established for these early yokes by manufacturer's bulletin and FAA AD. The yoke was redesigned to solve this problem. The yoke flexure was lengthened, the material changed to 6AL-4V BSTOA and a dynamically activated droop stop incorporated to protect the yoke flexure against high beamwise loads due to natural winds or winds generated by other helicopters operating nearby when the rotor was not operating.

In summary, this study of the 877 DMR exhibits of the four subject components revealed several interesting facts. In the 15 years since the Model 412 was fielded, not one accident has been caused by fatigue. The maintenance surveillance currently in place can detect potential problems such as wear, corrosion, etc., before they become serious. The damage limits published in the CR&O manual are realistic with respect to damage tolerance or crack growth thresholds. This data supports the 0.005 inch flaw size used in the crack growth study presented in this report, particularly as it applies to corrosion damage.

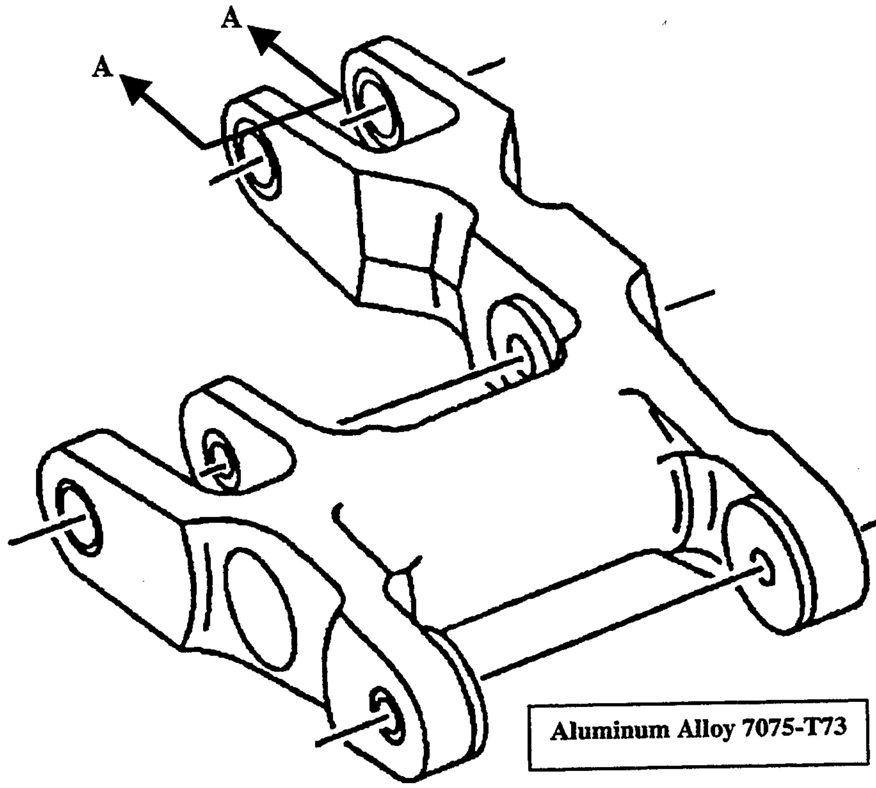

Figure 3.1 Rephase Lever Geometry

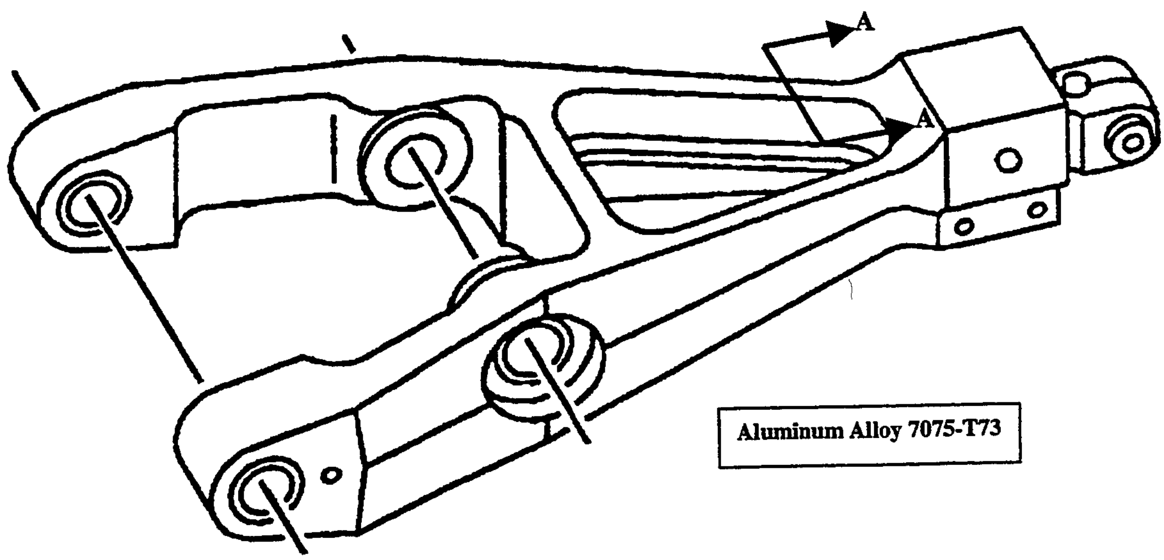

Figure 3.2 Collective Lever Geometry

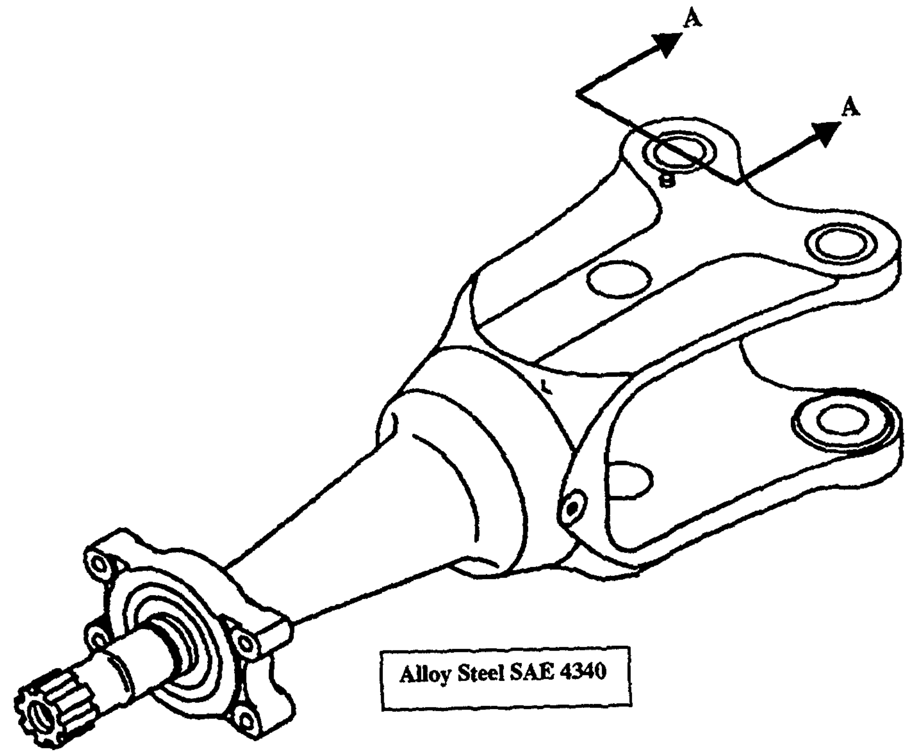

Figure 3.3 Main Rotor Spindle Geometry

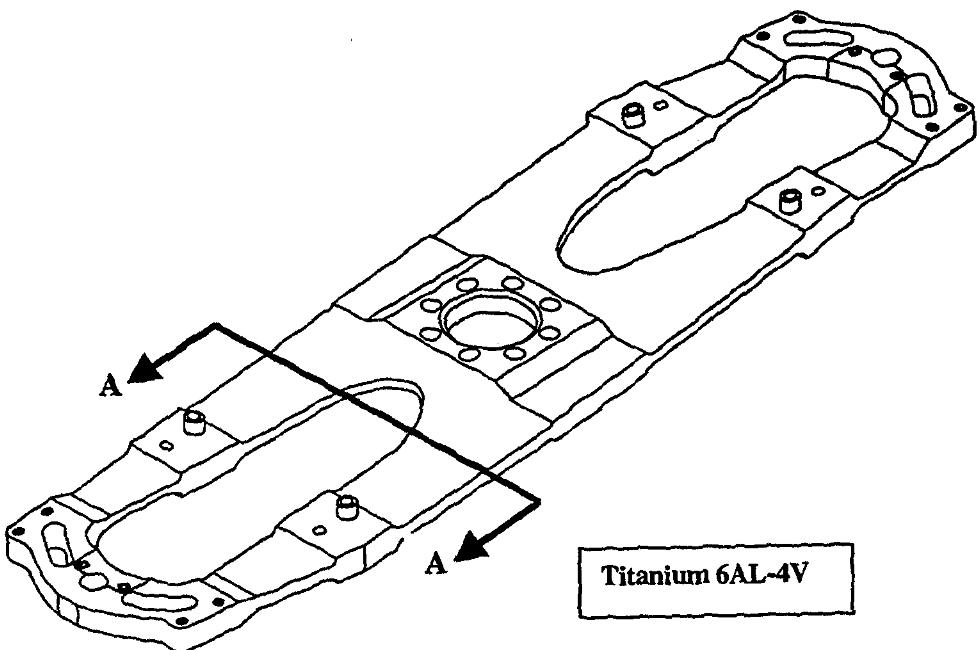

Figure 3.4 Main Rotor Yoke Geometry

4. Fatigue Life Analysis

4.1 Analysis Procedure

The fatigue analysis procedure of the ASHM data was performed on a basis that is consistent with the certification of the selected PSE's. Figure 4.1 shows a simplified overview of this procedure. The methodology remains unchanged from that used in the certification process. The only variation in assumptions from the certification procedure is the use of measured time-at-condition in place of the estimated time-at-condition. In addition to the certification procedure, component lives were calculated that include altitude effects.

1. Time-at-condition is determined from analysis of the measured flight parameters using flight condition recognition (FCR) software (see Reference 1 for FCR description).
2. The loads for each condition are taken from the FAA certification load survey. No additional loads are used in the HUMS data processing.
3. Component damage is calculated by combining the loads with the time-at-condition using FAA certification endurance limits.

The certification methodology uses an assumed worst case spectrum of time-at-condition to determine the life of helicopter components. When the FCR software processes recorded data, there is a small percentage of flight time that is not within the parameter set associated with any of the defined conditions. This time is considered to be unrecognized and is assigned the most damaging condition within the domain in which the event occurred.

The FCR software used in Reference 1 to process the GCM data was enhanced to reduce the time in unrecognized flight conditions. It was observed that the percentage of unrecognized condition reduced significantly when the ASHM data was processed though the revised FCR software. Reprocessing of the 450 hours of the GCM data was beyond the scope of the current effort, so the assumption was made that the software enhancements incorporated would have reduced the percentage of unrecognized maneuvers to an amount similar to that seen for the ASHM. Therefore, the percentage of unrecognized condition was reduced for the GCM to approximately the level seen in the ASHM data by redistributing the excess unrecognized time in the proportion of the recorded spectrum, and the lives were recomputed on that basis. The contribution of unrecognized conditions to total damage is indicated in Table 4.1 through Table 4.4 as Unrecognized Damage percentage (URD %).

