Power Usage Metric for Helicopter Transmissions[1]

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Abstract

This paper describes a novel power usage metric which is designed to accurately track the usage of rotorcraft power train transmissions. This power usage metric is a model for

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defining the relationship between input power and a Power Usage Factor (PUF) that for example increases from 0 at zero input power to 1 when the main rotor transmission is operated at 100% Normal Rated Power (NRP). The results of this process are recorded and summed over time to report the accrued mechanical usage as Power Usage Hours (PUH). This power usage product represents the hours of operations that are equivalent to operating hours conducted at 100% NRP. This power usage metric is more accurate than the traditional approach that uses flight time for scheduling the overhaul of rotorcraft transmissions. In addition the functionality is an affordable addition to HUMS installations.

Introduction

Overhaul inspections of helicopter transmissions are periodically conducted to detect parts that have experienced wear and fatigue-related defects due to power usage. This usage is attributed to the power that passes through the transmission from the engines to the main rotor, tail rotor and accessory modules. Typically transmissions are overhauled on a flight time schedule established by the OEM's maintenance program; a program approved by the FAA to insure continued airworthiness.

Operators in the support of Oil and Gas Producers frequently use HUMS data to intervene before seeing any exceedance from traditional cockpit indicators (*e.g.,* metal in an oil strainer, chip detectors and lubricant temperature gages). This is to avoid the possibility of an in-flight alert on an outbound leg over hostile surface environments which can lead to a variety of stressful events, not the least of which is a variety of unscheduled maintenances actions (Refs. 1, 2, 3, 4, 5, 6). While HUMS data are being used by operators to detect incipient defects based on vibration analysis, the ability to

make these detections is not a Government regulatory requirement for continued airworthiness (Ref. 7).

When HUMS data are analyzed on a daily basis the operator has the option to plan an intervention before the wear detected by HUMS has progressed to the point where the emerging defect can threaten airworthiness. While not being required by the OEM as an integral part of their maintenance program, this planned intervention is extremely important since it substantially improves the airworthiness reliability of the transmission.

A HUMS installation can also be used to enable the operators to track the power usage of a main rotor transmission. The engine output torque time history is captured on every flight and processed into a power usage metric which, when collected for all flights and turn-ups, can be used to determine a point in time when a given transmission should be scheduled for overhaul. When a tail rotor torque sensor is installed the HUMS torque time history of the tail rotor drive system can be used to track the usage of the tail rotor drive transmissions.

Power usage tracking is an appropriate improvement for the following reasons:

- While flight time has been used as the traditional metric for establishing periodic inspections/overhauls of helicopter transmissions for decades, experience has demonstrated that flight time is an imperfect metric when establishing the time between overhaul for all helicopter transmissions.

- While it is not possible to measure mechanical usage directly it is possible to record the time history of torque and convert such information into mechanical power usage.

- When HUMS is installed, the addition of a power usage tracking process can be added to the HUMS processor at little additional cost.

Power Usage Metric

The concept of tracking power usage was developed between 1995 and 2002. This was followed by a study conducted by the University of South Carolina's Mechanical Engineering Department that validated the efficacy of the concept. This study concluded that using power usage to track power train transmissions was far superior to using flight time (Ref. 7).

Fatigue, Load and Power Usage

The engine power, aerodynamic loading and vibratory loading sustained by a transmission are the principal causes of transmission component defects when the transmission is well lubricated. Furthermore, aerodynamic loading and vibratory loading are in general a function of power. The rate of defect propagation, the point of fracture and wear due to contact fatigue are all a function of the time spent at different power settings (Refs. 8, 9).

Contact fatigue is common for rolling element bearings and wear at the pitch line of gears in a power train system. Shorter fatigue life can be expected when the transmission is subject to higher load (see Figure 1). Fatigue results when the high shear stresses from rolling contact cause subsurface microcracking. These microscopic cracks begin under the surface of the roller or race or gear tooth. The cracks later become interconnected and then intersect the surface. Eventually the particles get released to the oil, leaving behind a

delamination or spall defect (Ref. 8). Therefore, tracking power usage is an appropriate way to track power train life consumption.
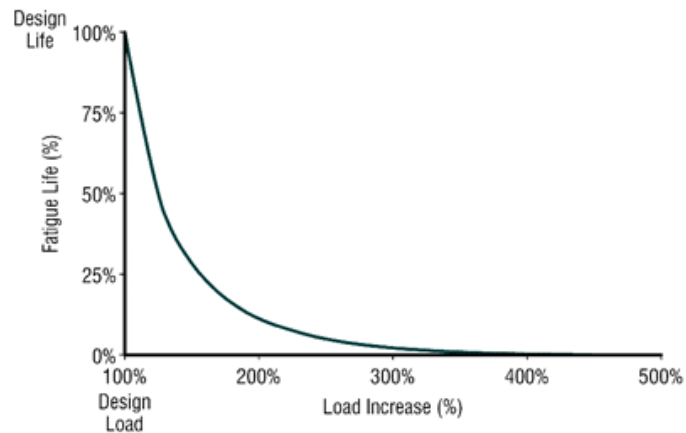

Figure 1. Fatigue life for bearings under excess loading conditions (Ref. 8).

