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Life Prediction of Helicopter Engines Fitted with Dust Filters

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Engine erosion in environments such as those that may be encountered by helicopters during hover, nap-of-the-Earth flight, dust storms, and generally dusty atmospheres can have significant effects on engine performance and life, resulting from the degradation of the first-stage compressor. Ingestion of dust into a turbine engine may be limited by means of dust filters fitted to the engine intakes. Efficient filtration of the dust results in a sparse dust concentration entering the engine that is comprised essentially of particles that have a diameter of less than 100 μm, and indicated negligible particle-on-particle interactions. The dependence of engine performance on the erosion of the first-stage compressor by sparse dust concentrations may be extended to enable the life of an engine to be predicted for a typical flight in a specific dust environment. The methodology for predicting engine life is presented.

Nomenclature

E = erosion, g or cm³
E_r = erosion rate, g/g or cm³/g
E_s = specific erosion, kg μm
E_0 = erosion rate if no collisions occur
$f_{\rm dust}(\phi)$ = function describing the fractional particle size distribution of the dust
$f(\phi)$ = function describing m_i for ϕ_i
k = constant dependent on engine and erodent properties
M = mass of ingested particles, kg
$M_{\rm fed}$ = dust mass fed to the filtration system, kg
M_i = dust mass in each particle size band i, kg
$M_{\rm ingested}$ = dust mass ingested by the engine, kg
M_s = dust mass scavenged from the filter system, kg
$M_{\rm scav}$ = dust mass scavenged by the filtration system, kg
m_i = M_i/M
P_1/P_2 = compressor pressure ratio
Q_i = volumetric airflow rate of the engine in each flight regime i, m³/s
S = scavenge ratio
$T_{\rm dust}$ = total time required to attain the given level of power deterioration when ingesting unfiltered dust, s
$T_{\rm filter}$ = total time required to attain the given level of power deterioration, s
$T_{\rm tube}$ = total time required to attain the given level of power deterioration when ingesting dust filtered using a specific vortex tube type, s
$T_{\rm unsteady}$ = total time required to stabilize the erosion process due to initial blade polishing taking place, s
t_i = time fraction of the specific flight regime i, i.e., 0.1 for 10%
V = impact velocity, m/s
W_r = rate of engine power loss, %/kg
α = exponent between 2.0–2.3
ΔW = percentage engine power loss, %
$\eta_{\rm erosion}$ = erosion-based filtration efficiency parameter
$\eta_{\rm FEL}$ = erosion-based filtration efficiency parameter required to obtain a specified engine mean-time-between-replacements
$\eta_{\rm mass}$ = mass-based filtration efficiency
λ_i = ambient dust concentration in the flight regime i, kg/m³
ϕ = particle size, μm
$\phi_{\rm eff}$ = effective particle size, μm
$\phi_{\rm effDust}$ = effective particle size of the dust distribution, μm
$\phi_{\rm ideff}$ = effective particle size of the unfiltered reference dust in flight regime i, μm
$\phi_{\rm iteff}$ = effective particle size (of the through-flow stream of the filter) of the representing dust type in flight regime i, μm
$\phi_{\rm mass\,mean}$ = mass mean particle size, μm
$\phi_{\rm max}$ = maximum ingested particle sizes, μm
$\phi_{\rm max\,Dust}$ = maximum unfiltered ingested particle sizes of the dust distribution, μm
$\phi_{\rm min}$ = minimum ingested particle sizes, μm
$\phi_{\rm min\,Dust}$ = minimum unfiltered ingested particle sizes of the dust distribution, μm

Introduction

DUSTY environments may be encountered by helicopters in dry conditions. Dust ingested by turbines can give rise to erosion of its components, especially the first-stage compressor blades that will result in a loss of performance, reduced mean-time-between engine overhauls, and an increase in logistic support and the associated costs. In extreme cases engine lives may be reduced to less than 50 h, which severely restricts the availability of the helicopter.