4.2 Life Limitations

As shown in Figure 4.2, a potential benefit from usage monitoring is part retirement extension if the actual usage severity is milder than the basis for certification. However recommended retirement lives derived for HUMS-equipped aircraft may be subject to limiting factors other than fatigue calculations. For example, maximum lives or minimum usage rates may be restricted due to reasons of practicality, including, but not limited to, corrosion, wear and component sensitivity to load variation.

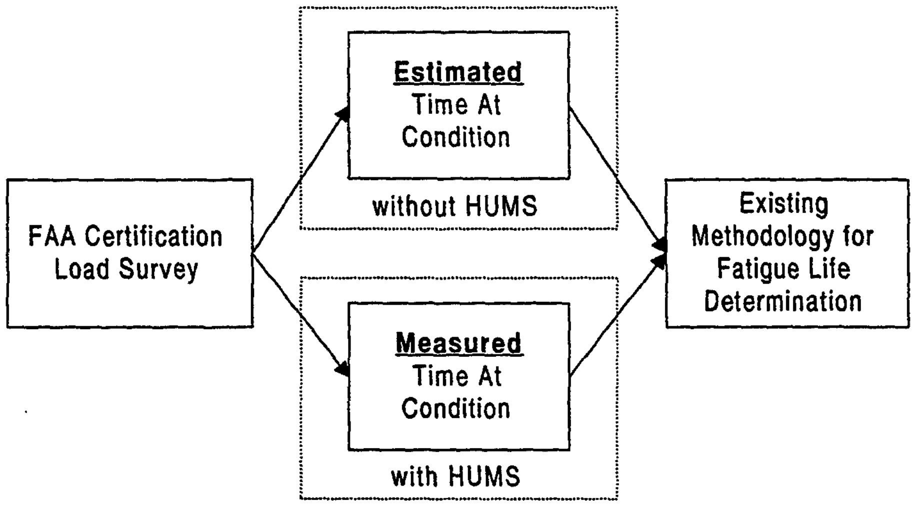

Figure 4.1 Certification and HUMS Methodologies

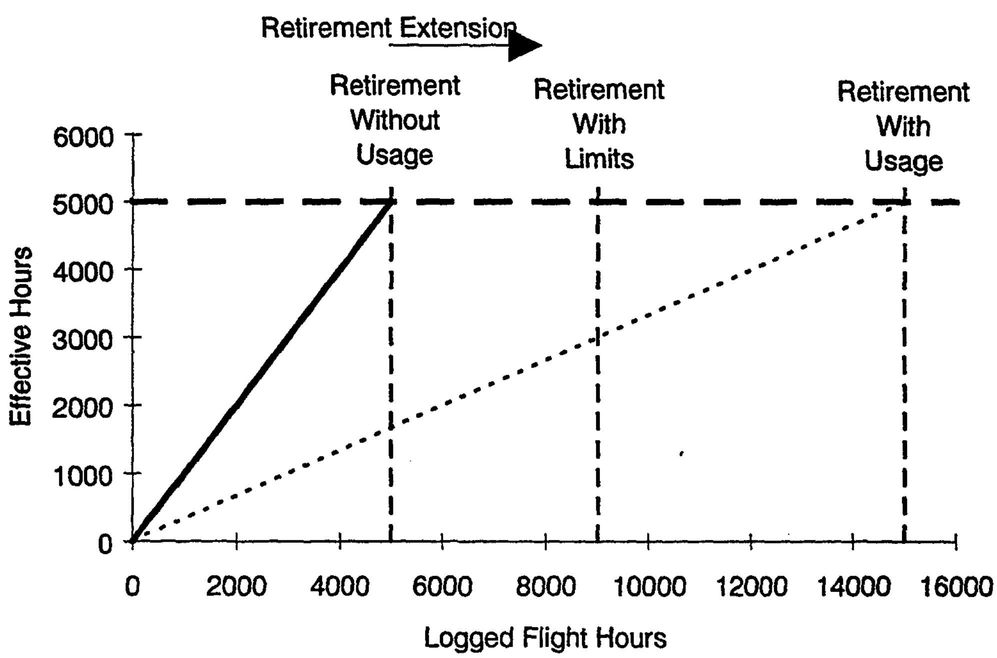

Figure 4.2 HUMS Usage

4.3 Rephase Lever Study

The Rephase Lever was analyzed for safe life in two configurations. The earlier configuration was certificated with a retirement life of 1,250 hours and employed cycle counting[1] in the analysis of transitory maneuvers to achieve this life. The replacement part was a design improvement over the earlier version and had a life goal of 5,000 hours. This goal was achieved, and the part certified, without resorting to cycle counting and is thus very conservative. When the redesigned part was analyzed using the ASHM spectrum for this study, the calculated life was 920 hours using the most conservative approach without the benefit of cycle counting. If cycle counting were to be used for the transient maneuvers (as were done for certification of the earlier configuration), the calculated life would increase to 18,430 hours with the ASHM spectrum and to 78,000 hours using the certification spectrum. In summary, the calculated safe lives for the two configurations are as follows:

Earlier configuration
Calculation Basis: Cycle counted transient conditions

- Certification spectrum 1,250 hours
- ASHM spectrum 1,380 hours

Redesigned configuration
Calculation Basis: No cycle counting

- Certification spectrum 5,000 hours
- ASHM spectrum 920 hours

Redesigned configuration
Calculation Basis: Cycle counted transient conditions (as Earlier configuration)

- Certification spectrum 78,000 hours
- ASHM spectrum 18,430 hours

[1] The process of cycle counting calculates the damage due to each recorded cycle within a record. The damage rate is then calculated from the sum of the individual cycle damages and the record duration, this is only used for transitory maneuvers. Analysis without cycle counting is a more conservative approach where the entire record is examined and the most damaging cycle is assumed to occur at each and every cycle of that record. Steady state conditions are rarely, if ever, cycle counted.

4.4 Analysis Results

Analysis results comparing fatigue safe lives for ASHM, GCM and certification data are summarized in Figure 4.3 through Figure 4.6 and in Table 4.1 through Table 4.4. The rate at which life is being consumed relative to certification is referred to as the component "Clock Rate." If usage indicates that the part is using life faster than certification, i.e. has a reduced life, then the part is said to have a "fast clock." The component safe lives were calculated without regard to altitude for direct comparison to the certification data. Certification does not employ an altitude breakdown because the operating altitude is unknown. Components are certificated using the most severe altitude within any condition. However, in this study, pressure altitude (H_p) and Outside Air Temperature (OAT) are recorded by the HUMS system allowing for the calculation of Density Altitude (H_d), which is required to take credit for altitude. Load level survey data, used as the basis for all life calculations, does not contain all data at all altitudes. For each condition, the survey contains records at 3000 ft and records at 6000 ft and/or 12000 ft for each of the Gross Weight, CG combinations flown. Therefore safe lives were also calculated using a split between high (>3000 ft H_d) and low ($\leq$3000 ft H_d) altitude data to ensure multiple records from which to select the most severe condition. This approach deviates from results previously published for the GCM data (Reference 1) which employed a full altitude breakdown. Calculations performed without an altitude split compare directly with certification data. Comparison of spectra with and without an altitude split indicate additional potential benefits due to HUMS.

The results of the comparison of the ASHM and GCM fatigue lives to the certification mission are as follows:

- Rephase Lever - With no altitude split, GCM calculated lives are higher and ASHM lower than the certification, but with altitude split, both are much higher. (Note that two configurations were analyzed, see Section 4.3.)

- Collective Lever - With no altitude split, both GCM and ASHM lives were about 40% greater than certification and much higher with altitude split.

- Main Rotor Spindle - With no altitude split, GCM is higher, and ASHM is lower, than certification and both are higher with altitude split.

- Main Rotor Yoke - With no altitude split, the GCM is higher, and the ASHM lower, than certification. With altitude split, the GCM is higher and the ASHM about the same as certification.

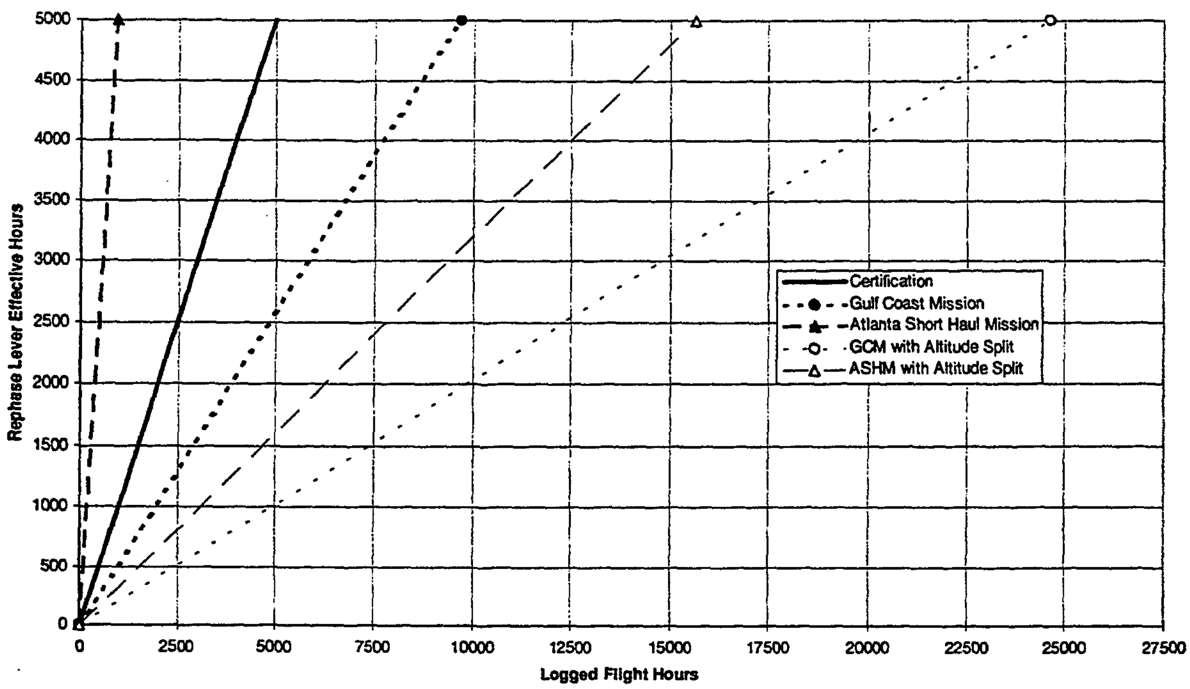

Figure 4.3 Effective Usage Rephase Lever

Table 4.1 Rephase Lever Calculated Fatigue Life

		Calc Hours	% of Cert	Clock Rate[1,2]	URD[3] %
No Altitude Split	Certification Mission	5,000	100%	100%	0%
	Gulf Coast Mission	9,710	194%	51%	8%
	Atlanta Short Haul Mission	920	18%	543%	1%
Low/High Altitude	Gulf Coast Mission	24,610	492%	20%	8%
	Atlanta Short Haul Mission	15,620	312%	32%	1%

Notes:

1) Clock Rate - the rate of life consumption relative to certification.
2) Limitations (see Section 4.2) may apply that restrict usage clock rate.
3) URD % - Damage contribution from Unrecognized conditions