While it is not possible to measure mechanical usage directly, it is possible to record the time history of torque and convert that power information into mechanical usage. This usage can in turn be used as a metric to establish a limit for the accrued transmission power usage between inspections.

Power Usage Model

Establishing a reliable power usage model is essential when the objective is an easily applied mechanical usage metric for establishing the Time Between Overhaul (TBO) of transmissions. The output of the model is called Power Usage Factor (PUF) which is a continuous term that has a different finite value for each power setting.

This factor is based in part upon the expected life of the transmission while being operated at very high power (Refs. 10, 11, 12, 13, 14, 15). For example, if the OEM designed useful life of the transmission is 50 operating hours at 140% Normal Rated Power (NRP), then all parts in a gearbox assembly would be expected to remain

serviceable during an endurance demonstration involving 50 hours of continuous operation at 140% of NRP.

Another key factor is the rate of mechanical usage associated with the low end of the usage spectrum. For the sake of explanation, it is assumed that the OEM design studies concluded that the rate of usage at very low power (30% or 40% NRP) is near zero.

When transmission endurance has been computed by OEM engineering for a series of power settings, it is possible to define a worst case *S-N* curve for a transmission (see Figure 2). This series should including at least one very high setting and a low power settings representative of flat pitch ground operations. Alternately, the OEM can simply construct the usage relationship as a tailored power usage function or a look-up table. In either event the relationship would typically result in a PUF that would be progressively reduced by half for each 8% to 12% decrease in applied power below 100% NRP. Similarly the PUF will doubles for each 8% to 12% increase in torque above 100% NRP.
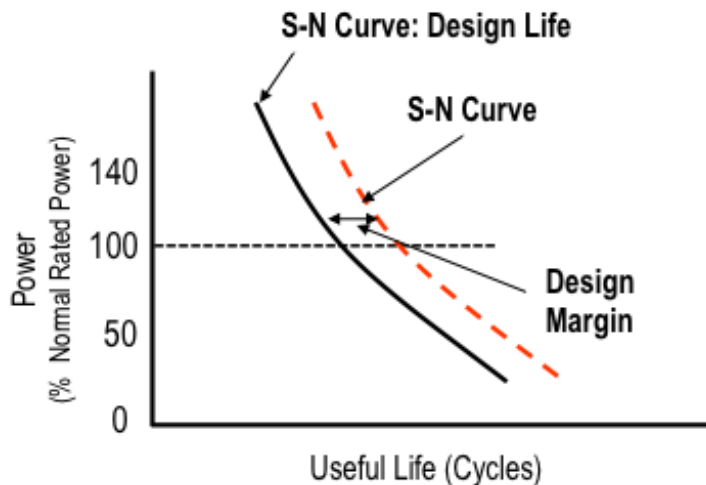
Figure 2. Relationship between S-N curve and power.

As an example, the first three columns in Table 1 include two hypothetical sets of OEM design data that represent the relationship between each power setting and its

expected useful life when operating at a particular power level. Column Two represents a "Very Robust" transmission and Column Three represents a "Less Robust" transmission.

In the "Less Robust" case, the expected useful life at 120%Q is only 50 hours as opposed to 200 hours for the "Robust" case. The PUF column was developed to represent the ratio between the expected useful life at 100%Q (*i.e.,* 800 hours for a robust transmission and 200 hours for a less robust one) and the useful life at a particular power setting. The PUF values remain the same for both gearbox designs since PUF is normalized to 100% NRP. This commonality is a significant attribute of the power usage metric.

Table 1. Data representing the relationship between power levels, useful life and power usage factors.

Power Level (% Q)	OEM Calculated Useful Life (Operating Hours)		PUF
	"Very Robust"	"Less Robust"	
140%	50		16
130%	100		8
120%	200	50	4
110%	400	100	2
100%	800	200	1
90%	1,600	400	0.5
80%	3,200	800	0.25
70%	6,400	1,600	0.125
60%	12,800	3,200	0.0625
50%	25,600	6,400	0.0312
40%	51,200	12,800	0.0156
30%	102,400	25,600	0.0078

Baseline Power Usage Metric Formula

The above relationship between torque and power usage factor can be appropriately modeled as a base 2 exponential growth function (see Figure 3), and can be expressed as follows:

$$PUF = 2^{a(10.04Q(t)-10.056)}$$
$$\approx 2^{10a(Q(t)-1)}$$

where Q is the torque value (as a <u>fraction</u> of engine NRP) measured at a fixed time interval. The exponent of the formula can be adjusted to fit a certain gearbox by increasing or decreasing the value of the coefficient α, which has a nominal value of 1.
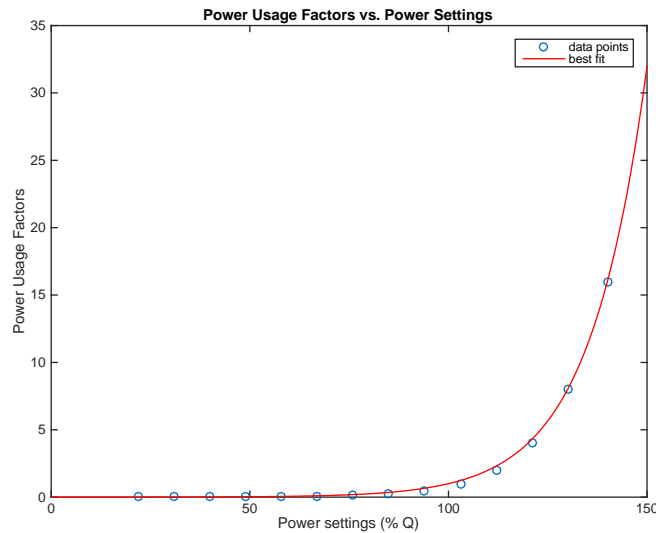

Figure 3. Variation of power usage as a function of operating power.