Dust may, to a large extent, be prevented from being ingested into an engine by means of dust filters that remove most of the larger diameter fractions of the dust from the air drawn into the engine. It was dramatically demonstrated during the Gulf War in 1991 that several of these intakes offered inadequate erosion protection. While a predictive capability may be essential under certain operating conditions, it appears that published research carried out to-date on the relationships between the performance of filtered intakes and the resulting erosion of helicopter turbine engines is virtually nonexistent, and that only the operation of filters are mostly described in the literature.[1–7] This may be partly attributed to the high cost of carrying out tests on turbine engines or on their compressors. Although Duffy et al.[1] reports on erosion tests on the T700 engine fitted with an integral particle separator, no analytical relationships between engine erosion and the erodent are discussed.

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An experimental program was carried out by van der Walt[8] to analyze the relationships between filtration efficiency, ingested particle properties, environmental properties, and engine erosion. These relationships are then adapted to enable the prediction of engine life. The method is based on a macroscopic approach to the effects of erosion, i.e., the erosion of the engine as a whole is considered rather than considering detailed wear patterns resulting from an analysis of particle trajectories in the engine as considered by Tabakoff[9] and his co-workers.

Mass-Based Filtration Efficiency

The mass-based filtration efficiency for a scavenged filter system[8] may be defined as

$$\eta_{\text{mass}} = \frac{1}{1 - S}\left(\frac{M_s}{M_{\text{fed}}} - S\right) \tag{1}$$

Engine Erosion Analysis and Experimental Results

The erosion of metal test pieces by the impingement of different solid particles is a well-covered subject, although all the mechanisms of erosion are not yet fully understood. It is therefore surprising to find that only limited information on the specific erosion environment in which helicopter engines operate exists in the open literature. Erosion rate, based on mass or volume, can be expressed in terms of a unit mass of ingested particles:

$$E_r = (E/M) \tag{2}$$

Relationship Between Engine Erosion, Power Deterioration, and Filtration Efficiency

The most important parameters influencing engine erosion were obtained after a literature survey and are categorized in Table 1.

It has been shown during an extensive research program[8] that for sparse dust concentrations in which particle-on-particle interactions are negligible, the erosion of the first stage compressor is given by

$$E = kM\phi V^{\alpha}$$

or

$$E_r = k\phi V^{\alpha} \tag{3}$$

and since the power degradation has been found[8] to be proportional to the erosion of the first-stage compressor, the power degradation is given by

$$\Delta W = kM\phi V^{\alpha}$$

or

$$W_r = k\phi V^{\alpha} \tag{4}$$

which apply to an erodent comprised of particles with a constant effective diameter. For the case of an erodent dust that is comprised of particles of various diameters, which are typical of those encountered during helicopter operations, it may be shown[8] that the power reduction may be given by

$$\Delta W = kM_1\phi_1V^{\alpha} + kM_2\phi_2V^{\alpha} + \cdots + kM_n\phi_nV^{\alpha}$$

$$= kV^{\alpha}\sum_{i=\phi_{\min}}^{\phi_{\max}} M_i\phi_i = kV^{\alpha}M\phi_{\text{eff}}$$

and thus

$$W_r = kV^{\alpha}\phi_{\text{eff}} \tag{5}$$

which, in terms of the mass fraction distribution, may be written

$$\Delta W = kV^{\alpha}M_{\text{ingested}}\sum_{i=\phi_{\min}}^{\phi_{\max}} m_i\phi_i$$

$$= kV^{\alpha}M_{\text{ingested}}\int_{\phi_{\min}}^{\phi_{\max}} f(\phi)\phi\, \mathrm{d}\phi \tag{6}$$

Combination of Eqs. (1) and (5) gives

$$\Delta W = kV^{\alpha}(1 - \eta_{\text{mass}})M_{\text{fed}}\int_{\phi_{\min}}^{\phi_{\max}} f(\phi)\phi\, \mathrm{d}\phi \tag{7}$$

Equation (7) may be used to show that the ratio of power deterioration or erosion rate for the filtered and unfiltered ingested air is given by

$$\eta_{\text{erosion}} = \frac{\int_{\phi_{\min\text{Dust}}}^{\phi_{\max\text{Dust}}} f_{\text{Dust}}(\phi)\phi\, \mathrm{d}\phi}{(1 - \eta_{\text{mass}})\int_{\phi_{\min}}^{\phi_{\max}} f(\phi)\phi\, \mathrm{d}\phi} = \frac{\phi_{\text{eff Dust}}}{(1 - \eta_{\text{mass}})\phi_{\text{eff}}} \tag{8}$$

This relationship provides a direct measure of the ratio of the rates of engine power deterioration for the unfiltered and filtered ingested air. Consequently, Eq. (8) may be used to assess the improvement in engine life that may be obtained for a given filtration system.