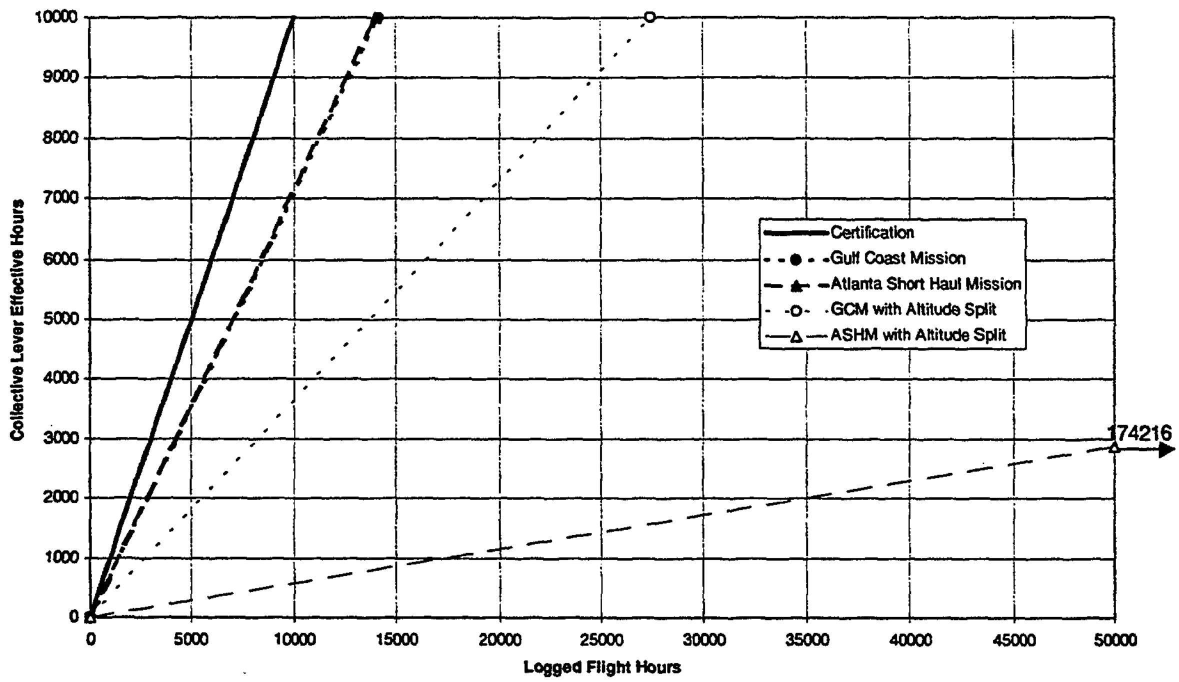

Figure 4.4 Effective Usage Collective Lever

Table 4.2 Collective Lever Calculated Fatigue Life

		Calc Hours	% of Cert	Clock Rate[1,2]	URD[3] %
No Altitude Split	Certification Mission	10,000	100%	100%	0%
	Gulf Coast Mission	14,160	142%	71%	7%
	Atlanta Short Haul Mission	14,010	140%	71%	5%
Low/High Altitude	Gulf Coast Mission	27,410	274%	36%	6%
	Atlanta Short Haul Mission	174,220	1742%	6%	8%

Notes:

1) Clock Rate - the rate of life consumption relative to certification.
2) Limitations (see Section 4.2) may apply that restrict usage clock rate.
3) URD % - Damage contribution from Unrecognized conditions

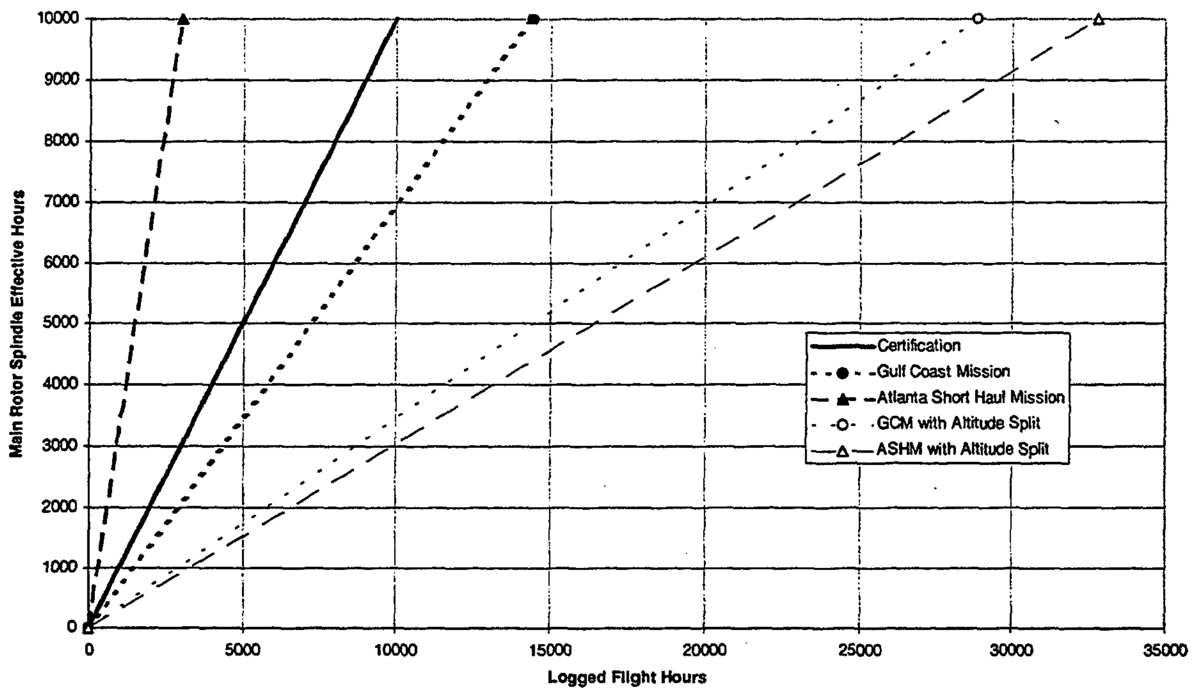

Figure 4.5 Effective Usage Main Rotor Spindle

Table 4.3 Main Rotor Spindle Calculated Fatigue Life

		Calc Hours	% of Cert	Clock Rate[1,2]	URD[3] %
No Altitude Split	Certification Mission	10,000	100%	100%	0%
	Gulf Coast Mission	14,440	144%	69%	11%
	Atlanta Short Haul Mission	3,030	30%	330%	2%
Low/High Altitude	Gulf Coast Mission	28,840	288%	35%	18%
	Atlanta Short Haul Mission	32,810	328%	30%	16%

Notes:

1) Clock Rate - the rate of life consumption relative to certification.
2) Limitations (see Section 4.2) may apply that restrict usage clock rate.
3) URD % - Damage contribution from Unrecognized conditions

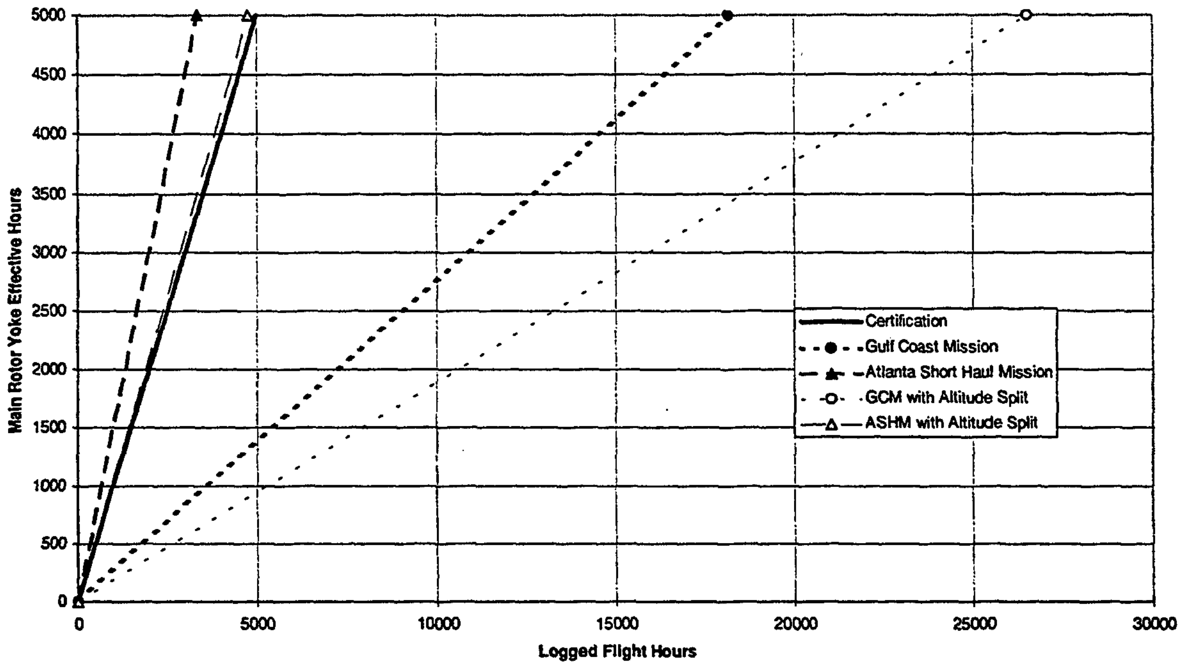

Figure 4.6 Effective Usage Main Rotor Yoke

Table 4.4 Main Rotor Yoke Calculated Fatigue Life

		Calc Hours	% of Cert	Clock Rate[1,2]	URD[3] %
No Altitude Split	Certification Mission	5,000	100%	100%	0%
	Gulf Coast Mission	18,170	363%	28%	11%
	Atlanta Short Haul Mission	3,360	67%	149%	2%
Low/High Altitude	Gulf Coast Mission	26,510	530%	19%	10%
	Atlanta Short Haul Mission	4,760	95%	105%	3%

Notes:

1) Clock Rate - the rate of life consumption relative to certification.
2) Limitations (see Section 4.2) may apply that restrict usage clock rate.
3) URD % - Damage contribution from Unrecognized conditions

5. Damage Tolerance Analysis

The critical locations and critical flaw sizes were established for each of the PSE's, as well as the maximum probable initial flaw size. The service history of the PSE's is provided in Section 3 of this report.

This is only a preliminary analysis to determine relative crack growth rate for three different spectra. The analysis was performed for the time-at-condition spectra from the Certification Spectrum and spectra generated from the HUMS data collected during the Gulf Coast Mission and Atlanta Short Haul Mission. Analysis was generated for initial flaw sizes (I_o) of 0.005 inch representing a manufacturing durability limit and 0.015 inch to represent an in-service detectable flaw.

The individual part fatigue test reports were used to determine the critical locations for the crack growth analysis. Analysis was performed at the failure location as indicated by test results.

The certification load/stress spectrum and crack growth based analysis methods, CRKGRO (Reference 2) were used to calculate the inspection threshold and the subsequent inspection intervals.

5.1 Rephase Lever

Material: Aluminum Alloy 7075-T73

Figure 5.1 presents the Rephase Lever section; the geometry was described in Figure 3.1. Crack growth analysis was performed for the Rephasing Lever at Lug 2, section A-A.

Loads normal to the lug were not considered in this analysis, therefore a damage tolerance life only applies to the loads in the plane of the lug. Mean and oscillatory Pitch Link loads were used to generate the loading spectra for the crack growth analysis.