Summing the PUF over the entire duration of the operation (T) produces the power usage metric which has a unit of seconds if the torque data is recorded at 1 Hz. It is more convenient to represent this value as hours by dividing the sum by 3,600, as shown

below. The result is referred to as Power Usage Hours (PUH) and is understood to mean Hours of Operations that are equivalent to operations at 100% Q.

$$PUH = \frac{1}{3600} \sum_{t=1,2,...}^{T} 2^{10\alpha(Q(t)-1)}$$

In the absence of OEM's participation the operator is left to use the baseline formula which normalizes power usage to 100% NRP.

Impact of Usage Metric Formula Adjustments

As mentioned earlier, the relationship between applied power and PUF can be modeled as a generic exponential growth function (or power function) as follows:

$$y = f(x) = cb^{ax}$$

where b is the base, αx is the exponent, and c is a constant. In the case of PUF described earlier, the parameter values were estimated based on data from a mid-size twin-engine helicopter model. Specifically the PUF function has the form:

$$PUF = f(Q(t)) = b^{\alpha 10(Q(t)-1)}$$

with the base $b = 2$ and the exponent constant $\alpha = 1$. For other models when OEM's data is available, then the value of b and/or α can be fine-tuned accordingly.

The effect of α (1±10%) on PUF can be shown in Figure 4 (in all three cases, we set $b = 2$), where a larger α will produce a larger PUF when the power is above 100% NRP, but a smaller PUF when below 100%. In all cases, PUF = 1 when the power is 100%.
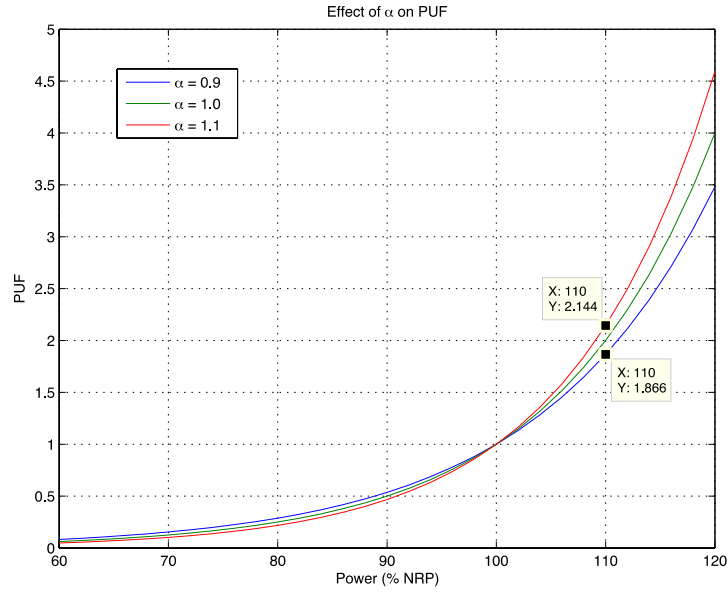
Figure 4. Effect of α on PUF when $b = 2$.

Similarly, the effect of b (2±10%) on PUF can be shown in Figure 5 (in all three cases, we set $\alpha = 1$), where a larger b will produce a larger PUF when the power is above 100% NRP, but a smaller PUF when below 100%. In any case, PUF = 1 when the power is 100%.
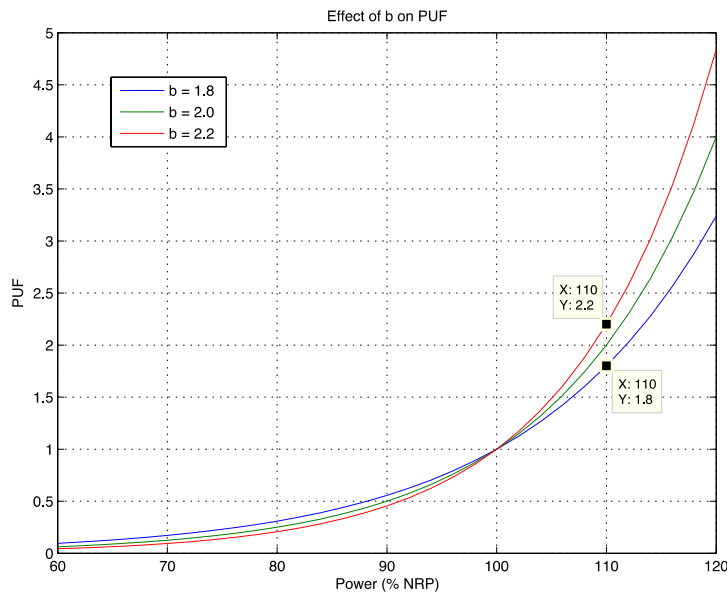

Figure 5. Effect of b on PUF when $\alpha = 1$.