Experimental Test Results from an Actual Engine

For the real engine experimental program, an overhauled Turmo IVB Puma helicopter engine was installed in an engine erosion test facility. In the first test, the filtered engine intake was removed and SAE coarse test dust was fed directly into the engine. The engine power was monitored regularly as a function of the mass of dust fed. The test was repeated on the same engine with the filtered air intake in place. The filtered air intake was fitted with vortex tubes and had a confirmed mass based filtration efficiency of 95%. Due to the extremely high cost of engine overhauls, the filtered air intake was not tested with other vortex tube types or dust grades. Results from these tests, expressed in terms of the dust mass ingested by the engine is shown in Fig. 2 instead of the dust mass fed from the dust feeder (Fig. 1).

One of the striking observations that can be made from Fig. 1 is the well-known initial power increase due to dust

Table 1 Parameters influencing solid particle erosion

Material properties	Erodent properties	Environmental properties
Material composition[10,11]	Particle size[13,14]	Particle impact velocity[10,11,18]
Material hardness and ductility[12]	Mass of ingested particles[15]	Particle concentration[17]
	Particle hardness[12]	Particle impact angle[11]
	Particle shape[16]	Particle slip velocity[19]
	Particle fragmentation[17]	Temperature[14,20]
	Quartz content of erodent[11]	Humidity[21,22]

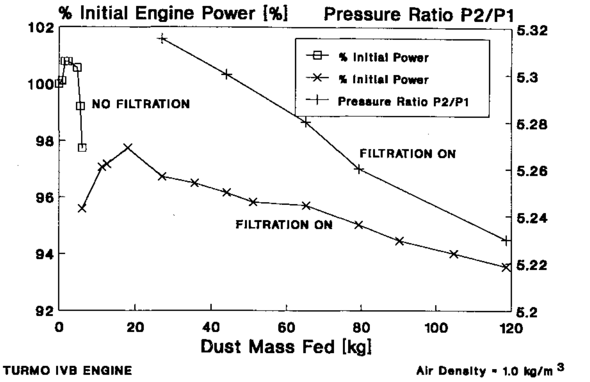

Fig. 1 Turmo IVB engine power and pressure ratio deterioration rates as functions of dust mass fed (with and without a 95% efficient filtration system).

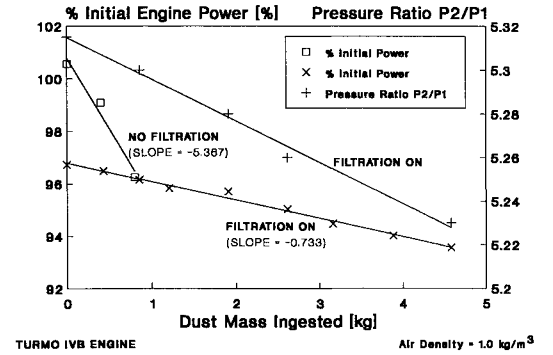

Fig. 2 Turmo IVB engine steady-state power and pressure ratio deterioration rates vs dust mass ingested (with and without a 95% efficient filtration system).

polishing the blade surface. During this phase the erosion rate is a function of the ingested dust mass and will be referred to as the unsteady phase. It is not intended to include the initial unsteady incubation phase in the analysis because it is influenced by numerous factors other than filtration performance related properties, and is a study on its own. Since the differences in the unsteady phases shown in Fig. 1 should mainly be due to differences in erosion, it will be assumed for this analysis that the length of the unsteady phase (mass of dust required to stabilize the erosion process) will also be governed by Eq. (7). This implies that sufficiently accurate engine life comparisons, as given by Eq. (8), can be drawn by investigating only the phases where the erosion rates are independent of the ingested dust mass (referred to as the steady phase), and thus, it is an unnecessary complication to analyze them during the unsteady phase. When the steady phase is reached, a near-linear relationship between engine power and ingested dust mass exists. In this condition, it is assumed that all variables not related to filtration performance remain constant as discussed in the previous paragraphs. This enables the analysis of filtration performance to be carried out independently of other factors.