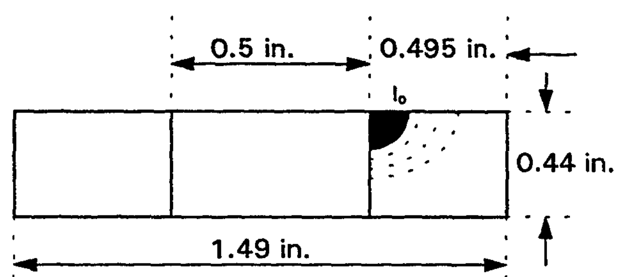

Figure 5.1 Rephase Lever Section at Section A-A

5.2 Collective Lever

Material: Aluminum Alloy 7075-T73

Detail of the analyzed section is presented in Figure 5.2. The Collective Lever part geometry is presented in Figure 3.2.

Crack growth analysis was performed at section A-A of Figure 3.2. The Collective Boost Tube mean and oscillatory load spectrum was used to derive the crack growth spectra.

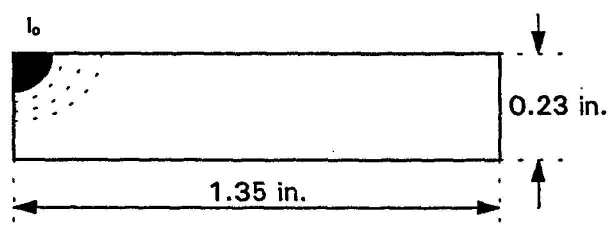

Figure 5.2 Collective Lever Section A-A

5.3 Main Rotor Spindle

Material: SAE 4340 Alloy Steel

Main Rotor Spindle section, geometry and part detail are presented in Figure 5.3.

Crack growth analysis was performed for the Main Rotor Spindle at the blade attachment lug (Sta 32.0) section A-A of Figure 3.3. Blade beam and chord mean and oscillatory bending moments were the reference loads used to generate the crack growth spectra.

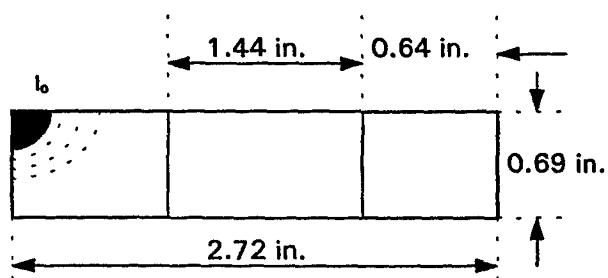

Figure 5.3 Main Rotor Spindle Section A-A

5.4 Main Rotor Yoke

Material: Titanium 6AL-4V

The analyzed section is presented in Figure 5.4 and the Main Rotor Yoke geometry is presented in Figure 3.4.

Crack growth analysis was performed at blade station 4.8, section A-A.

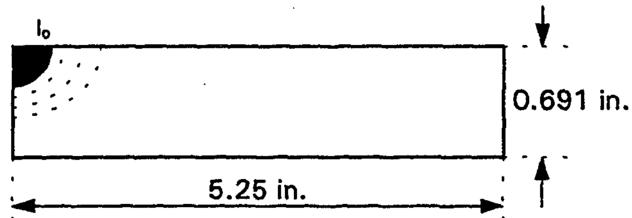

Figure 5.4 Main Rotor Yoke Section A-A

Table 5.1 Flight Hours to Critical Crack Length - 0.005 inch Initial Crack

	Certification Mission	Gulf Coast Mission	Atlanta Short Haul Mission
Rephase Lever	No Growth	No Growth	No Growth
Collective Lever	192	271	554
Main Rotor Spindle	No Growth	No Growth	No Growth
Main Rotor Yoke	160	7,790	2,910

Table 5.2 Flight Hours to Critical Crack Length - 0.015 inch Initial Crack

	Certification Mission	Gulf Coast Mission	Atlanta Short Haul Mission
Rephase Lever	78	259	154
Collective Lever	13	16	31
Main Rotor Spindle	143	104	2,557
Main Rotor Yoke	20	50	70