Changing either b or α has a similar effect but with a slightly different sensitivity. However in practice two PUF functions may be used in order to raise the PUF when power is above and below 100%. For example we can use $\alpha = 1.1$ for power greater than or equal to 100% and $\alpha = 0.9$ for power less than 100%, as shown in Figure 6 below.
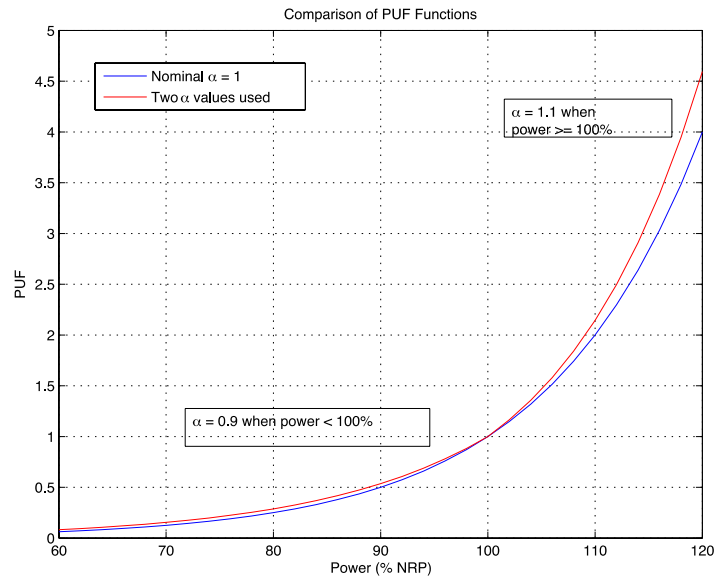

Figure 6. Using a combination of $\alpha = 1.1$ when power >= 100% and $\alpha = 0.9$ when power < 100%.

Implementation

Power Usage can be computed using the time history of engine torque recorded in flight by HUMS or FDR systems. In either case the torque time history is downloaded to a ground station. The power usage metric calculation typically refers to the usage associated with each 1% incremental increase in power above flight idle settings up to and including 120% of NRP.

This calculation is typically accomplished once a second and then summed to determine the usage for the flight. This calculation is repeated for all flights. For example, the total power usage acquired since new or overhaul of a transmission is

summed for all flights and recorded on a history card attached to the historical records of the transmission when the transmission is removed (and replaced) for overhaul or transfer to another aircraft.

Alternately a torque spectrum can be developed for each flight and the results are summed (tracked). This process is initiated when a transmission is installed after an overhaul. This torque spectrum is a function of Rotor Turn Time (RTT). Periodically the torque spectrum is converted to PUH and summed over time as discussed above.

This power usage metric has been implemented on several helicopter models such as S-76, S-92, AW139, Bell-206, and H-60. The software program is capable of extracting flight parameter data from HUMS databases by several HUMS OEM's and calculating PUH automatically. An Excel workbook with embedded Visual Basic Application (VBA) code takes in PUH data as well as other important flight data and creates a summary report on a monthly basis.

Figure 7 shows an example of a power usage summary report based on data collected from an S-76C helicopter.

Detailed Usage Record of the Main Rotor Transmission

Date   8/15/2014   Execute

Flight Time Logged On Maintenance Records at End of Month

Month	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14
Hours	7,211	7,279	7,342	7,379	7,433	7,526	7,611	7,705	7,787	7,868	7936			
Monthly Hrs		68	63	37	54	93	85	94	82	81	68			

TOTAL		Logged Hrs	Difference
Files	1047		
Recorded Hrs	844.68		
Rotor Not Turning Hrs	50.25		
Rotor Engagement	437		
Rotor Turn Hrs (Nr > 50%)	794.42		137.42
Flight Hrs (Airborne)	617.85	657	-39.15
Low Speed/Hover Hrs (< 40 KTS)	34.45		
High Speed Hrs (> 129 KTS)	409.15		
Landings	1024		
E1 Overspd (counts)	0		
E2 Overspd (counts)	1		
		NPH/RTT	NPH/FT
MR PUH	65.28	0.082	0.106
Engine #1 PUH	64.23		
Engine #2 PUH	68.90		