The deterioration of the engine compressor pressure ratio P_2/P_1 as a function of dust mass fed (filtration system active) is shown in Fig. 1 for the steady region, using the right-hand ordinate. Linear regressions on the steady portions of the two power deterioration curves as well as the pressure ratio deterioration curve are shown in Fig. 2. Within the first 5–10% power loss, which is the area of interest, a linear relationship seems to exist for all three relationships. For the test case with no filtration system fitted, a least-squares correlation coefficient of 0.967828 was obtained, and for the test where the 95% efficient filtration system was fitted, a correlation coefficient of 0.989399 resulted for the engine power deterioration, and a correlation coefficient of 0.992094 for the pressure ratio deterioration. These linear relationships hold up to 10% power deterioration that is normally the range of useful engine life.

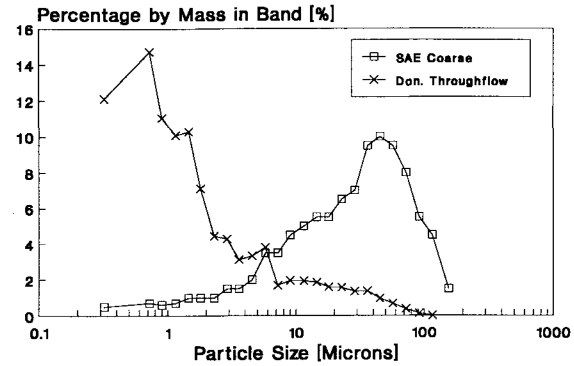

Fig. 3 SAE coarse and Donaldson through-flow (SAE coarse dust ingested) particle size distribution expressed as mass fractions.

The second observation that can be made from Figs. 1 and 2 is the near-linearity of the pressure ratio deterioration with the dust mass fed to the filtration system. This result supports the observation made earlier[8] that gas turbine compressor performance and erosion are linearly related for the experiments conducted, and that the erosion correlation given in Eq. (3) can be readily applied to provide measures of power deterioration as given in Eq. (7). A third observation from Fig. 2 is the difference between the slopes of the two power deterioration graphs. Since the slope of these graphs do in fact represent the steady-state rate of engine power deterioration, they were tested against the newly proposed engine erosion correlation.

These slopes will be used to verify the engine erosion correlations previously derived. Particle size analysis, using a Sedigraph, was performed on a sample of Standard SAE coarse test dust and the dust that remained in the main airstream after filtration of SAE coarse dust by a vortex tube. Figure 3 shows the particle size distributions expressed as mass fractions. Application of the method of analysis given by Eq. (5) allows the effective particle sizes to be calculated for both dust types. Since the engine power loss is known for both cases, the constant k can be calculated. This constant is dependent on the engine characteristics as well as dust properties. Application of Eq. (6) rather than Eq. (5) results in a simplified analysis since the function representing the mass fraction of the particle size distribution can be integrated directly, and therefore, no calculation of actual masses for each particle size band is needed.

The ϕ_{eff} for unfiltered SAE coarse and the through-flow stream of the Donaldson vortex tube were found to be 38.737 and 4.93 μm, respectively, the ratio of which agrees well with the ratio of the slopes in Fig. 2. Since the effective particle sizes, as well as the mass-based filtration efficiency is known; η_{erosion} for the Donaldson vortex tube can be calculated by application of Eq. (8). Unfiltered SAE coarse test dust is used as the reference base:

$$\eta_{\text{erosion}} = \frac{38.74}{(1 - 0.95)4.93} = 157 \tag{9}$$

This result provides a direct measure of the erosion reduction (and, thus, life improvement) brought about by the vortex tube. When fitted with the vortex tube filtration system, the engine will last 157 times longer than if no filtration was applied and the engine ingested unfiltered SAE coarse. The experimental erosion rates given by the slopes in Fig. 2 agree well with the calculated erosion rates using the effective particle sizes. Since the same engine was used for both tests, the same engine erosion constant should emerge. This condition was satisfied when effective particle sizes were used (ϕ_{eff} =

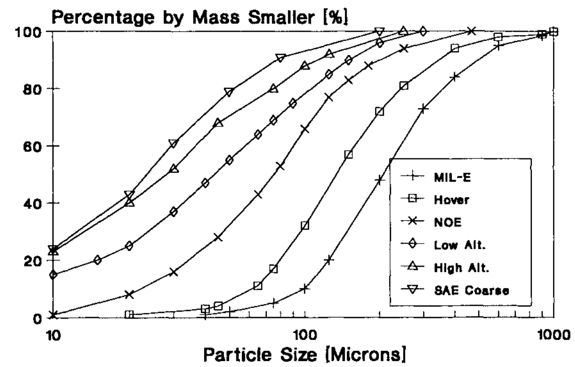

Fig. 4 Particle size distributions of South African ambient dust for various flight altitudes (log scale on abscissa).