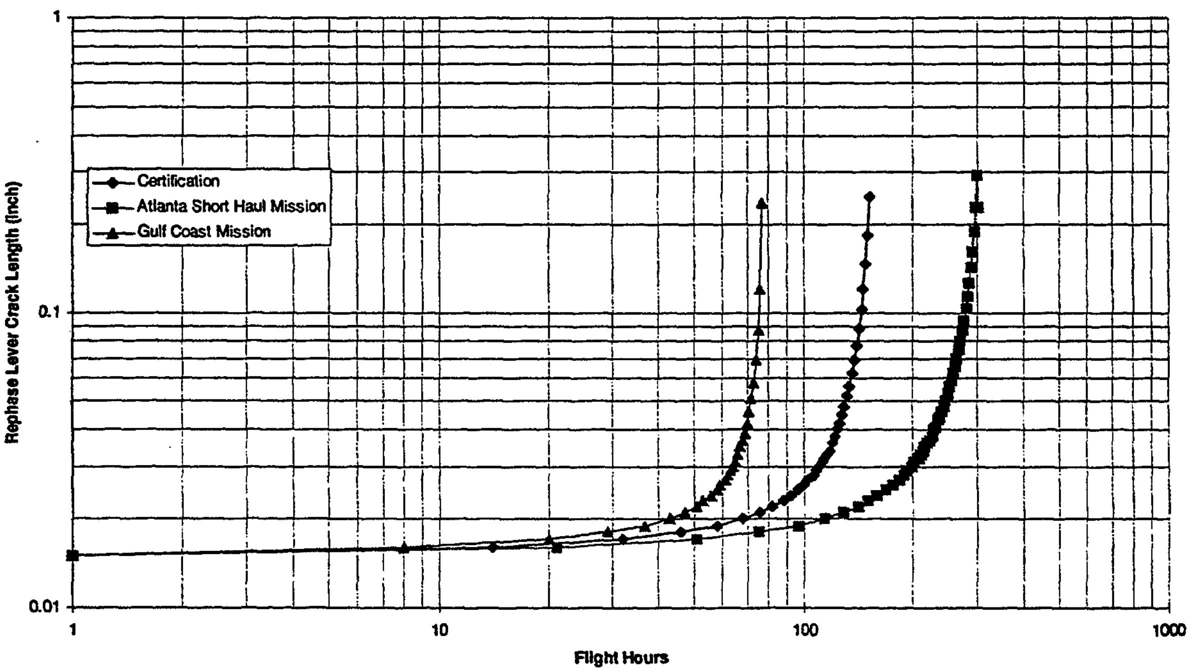

Figure 5.5 Rephase Lever - 0.015 inch Initial Crack

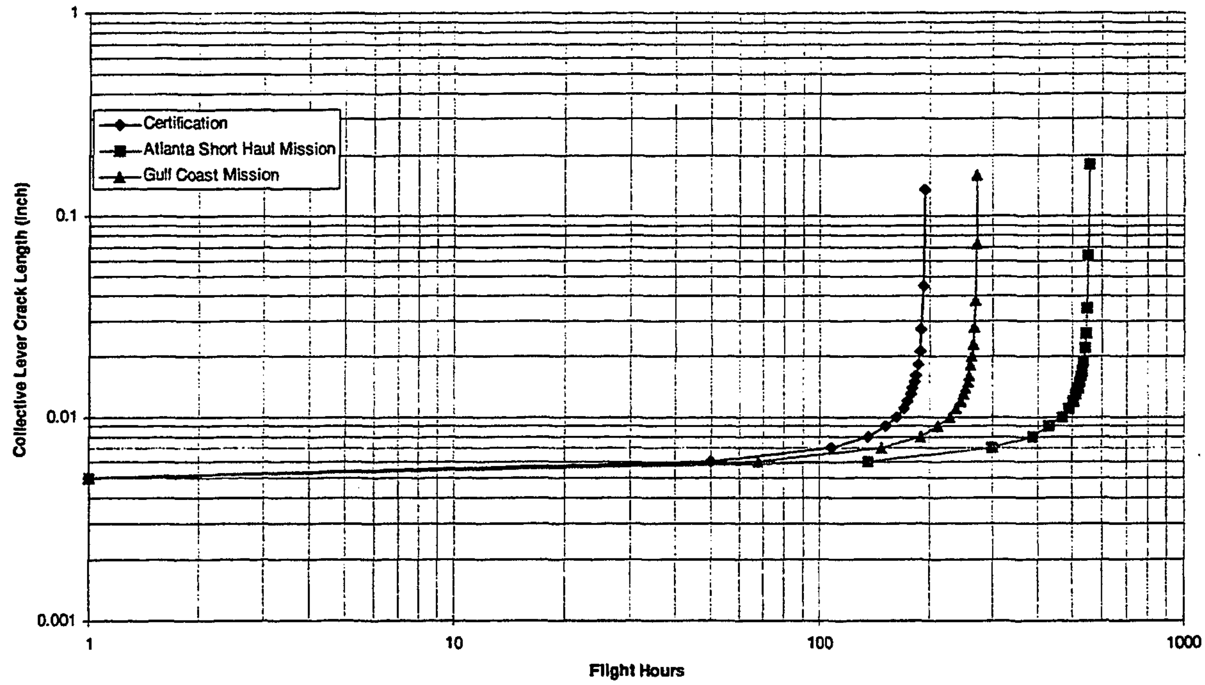

Figure 5.6 Collective Lever - 0.005 inch Initial Crack

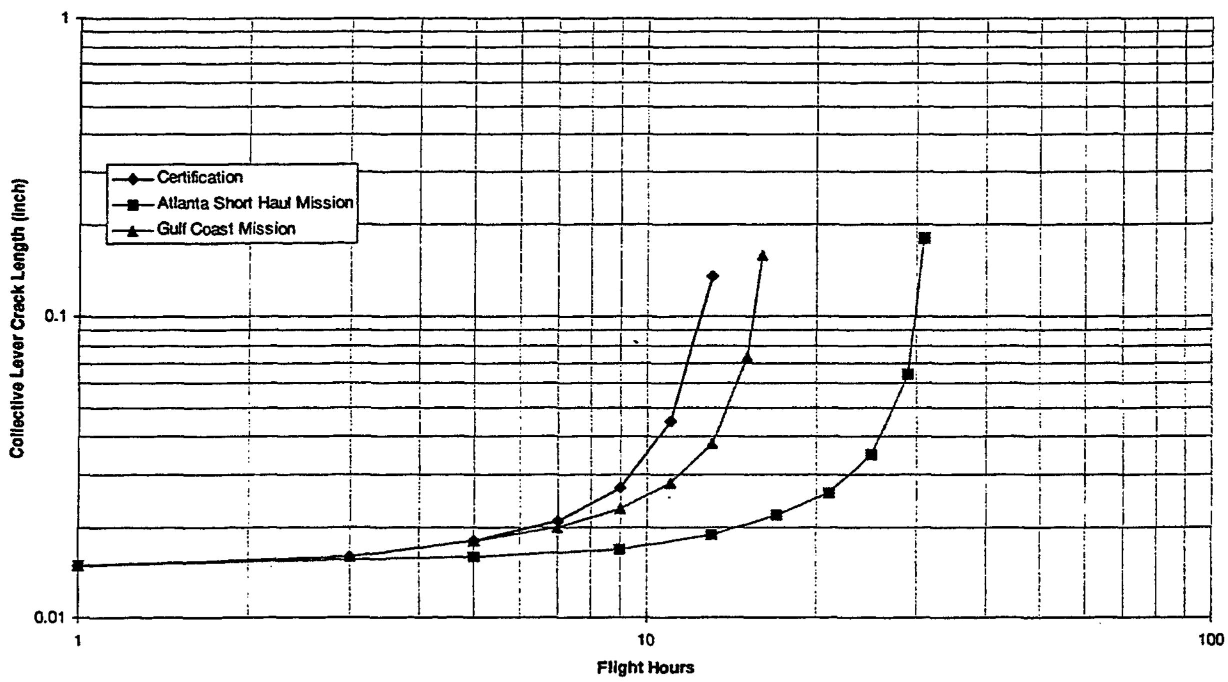

Figure 5.7 Collective Lever - 0.015 inch Initial Crack

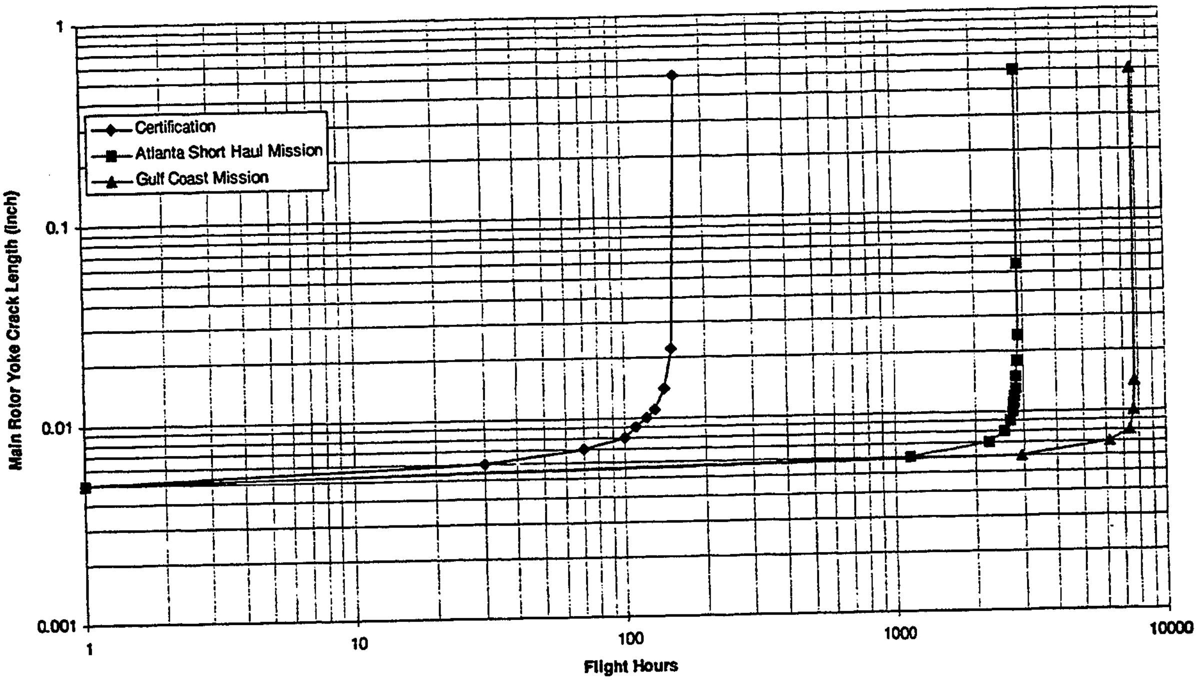

Figure 5.8 Main Rotor Yoke - 0.005 inch Initial Crack

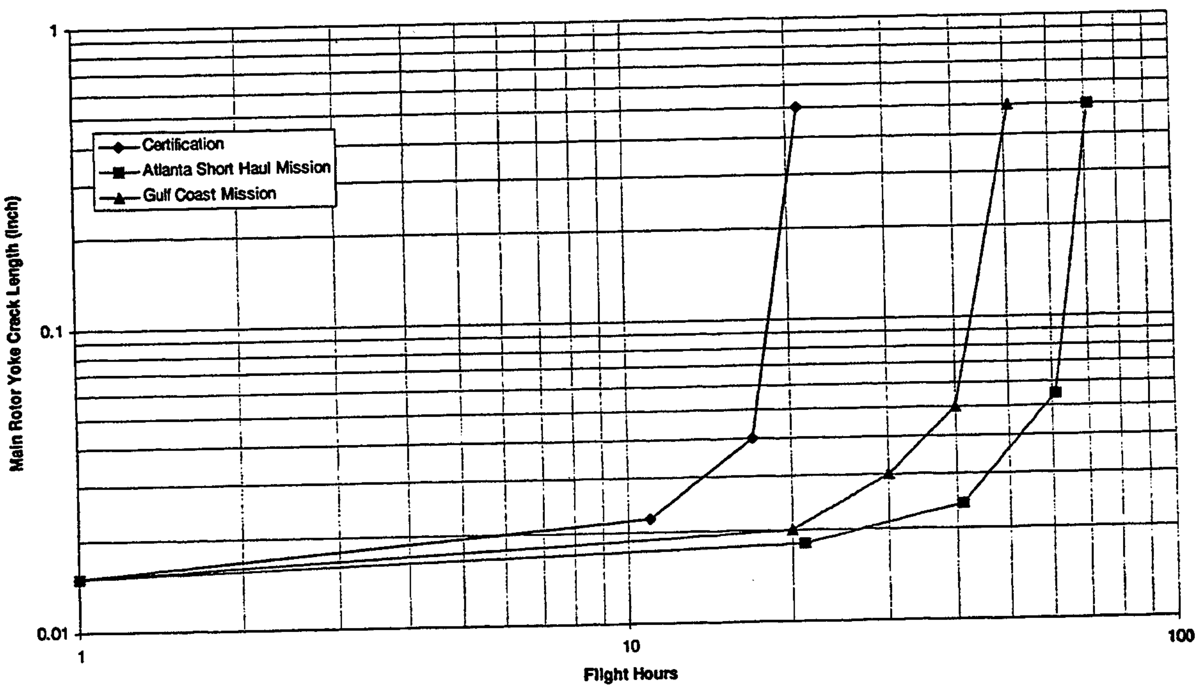

Figure 5.9 Main Rotor Yoke - 0.015 inch Initial Crack

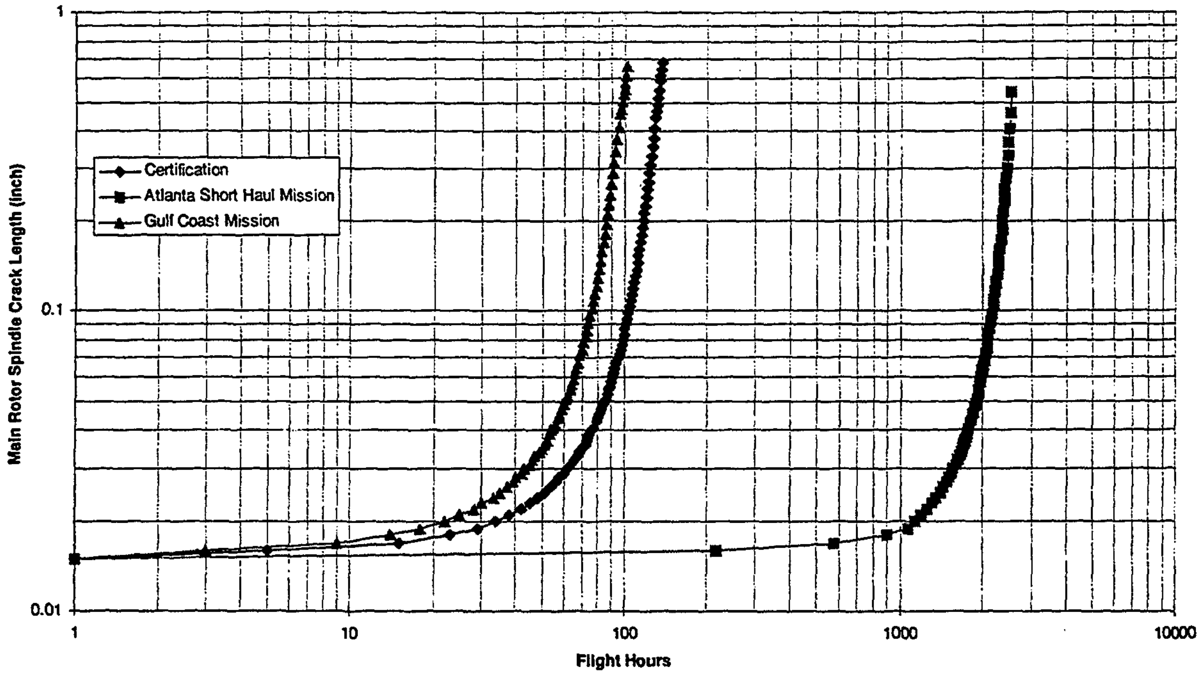

Figure 5.10 Main Rotor Spindle - 0.015 inch Initial Crack

6. Measured Load Comparison

A very limited set of oscillatory loads data were measured during the ASHM. These data comprise the Collective Boost Tube, Left Cyclic Boost Tube, and Right Cyclic Boost Tube. These data were collected to provide reference data to indicate the level of conservatism that is built into the analysis. These data was analyzed to determine the frequency of occurrence at various load levels and were processed to generate the measured load exceedance curves presented in Figure 6.1 through Figure 6.3. The curve represents the number of times per hour a given oscillatory load will exceed a given level, e.g. 47 cycles/hour exceeded 200 lb for the collective boost tube (Figure 6.1).

Recorded data were extracted from the load level survey database and processed with the time at condition measured for the three available missions. These data were then processed as above and plotted for comparison in Figure 6.1 through Figure 6.3.

This comparison indicates that the measured cumulative load data is approximately two orders of magnitude lower than that predicted by the flight load survey data in the region at and above the endurance limit. The Left and Right Boost Tube plots exhibit similar characteristics.