Select month to compare

Oct-13
Dec-13

Torque bins (%)	Time (%)	Time (hrs)	NPH Factor	NPH (hrs)
10	13.14%	104.39	0.001953	0.20
13	2.83%	22.50	0.002405	0.05
16	1.18%	9.40	0.00296	0.03
19	2.54%	20.19	0.003645	0.07
22	1.88%	14.91	0.004487	0.07
25	0.64%	5.08	0.005524	0.03
28	0.48%	3.84	0.006801	0.03
31	0.50%	3.96	0.008373	0.03
34	0.59%	4.71	0.010309	0.05
37	0.73%	5.83	0.012691	0.07
40	0.84%	6.71	0.015625	0.10
43	1.09%	8.67	0.019237	0.17
46	1.44%	11.40	0.023683	0.27
49	1.68%	13.31	0.029157	0.39
52	2.42%	19.20	0.035897	0.69
55	3.62%	28.75	0.044194	1.27
58	4.57%	36.29	0.054409	1.97
61	7.13%	56.60	0.066986	3.79
64	9.92%	78.79	0.082469	6.50
67	10.72%	85.19	0.101532	8.65
70	13.92%	110.56	0.125	13.82
73	10.82%	85.97	0.153893	13.23
76	4.36%	34.62	0.189465	6.56
79	1.44%	11.48	0.233258	2.68
82	0.56%	4.41	0.287175	1.27
85	0.45%	3.60	0.353553	1.27
88	0.27%	2.14	0.435275	0.93
91	0.15%	1.20	0.535887	0.64
94	0.06%	0.50	0.659754	0.33
97	0.02%	0.16	0.812252	0.13
100	0.01%	0.04	1	0.04
103	0.00%	0.01	1.231144	0.01
106	0.00%	0.00	1.515717	0.00
109	0.00%	0.00	1.866066	0.00
112	0.00%	0.00	2.297397	0.00
115	0.00%	0.00	2.828427	0.00
SUM	100.00%	794.42		65.36
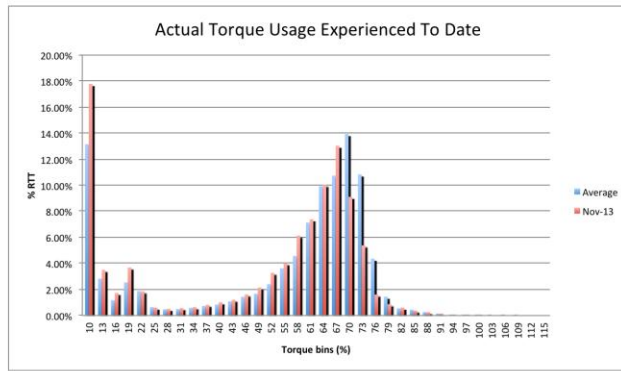
Airspeed bins (KTS)	Time (%)	Time (hrs)
10	4.06%	25.06
20	0.42%	2.61
30	0.50%	3.08
40	0.60%	3.69
50	0.53%	3.26
60	0.50%	3.07
70	0.65%	4.04
80	1.49%	9.22
90	2.06%	12.75
100	2.54%	15.69
110	2.58%	15.92
120	2.49%	15.36
125	3.76%	23.25
130	8.44%	52.17
135	14.61%	90.27
140	26.45%	163.44
145	23.95%	147.96
150	4.31%	26.60
155	0.05%	0.33
160	0.00%	0.02
165	0.00%	0.00
170	0.00%	0.00
175	0.00%	0.01
180	0.01%	0.05
SUM	100.00%	617.85

Actual Torque Usage Experienced To Date

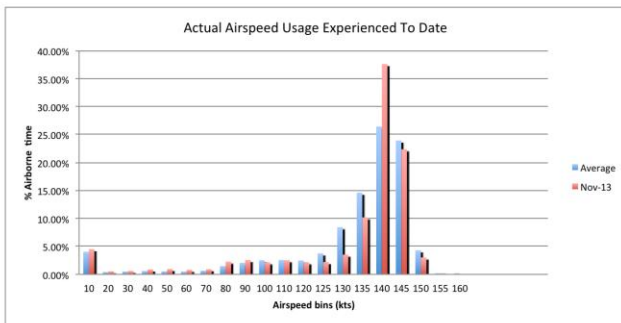Actual Airspeed Usage Experienced To Date

Figure 7. Example of automated power usage calculation and reporting.

Optional Paths for Implementation

When the power usage metric is accepted by the OEM Transmission Design Team and the MSG-3 (Helicopter) Working Group, the OEM documentation supporting a new helicopter will include guidance on how the products of the power usage algorithm will be recorded and applied (Ref. 17).

In addition, OEM and maintenance engineers will work together to:

- develop an OEM and helicopter model unique variant of the power usage metric,

- define the upper boundary of benign usage, moderate usage, high performance usage,

- establish the TBO based upon the power usage hours and flight time, and

- include maintenance and operational instructions in the OEM (regulator approved) documentation.

When an operator has a fleet of a single helicopter model, the operator will use the baseline power usage metric formula to support a lead the fleet proposal (Ref. 17) to the FAA requesting approvals of transmission TBO extensions based upon flight time and supported by the following:

- Transmission overhaul with records documenting excellent inspection results.

- Concurring HUMS history health/condition data history.

- Power usage history documentation.

- Power usage limit that will not be exceeded.