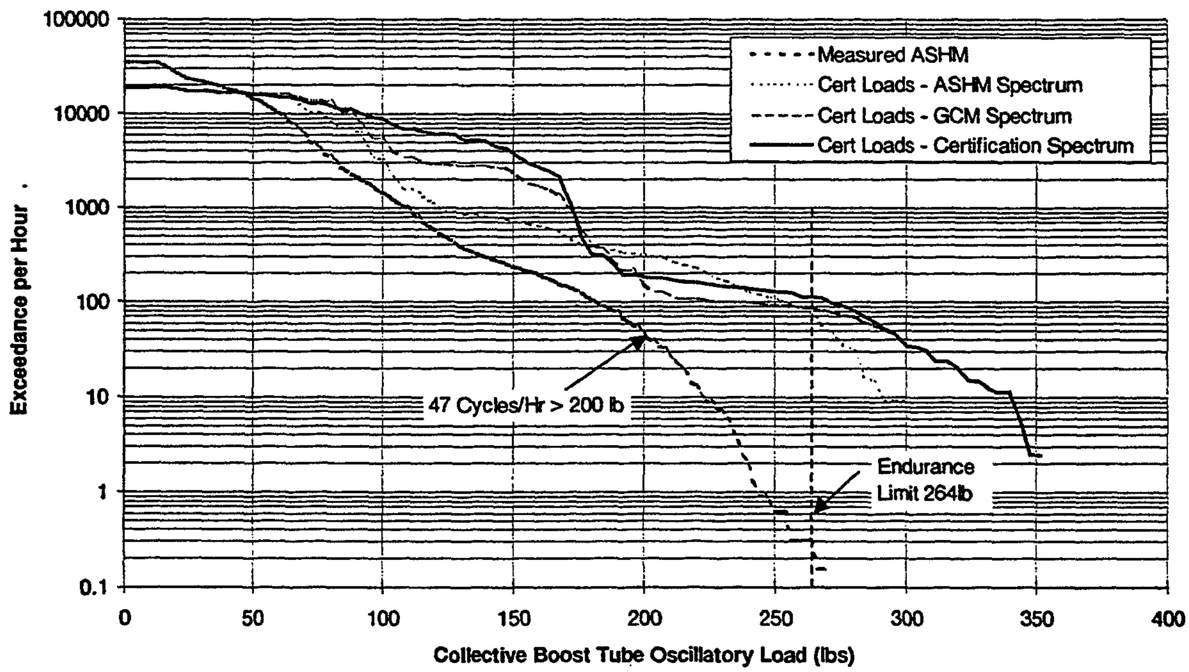

Figure 6.1 Collective Boost Tube Load Comparison

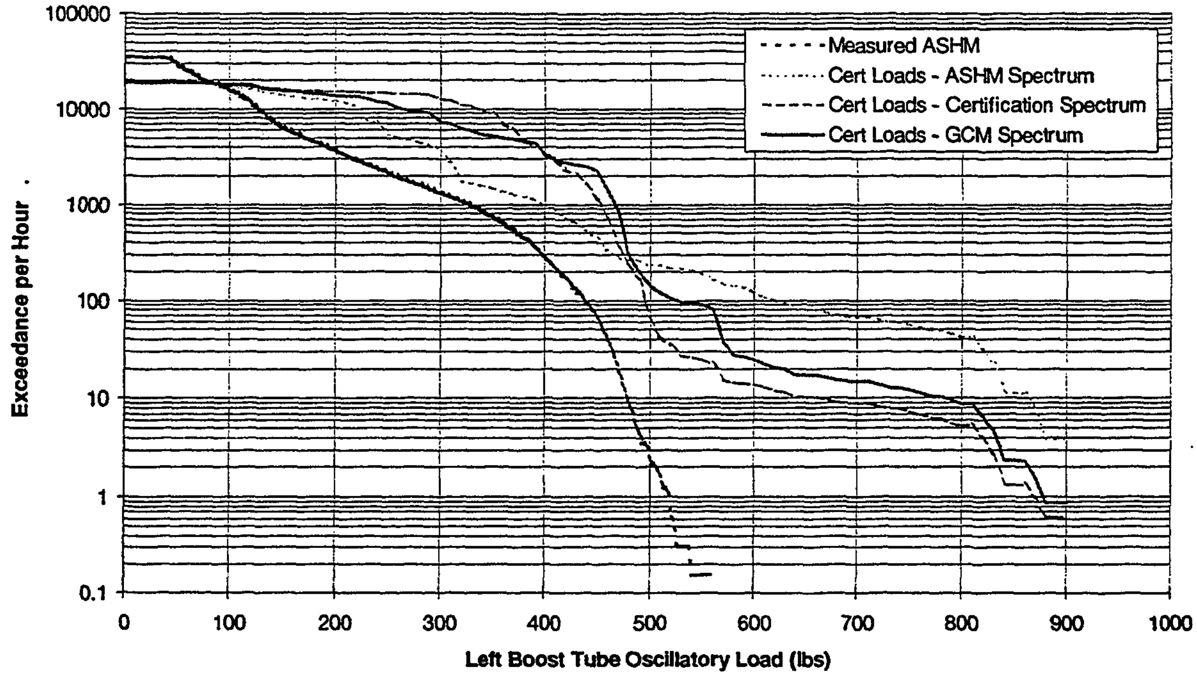

Figure 6.2 Left Boost Tube Load Comparison

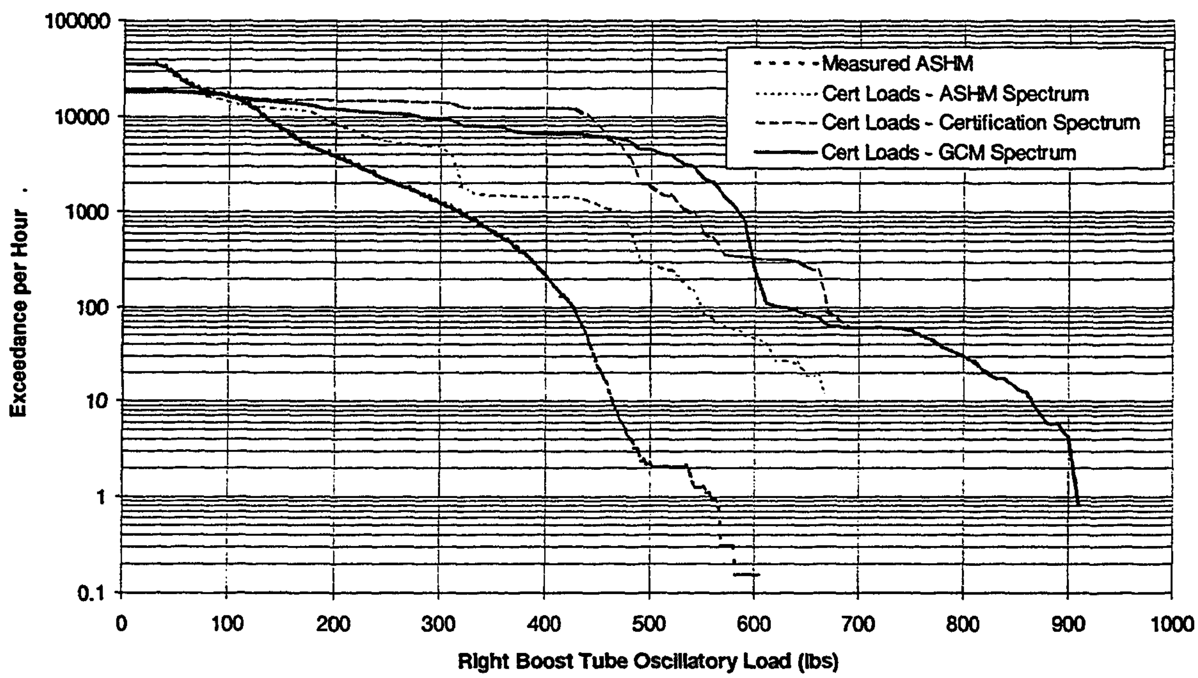

Figure 6.3 Right Boost Tube Load Comparison

7. Sensor and Equipment Investigation

Based on the results of the ASHM and GCM studies, an investigation was conducted of sensors and equipment that could potentially enhance usage monitoring. These include gross weight and center of gravity measurement, a cockpit display, and a Global Positioning System (GPS). The results are discussed in this section.

7.1 Gross Weight

An investigation was undertaken to evaluate methods of determining accurate aircraft gross weight. The data collected in the Gulf Coast mission used strain gauged aft cross tubes and forward landing gear attachment fittings to measure gross weight. The only sensor added for the ASHM study was a strain gauge on the Lift Link, the remaining sensors had been installed for the Gulf Coast Mission.

The use of a strain gage on the Lift Link was examined to see if it would improve the accuracy of the gross weight algorithm, as this had provided promising results in preliminary studies. However, it was determined that the interaction between the transmission mounts and the lift link became very difficult to predict when fore and aft cyclic stick was applied at the same time as collective stick. Initially efforts were made to integrate these effects and then to eliminate them. A good correlation could only be achieved when there was little or no collective applied. Under these circumstances, the results showed no significant improvement over those being predicted by the improved gross weight algorithm without the Lift Link.

The gross weight prediction algorithm used in this study is based upon weight on gear loads with a correction for rotor RPM and collective pitch. There is good correlation between HUMS calculated and pilot recorded gross weight. A cross plot of the gross weight data is presented in Figure 7.1. The revised gross weight algorithm improved the prediction such that the preponderance of the data falls within a 500 lb variation band. An investigation of some of the outlying points revealed a possible "time shift" between data entered by the pilot and that recorded by HUMS. This phenomenon is indicated by the ellipses in Figure 7.2. A detailed study of the available data suggested that the HUMS data is correct, and somehow the written data became shifted.

7.2 Center of Gravity

The correlation of pilot vs. HUMS CG was disappointing because it did not correlate as well as the gross weight as shown in the cross plot of the ASHM CG data presented in Figure 7.3. It was decided not to investigate or refine the algorithms, as CG is not used in the present methodology. The CG data, however, would be useful if displayed to the crew, as it would assist them in complying with flight envelope limits. Further improvements in the gross weight algorithm may give better results.

7.3 Cockpit Display

The preferred method of determining the aircraft gross weight is to have the pilot punch in the data at or before takeoff. This method is inexpensive and the timeliness of data entered into the recording system at flight start should ensure that the "data shift" experienced during the ASHM is avoided. However, the use of an accurate gross weight measurement system would also eliminate such problems.

7.4 Global Positioning System

Global Positioning System (GPS) data was not recorded during the ASHM. It was anticipated that the GPS would provide data that would allow refinement or replacement of data collected by multiple sensors. The number of possible parameters available from GPS is still not known nor are their resolutions. It was anticipated that GPS would provide accurate aircraft track and possibly altitude data that could be used to improve the turn, climb, and velocity portions of the HUMS algorithms. It is most likely that forward groundspeed could be derived from GPS. The flight path of the aircraft would be known but not the forward velocity component. The current methodology uses calibrated airspeed.

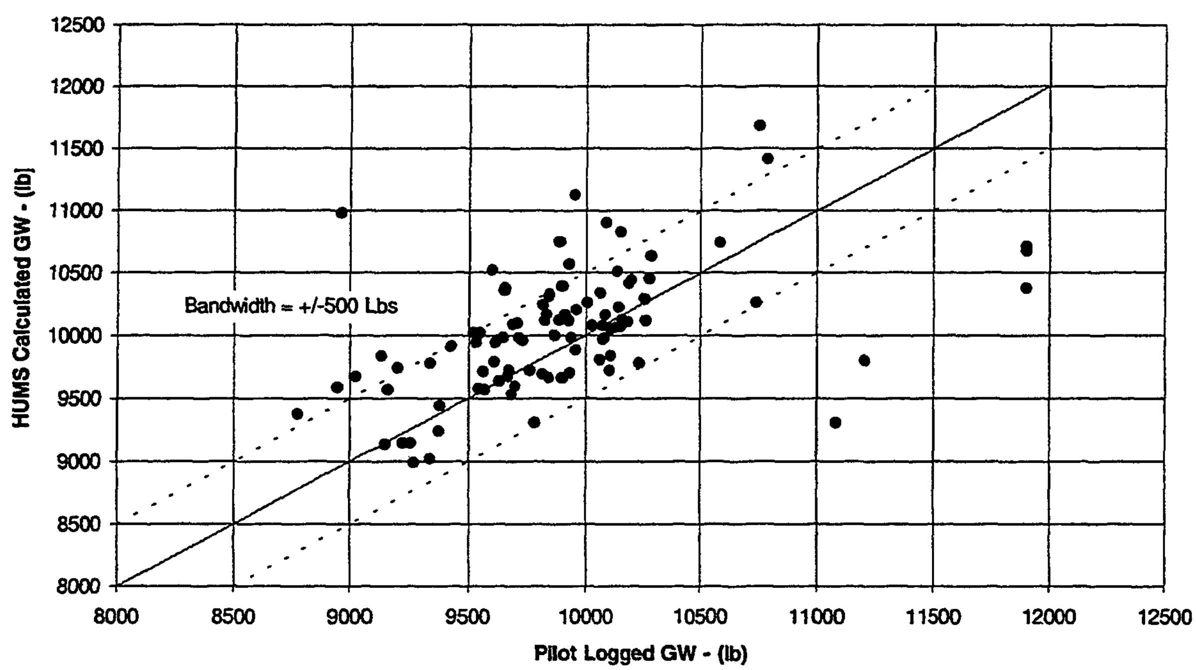

Figure 7.1 Gross Weight Correlation

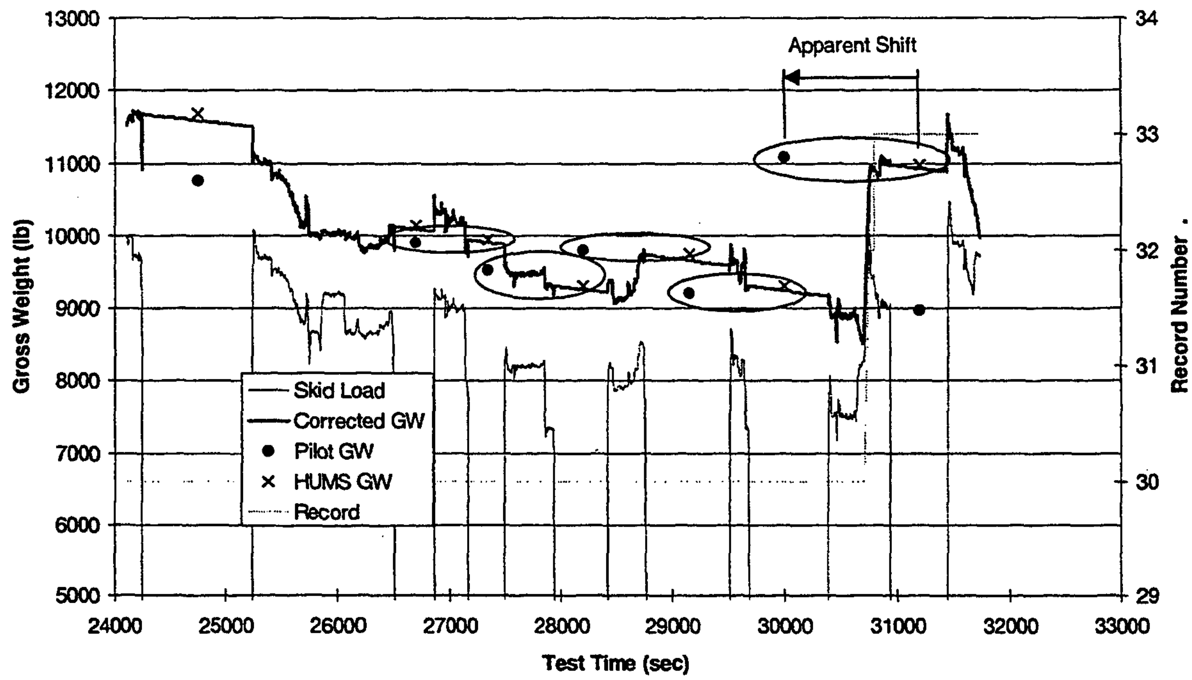

Figure 7.2 Gross Weight Detail

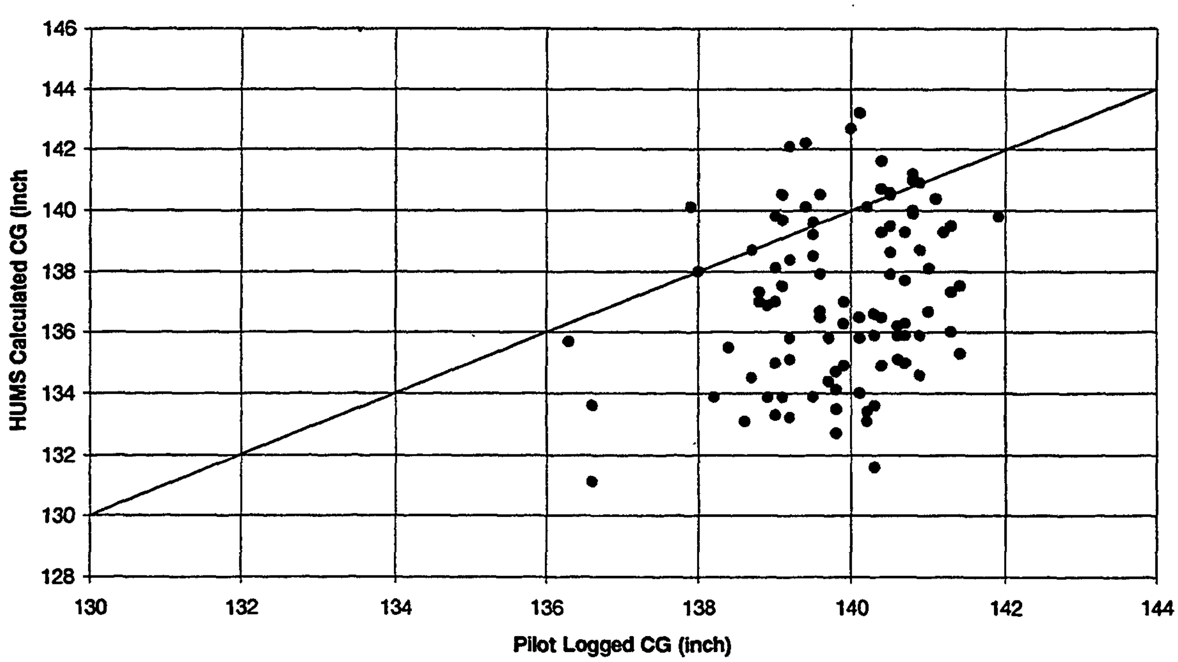

Figure 7.3 Center of Gravity Correlation

8. Guidelines for Certification

For transport category rotorcraft governed by FAR 29, the requirement is that all new rotorcraft be equipped with a flight data recorder (See Paragraph 29.1459 of Reference 3). At the present time, the FAA has no specific regulatory requirement that makes a HUMS mandatory. There is a draft of an advisory circular currently being worked by a joint FAA/JAA task force that outlines what constitutes a HUMS and contains suggested certification methods.

In accordance with FAR 21 the system may be certificated by the manufacturer as part of the Type Certificate (TC) of a production helicopter or as a Supplemental Type Certificate (STC) by the manufacturer, a modifier, an equipment manufacturer, or an operator. If the system is to be retrofitted to existing aircraft, the most logical method would be an STC as a kit. This would not preclude the system from being installed on the production line in a new aircraft by the manufacturer.

No matter what the certification vehicle, TC or STC, a complete set of engineering drawings and specifications must be submitted to the certifying agency. The applicant must show that the addition of the onboard equipment would in no way be a hazard to the safe operation of the aircraft. The FAA has suggested using AC No. 25.1309-1A (Reference 4) as a guideline for safety and hazard analysis in connection with the installation of a HUMS. The hazard analysis covering both airborne and ground based aspects should be submitted to the certifying agency.

The certification process for a HUMS differs somewhat from current processes because of the use of ground based equipment including computers and software. Certification involves addressing the installation of the equipment, maintenance credit validation, and continuing airworthiness. These aspects are discussed in some detail in an American Helicopter Society paper (Reference 5). The paper suggests the following steps toward obtaining certification of a HUMS:

1. Establish a certification project with the responsible certifying authority.
2. Develop an end-to-end system design concept.
   a) Define the desired maintenance credits.
   b) Identify the functional partitioning between airborne and ground.
   c) Identify the functional partitioning between HUMS and the maintenance system.
   d) Select Commercial Off The Shelf (COTS) software and hardware with an established service history.
   e) Clearly identify the end of the credit function (algorithm).
   f) Define a user interface that will meet the desired objectives.
3. Prepare and submit hazard assessments.
   a) For the airborne installation.
   b) For the maintenance credits expected or desired.
4. System development:
   a) Develop hardware to meet the system qualification requirements.
   b) Develop application software to the required DO-178B levels.

5. Test the application in the COTS environment.
6. Validate the COTS using an independent means of verification.
7. Develop a user operating manual for the system defining credit requirements.
8. Modify maintenance and or flight manuals for the proposed credits.
9. Certify the airborne installation.
10. Conduct a Controlled Service Introduction (CSI) for credit validation.
11. Helicopter operator to obtain credit approval for his aircraft.

Since one of the objectives of the HUMS usage function is to obtain credit, such as component life extensions, it is important to show end-to-end integrity of the system. Figure 8.1 (taken from Reference 5) depicts a HUMS maintenance concept. The system records all usage parameter raw time history data onboard the aircraft. The data are transferred to a ground station for processing to determine the effective component time. These data are then input to the existing operator maintenance data base. The level of airborne and ground based software criticality required must be addressed in addition to the use of (COTS) software.

The certification and implementation of a commercially viable HUMS will require the close cooperation of the applicant, the certifying agency, and the manufacturer. The HUMS concept is relatively new on the scene and must be approached cautiously especially regarding life extensions. The system design and installation, validation of the procedure for obtaining credit, and continuing airworthiness aspects including operator procedures and training must be complete and thorough. Of utmost importance is the need to clearly establish airborne and ground based software criticality levels and provide rationale and justification for the level chosen.

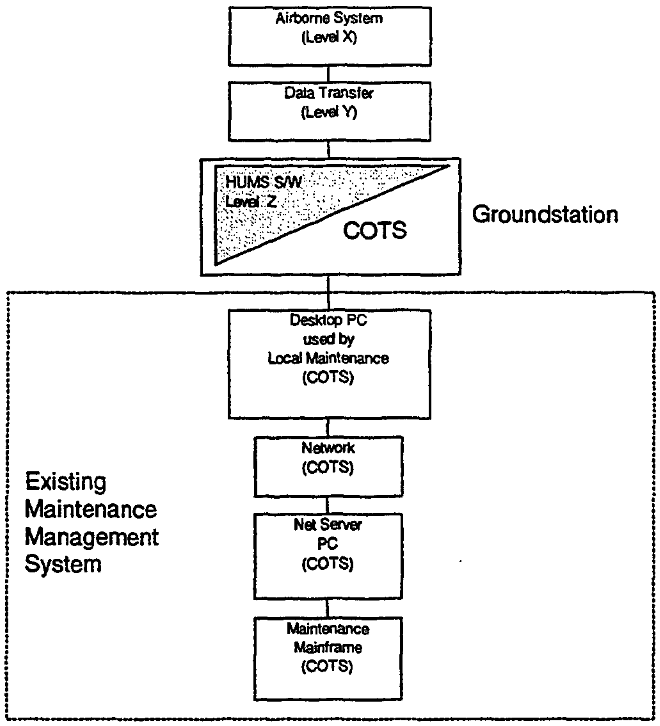

Figure 8.1 HUMS maintenance concept

9. Economic Impact

The economic impact of incorporating a HUMS on a Model 412, based on cost estimates from the Operators Evaluation of a HUMS (Reference 6) are presented in this section. An attempt to represent more realistically the effects of practical limitations (Section 4.2) on the retirement extension, including causes for retirement other than safe life limitations, has been made. This was achieved by limiting the safe life derived from measured spectra to twice that derived from the certification spectrum, this is referred to as "double life limitation." After stating these assumptions the estimated operating cost savings are summarized in Table 9.1 without life limitation and Table 9.2 with a double life limitation.