Civil Operational Experience

The following two examples are used to demonstrate the effectiveness of this metric in capturing power usage in various operations. Figure 8 illustrates how power usage is accumulated during a single point-to-point personnel transport flight with one takeoff and one landing.
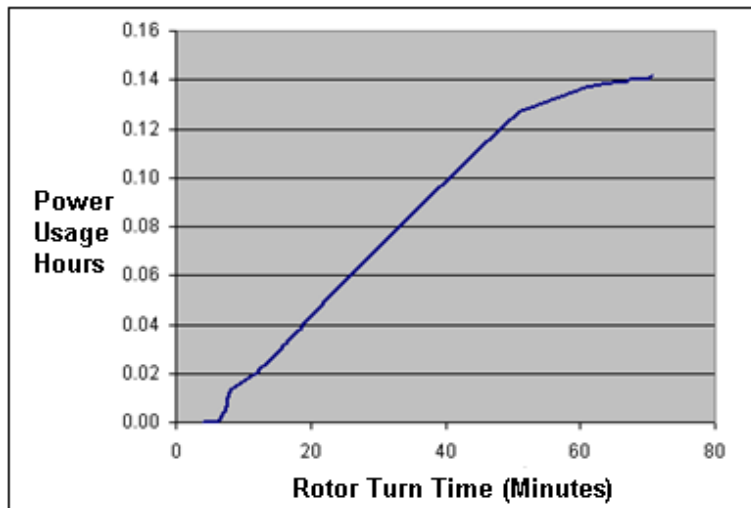

Figure 8. Time history of power usage hours accumulated during a single leg operation.

In contrast, the flight illustrated in Figure 9 below involved a number of takeoffs, climbs to cruise altitude followed by descents to landings with significant time on the ground at flight idle. When the aircraft is on the ground at flight idle essentially no increase in power usage is accumulated but high rates of increase in power usage occur during climbs to cruise and cruise are observed.
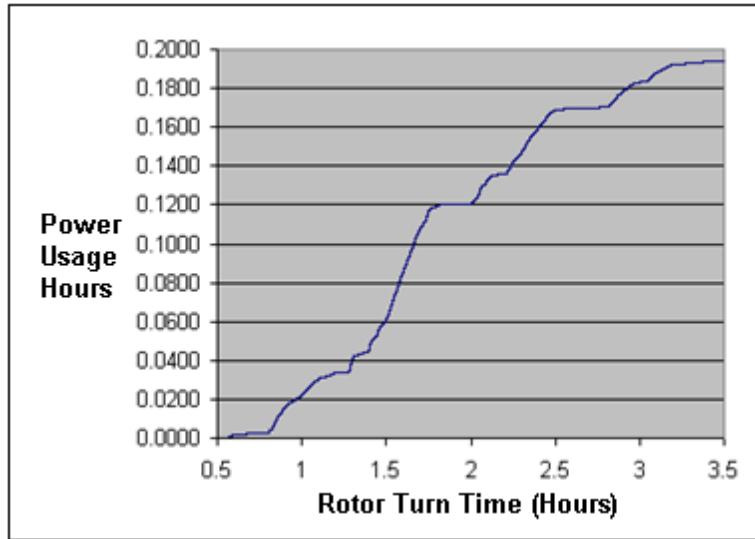
Figure 9. Time history of power usage accumulated during a flight involving several ground operations, hovers, climbs, transits at altitude with descents to vertical landings.

The PUH metric also has the capacity to characterize different missions. Figure 10 illustrates the way it can vary for a single model helicopter operated at different levels of power usage. If the aircraft is operated at the most severe level of usage, the usage rate can be 10 times that of the least severe usage rate. Regardless, currently all helicopters of a single model are treated identically when it comes to time between inspections and overhaul for the main transmission.
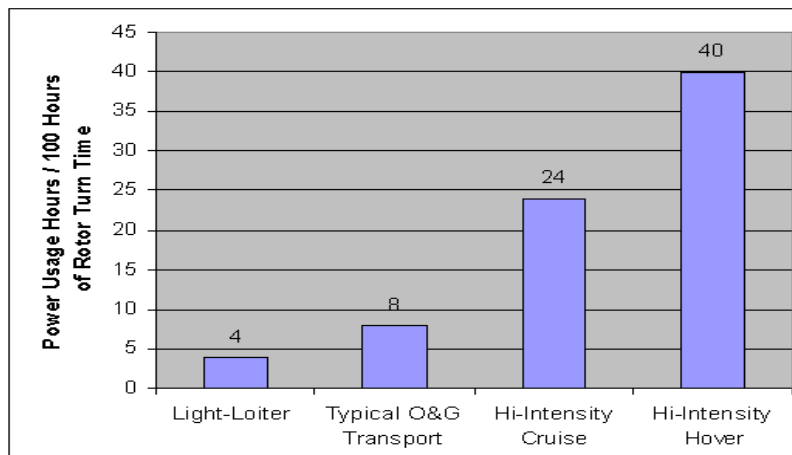

Figure 10. Power usage as a function of mission severity.

Figure 11 compares the moderate usage typical of that experienced with S-76C+ helicopters flying a typical transport mission for Oil and Gas Producers in the Gulf of Mexico to the usage spectrum estimated for the same model helicopter flying a near max gross, high speed cruise profile. Except for hovers, takeoffs and landing maneuvers, this profile involves cruise flight that approaches but does not exceed the power setting for max continuous power and takeoff power never exceeds the 2 minute limit. This profile is demanding but is expected to be well within the envelope of usage used by all OEMs for the design and engineering demonstrations of the main transmission.
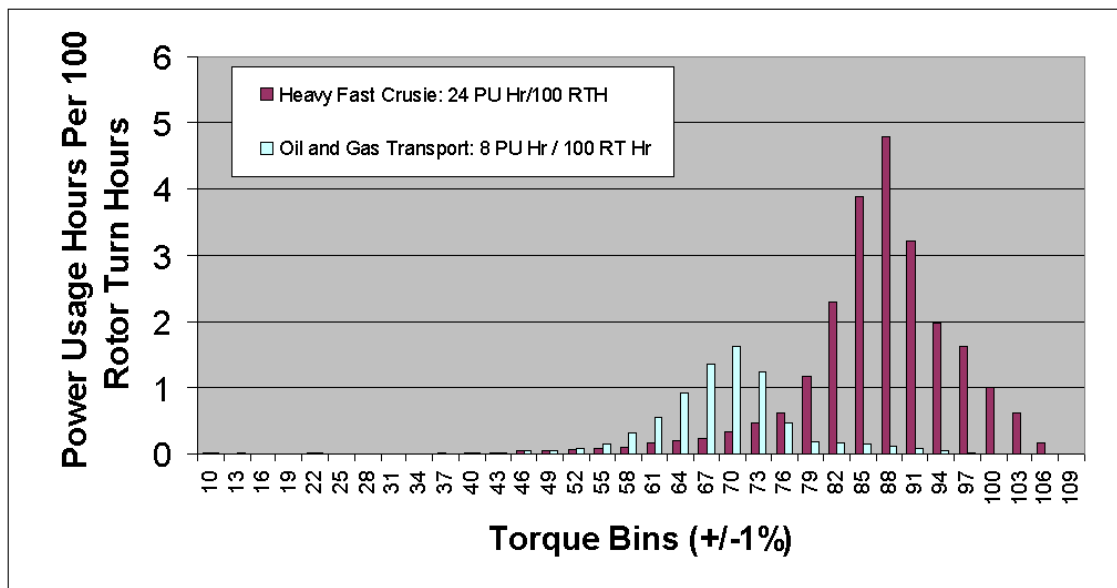

Figure 11. Power Usage as a function of two different mission profiles.

The same concept can also be applied to the tail rotor drive system. Figure 12 and Figure 13 illustrate the application of tail rotor torque and tail rotor drive power usage factor during a transport flight between two heliports. The cumulative power usage accrued during this flight equals 0.00295 PUH. While not shown, the total time in service or RTT of this flight was close to 1 hour. Therefore, the rate of tail rotor power usage

consumption relative to time in service is roughly 0.00295 PUH/RTT. This relative low

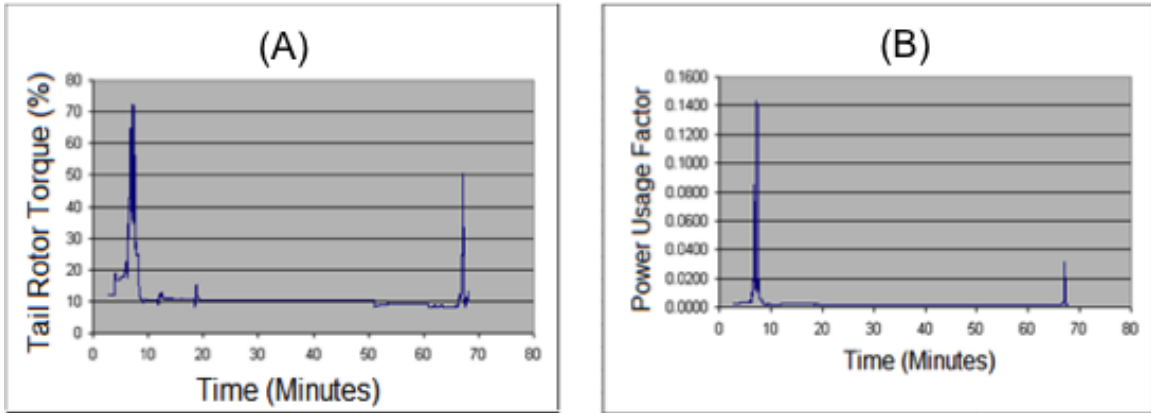usage rate reflects the fact that there was only one takeoff and one landing.

Figure 12. Tail rotor torque (A) during a single transport flight, and its corresponding
power usage factor (B).

Figure 13 presents the power usage factor time history during the brief period of time

required to takeoff and depart. There were three applications of tail rotor power during
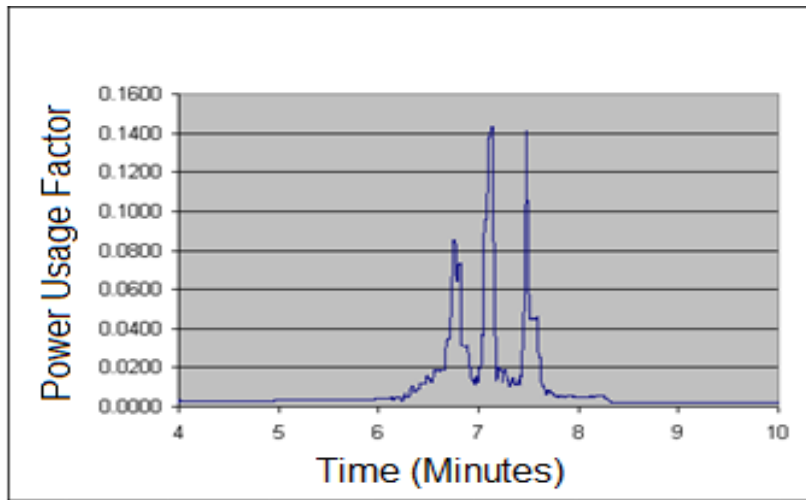
the departure.