Assumptions:

1. Model 412 total cost per Flight Hour (FH) is $615.89
   a) Parts replacement cost is $254.82/FH
   b) Labor cost is $42.94/FH
   c) Fuel/Lube, Powerplant cost is $318.13/FH

2. Cost of hub parts based on 5000 hours of operation is $221,891.08
   a) Two Main Rotor Yokes cost $69,932 and have a 5,000 hour Retirement
   b) Four Main Rotor Spindle Assemblies cost $85,590 and have a 10,000 hour Retirement

3. Usage of other life limited components follow the pattern of the yoke and spindle

Table 9.1 Without Life Limitation

	Yoke Rate	Spindle Rate	Cost/Hr	%Saving
Certification Spectrum	1.00	1.00	$22.55	-
GCM Spectrum	.28	.70	$9.26	59%
ASHM Spectrum	1.49	3.36	$49.61	(120%)
GCM (Altitude Split)	.19	.35	$5.65	75%
ASHM (Altitude Split)	1.05	.31	$17.34	23%

Table 9.2 With Double Life Limitation

	Yoke	Spindle	Cost/Hr	%Saving
Certification Spectrum	1.00	1.00	$22.55	-
GCM Spectrum	.50	.70	$12.99	42%
ASHM Spectrum	1.49	3.36	$49.61	(120%)
GCM (Altitude Split)	.5	.5	$11.28	50%
ASHM (Altitude Split)	1.05	.5	$18.97	16%

10. Mini HUMS

Two possible simplified or "mini-HUMS" configurations were investigated. The first configuration of a simplified HUMS attempted to reduce the number of sensors and therefore the complexity and the cost of the system by allowing larger groups of conditions to be lumped together. The second configuration took a simplistic approach, based upon other analysis within this contract. The certification spectrum was applied to time at altitude with the FCR reduced to high or low altitude determination, essentially the HUMS became a recording altimeter. This had the added advantage that unrecognized conditions did not contribute to the damage as the certification spectrum is fully defined.

10.1 Simplified HUMS

The simplified methodology involves broadening the conditions that are recognized by the system. The suggested configuration and parameters are listed in Table 10.1 and a broad category breakdown is shown in Table 10.2. The safe lives resulting from the implementation of this analysis (Table 10.3) did not agree well with the results obtained from the full-up HUMS. This is due to the lack of correlation between the broad categories and the certification spectrum. The indications therefore are that the categories need be to refined and that broadening them does not provide sufficient useable data. An overview of the simplified procedure follows:

1. Measure time in broad condition types,
2. Accumulate certification damage for broad conditions, and
3. Factor damage sums from 1 and 2 by the ratio of measured time to the time from the certification spectrum.

Table 10.1 Simplified Mini HUMS configuration

Parameter	Status	Note / Requirement
Gross Weight	Add	Measured or Pilot Input
Nz	Add	Load Factor and Symmetric Maneuvers
Roll	Add	Asymmetric Maneuvers
Squat Switch	Add	Ground/Air Time
Airspeed	Add	
Altitude	Add	
Rotor RPM	Existing	
Engine Torque	Existing	Torque Cycle count

Table 10.2 Simplified Mini HUMS

Full up HUMS		Mini Hums
Hover	\	
Side Flight	I	Hover time
Rear Flight	I	
Etc.	/	
Level Flight .4Vh	\	
Level Flight .6Vh	I	
Level Flight .9Vh	I	Level
Level Flight 1.0Vh	I	
Etc.	/	
Right Turn .6Vh	\	
Right Turn .9Vh	I	
Left Turn .6Vh	I	Maneuver
Left Turn .9Vh	I	
Etc.	/	
Take Off	\	
Landing	I	Events
Engine Start	I	
Etc.	/	

Table 10.3 Simplified Mini HUMS Fatigue Life

	Certification (Hours)	GCM (Hours)	ASHM (Hours)
Rephase Lever	5,000	3,360	2,280
Main Rotor Spindle	10,000	6,060	5,400
Main Rotor Yoke	5,000	18,870	6,720

10.2 Recording Altimeter

Use the certification time at condition with the recorded time at altitude to determine the usage. This is equivalent to producing two certification data sets, one for below 3000 ft and another for at or above 3000 ft. The Fatigue Life calculations were reprocessed with the above assumptions and the results presented below.

This method has the advantage that there is very little required equipment, little or no deviation from the certification methodology and demonstrates significant life extension. Simplicity is the key to this system as it makes no attempt to measure any time at condition, only time at altitude, and therefore is simple to verify. Failures of the system would involve reverting to the existing certification data, i.e. no credit for altitude.

Table 10.4 Recording Altimeter Fatigue Life

		Hours	Life	Clock
Rephase Lever	No altitude split (Certification)	5,000	100%	100%
	Gulf Coast Altitude Split	12,910	258%	39%
	Atlanta Short Haul Altitude Split	80,320	1606%	6%
Collective Lever	No altitude split (Certification)	10,000	100%	100%
	Gulf Coast Altitude Split	20,730	207%	48%
	Atlanta Short Haul Altitude Split	45,170	452%	22%
Main Rotor Spindle	No altitude split (Certification)	10,000	100%	100%
	Gulf Coast Altitude Split	19,000	190%	53%
	Atlanta Short Haul Altitude Split	33,090	331%	30%
Main Rotor Yoke	No altitude split (Certification)	5,000	100%	100%
	Gulf Coast Altitude Split	5,760	115%	87%
	Atlanta Short Haul Altitude Split	5,460	109%	92%

Table 10.5 Recording Altimeter Economics

	Yoke	Spindle	Cost/Hr	%Saving
No Altitude Split	1.00	1.00	$22.55	-
Gulf Coast Altitude Split	0.87	0.53	$16.71	26%
ASHM Altitude Split	0.92	0.30	$15.44	32%

11. Conclusions

The usage monitoring of the Atlanta Short Haul Mission (ASHM) during the summer Olympics using a HUMS was effective. Several significant conclusions can be drawn from this study. These are listed below:

1. The ASHM usage data indicates a significantly different type of mission from the Gulf Coast mission and are as follows:
    a. Much shorter flight duration
    b. Many more maneuvers
    c. Lower cruise airspeeds
    d. A large portion of the operating time spent on the ground
2. The FCR software was able to recognize the maneuvers associated with the ASHM operation. The percentage of unrecognized data was extremely low.
3. The data sample for the ASHM is limited (approximately 17 hours of flight data) compared to the approximately 450 hours of flight data processed from the GCM. Because of the limited amount of data, care should be exercised regarding the mission characteristics presented.
4. While improved over the Gulf Coast Mission result, the gross weight system accuracy is still not acceptable for cockpit use by the crew. The use of the keyboard entry of gross weight is still the preferred method until the gross weight system accuracy can be improved.
5. The recorded cyclic and collective boost oscillatory loads verify the conservatism of the certification loads.
6. No anomalies associated with sensors were observed in the data.
7. The scripted flight was useful in trouble shooting and verifying the enhanced FCR algorithms.
8. Although there was a potential cost benefit from using a HUMS during the ASHM, it was not as significant as for the Gulf Coast Mission.
9. Since the four study components were designed and certificated to safe-life objectives, it was not unexpected that the inspection intervals indicated by the crack growth data were relatively low.
10. Historical data for the four study components indicated that the current maintenance procedures are adequate to catch corrosion, scratches and wear. In the 16 years since the Model 412 was certificated, no catastrophic fatigue failure has occurred in any of the PSE's.
11. To realize the maximum benefit from the FCR technique, it is recommended that a more refined load level survey is required. For example, the use of a low/high altitude split is justified from the current load level data. However, there are too many conditions that were not recorded during certification to consider a detailed altitude breakdown. Loads measured during the ASHM also suggest that the load level should include less severe categories of maneuvers and that the FCR should be refined to recognize the severity of maneuvers.

In summary, the usage function of HUMS performed acceptably for the ASHM using the FCR technique. This study present comparisons of significantly different mission scenarios that must be covered presently by a single certification spectrum and has indicated that a HUMS with the usage function can be used to monitor a wide range of spectrum types.

The crack growth lives calculated in this study indicate relatively short inspection intervals for components that were designed to safe-life methods. This is not unexpected since the crack growth threshold stresses at initial crack length of 0.015 inch used for damage tolerance are significantly lower than endurance limit stresses used for safe life. The recently certificated Model 430 was designed from the outset to be damage tolerant and uses a zero growth philosophy (no crack growth from a 0.015 inch flaw for any flight condition). No special inspections are required for the 430 components between normal overhauls.

12. Recommendations

Usage monitoring should enhance safe life and damage tolerance methodologies. After compiling and reviewing the ASHM data, the following recommendations are offered:

1. Further refinement of the Gross Weight system.
    a. Use a controlled study using an instrumented aircraft to improve algorithms
    b. Investigate a cockpit display of weight
    c. Explore the use of an inflight sanity check for weight (hover or level flight)
2. It would be useful to determine how the four PSE's in the study could be redesigned to a damage tolerant philosophy to meet a minimum 2500 hour inspection. Use FEM or measured stresses for these components to predict the required design changes. One of the most important results would be the component weight change required to meet the objective.
3. The majority of the dynamic components for the Model 412 are shotpeened. It has been widely recognized that this is a benefit in terms of damage tolerance, particularly for small flaws. Crack growth data should be generated for a typical helicopter material using small coupons. The X-ray defraction technique would be used to quantify the residual stress values in the compressive zone thus permitting a correlation to be made between crack growth rate and compressive residual stress.
4. The data from the ASHM points out the wide variation in mission types currently being flown by operators. This suggests that the HUMS equipped Model 412 used in this study should be used to acquire usage data for other missions. Suggested missions should include: (1) logging, (2) heli-ski operation, (3) emergency medical, and (4) law enforcement. These data would subsequently be used to evaluate component lives and inspection intervals using damage tolerance methods.
5. The use of GPS has the potential to replace several sensors currently required for usage monitoring and should be pursued. GPS would be particularly useful for a mini-HUMS on smaller helicopters where cost is an important consideration. This will require a study to include the installation and operation of a HUMS equipped aircraft in concert with GPS equipment. Accuracy and reliability are key issues that must be resolved by the proposed study.
6. Presently certification load level surveys are flown in a very conservative manner generally measuring data at the corners of the gross weight/c.g. envelope and at a minimum number of altitudes. Additionally, maneuvers are flown aggressively generally resulting in load magnitudes which are "top of scatter." The load level survey technique should be refined to investigate in more detail all aspects of the measurement of certification loads to take maximum advantage of the detailed spectrum information available from a HUMS equipped aircraft. A program should be undertaken to acquire this more refined loads data. These data could then be used to compare the four study component lives against the current methodology thus quantifying the benefits of a more complete load level matrix. The maneuvers should be flown multiple times by more than one pilot to investigate load variability.

13. References

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13. ABSTRACT ***(Maximum 200 words)***
This report describes the results of a research program to evaluate structural usage monitoring and damage tolerance methodology using data collected concurrently during a helicopter flight program. The helicopter (a Bell Model 412 equipped with a Health and Usage Monitoring System (HUMS) and data recorder) was operated by Petroleum Helicopters Inc. (PHI) during the 1996 Summer Olympic Games in Atlanta, Georgia, under the FAA's Project HeliSTAR. The mission was referred to as the Atlanta Short Haul Mission (ASHM) and involved many short flights to provide pick up and delivery service at the Olympics. The usage data collected for the ASHM was used to perform fatigue life calculations and damage tolerance evaluations on selected rotor system components know as Principal Structural Elements (PSE's). The usage data from the ASHM were compared to certification data and to data from a previous study for a mission called the Gulf Coast Mission (GCM) which involved primarily long cruise flights. Although the usage was more severe for the ASHM than the GCM, the results of the comparison showed that usage monitoring would provide benefits in extending retirement times or inspection intervals, compared to certification, especially if high/low altitude effects were considered. In addition to usage monitoring evaluations, guidelines for HUMS certification are discussed along with potential economic benefits and simplified "mini-HUMS" approaches to provide low cost systems with high paybacks.

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