Figure 13. Variation of tail rotor usage factor during and departure maneuvering.

Figure 14 shows the usage spectrum for the tail rotor torque from an AW139 over a two-month period with 52 hours of RTT. The PUH for the tail drive system is only 0.013 per RTT, which is about 1/10 of the main drive system (0.136 PUH per RTT).
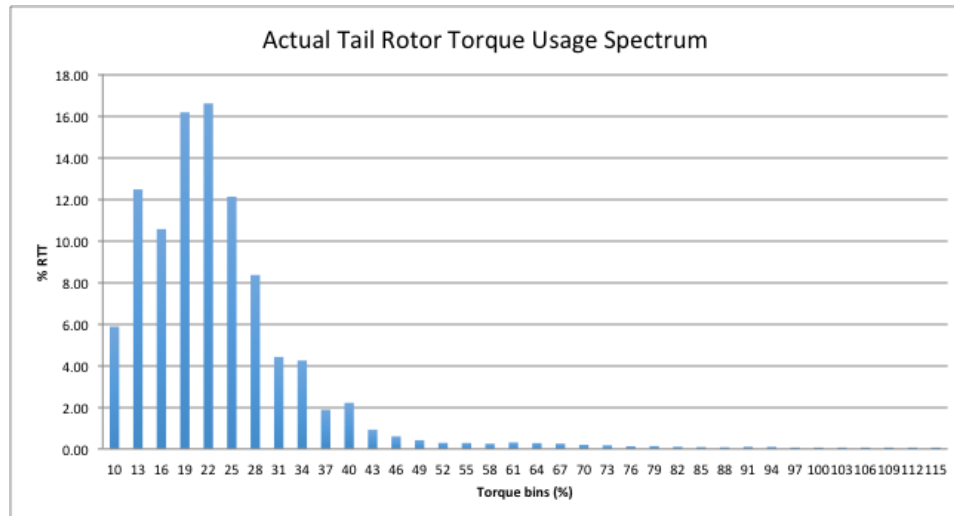

Figure 14. Tail rotor torque usage spectrum over a two-month period.

Early Military Experience

The power usage metric was demonstrated between 2004 and 2006 on Goodrich's IMD HUMS installed in several models of the H-60 helicopter during a HUMS demonstration program. A software tool called "MDAT" accompanied the Ground Station automatically computed PUH for all of the H-60 helicopters equipped with IMD HUMS. The MDAT software was capable of plotting Health Indicators (HI) of transmission components as a function of either the Power Usage Hours or Flight Time.

In one case the power usage history of the aircraft was collected for 27 months and downloaded to the MDAT database. The power usage of the main transmission during deployment was observed to be 2.7 greater than when the same aircraft were operated in training prior to deployment. This increase was explained by the fact that the deployed

aircraft were flying faster and at heavier gross weights than was the case during training in the pre-deployment phase of the demonstration.

Conclusions

In summary, flight time is an imperfect metric for scheduling TBO of rotorcraft transmissions. In contrast, the power usage metric presented in this paper enables an accurate and reliable method for scheduling transmission overhauls. The power usage metric can be easily integrated into an existing or future HUMS system; and when integrated into HUMS, the power usage metric algorithm accurately captures the power usage of the transmission based on collected flight data.

The power usage metric can be introduced into new rotorcraft during preliminary design with an OEM unique variant of the power usage algorithm but most likely as an integral feature of MSG-3 processes. Helicopter operators can also introduce the power usage metric via a lead the fleet program supported by overhaul/inspection findings, HUMS health/condition data and torque usage spectrum for post-flight processing into accumulated power usage hours.

Since baseline PUF formula is normalized to 100% NRP the baseline power usage metric formula is the same for all transmission designs. This commonality is a significant attribute of the power usage metric for it simplifies the burden of proof for operators desiring to propose a lead the fleet approach to transmission TBO extensions.

Based on several years of operational experience, the advantages of tracking power usage can be summarized as follows:

- When a helicopter is equipped with a HUMS the power usage metric can be used by the OEM to establish the TBO for rotorcraft transmissions.

- When commercial helicopter operators equip helicopters with HUMS, the baseline version of the power usage metric can be used in conjunction with the historical records of transmission overhaul inspections and a historical health record to apply for lead the fleet extensions of transmission TBO.

- When the PUH is tracked for a transmission along with the HI data (for the most worn part in the transmission) the maintainer can follow the trend and predict the need and plan for condition based intervention maintenance actions.

- When a problem is found in a gearbox assembly that is judged to be a safety of flight factor, the accumulated PUH and the last reported HI are two metrics that can be used to determine the significance of the issue to fleet readiness.

Acknowledgements

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