38.737 for SAE coarse dust, and $\phi_{\text{eff}} = 4.93$ for filtered SAE coarse dust), and could not be satisfied when mass mean particle sizes were used ($\phi_{\text{mass mean}} = 30$ for SAE coarse, and $\phi_{\text{mass mean}} = 1.21$ for filtered SAE coarse dust). Hence, it is concluded that Eqs. (7) and (8) are sufficient to predict the erosion process of filtered helicopter engines accurately.

Assessment of Replacement Critical Filtration Efficiency Limits

The replacement critical filtration efficiency limit (FEL) is defined as the erosion reduction factor (η_{erosion}) required to ensure engine life equal to that of the prescribed mean-time-between-replacement (MTBR) of the engine component most affected by dust wear. Factors that will influence this parameter are the environmental dust composition, environmental dust concentrations, a description of the typical flight envelope of the particular helicopter, and the operating mode (single or dual mode) of the intake.

To quantify the FEL the filtration system performance must be obtained and the intended flight envelope must be characterized such that a realistic representation is portrayed. The characterizing of the flight envelope depends on the mission of the helicopter as well as the local environmental variables, and can vary considerably for different helicopters and locations.

Table 2 Characterizing of a typical Puma ferry operation flight envelope in the Southern African region

Flight regime	Percent of flying time (ferry operation)	Dust concentration, mg/m^3	Dual mode filtration operation
Takeoff, hover, and landing	5	50	Active
NOE	20	15	Active
30–300 m	25	6	Bypassed
300 m and above	50	2	Bypassed

Evaluation of Local Environmental Dust Compositions

It is evident from the conclusions of local researchers,[23] as well as from the research by Duffy,[1] that the particle size distributions of dust encountered in most typical helicopter flight envelopes are embraced by the particle size distributions of SAE coarse and MIL-E-5007E test dusts. Results from the tests by Albertyn and Heinichen[23] are presented in Fig. 4.

Ambient dust particle composition was often found to approximate that of MIL-E-5007E during hover flight where larger particle sizes were stirred up by the rotor downwash. Finer dust compositions were measured at higher altitudes with a closer resemblance to the particle size distribution of SAE coarse. Subsequently, it was decided to divide the flight envelope into two regions where the environmental dust during hover flight is simulated with MIL-E-5007E dust, and the remainder of the flight envelope with SAE coarse test dust. Variations in the dust concentrations at the different flight altitudes were also considered.

Evaluation of Local Environmental Dust Concentrations

From the studies by De Reus[24] and Möhlmann and Chertkow[25] it seems that the typical flight envelope of an Aerospatiale SA330 Puma helicopter in the Southern African region can be approximated by four different dust concentrations. For hover flight a dust concentration of 50 mg/m^3 was suggested. This concentration was reduced to 15 mg/m^3 for nap-of-Earth (NOE) flight (below 30 m altitude), 6 mg/m^3 for flight between 30–300 m, and 2 mg/m^3 for flights higher than 300 m.

Flight Envelope Description

A typical ferry mission for a SA330 Puma helicopter is shown in Table 2.[25]

When the helicopter is fitted with a dual-mode filtered intake, the pilot can select the on/off status of the filtration system by opening or closing the intake bullet, allowing the air to bypass the filtration system, or to force it to flow through the filtration system. On the Puma helicopter the filtration system is activated automatically when the landing gear is lowered. This means that except for takeoff, hover, landing, and NOE flights (for the ferry operation), the filtration system will be bypassed.

Engine Life Prediction and Calculation of the Replacement Critical Filtration Efficiency Limit

Since the FEL depends on the MTBR of the first-stage compressor blades of the Turmo IVB engine for this analysis, the calculated engine MTBO, which includes the effect of engine erosion, must be equal to the compressor stage MTBR supplied by the manufacturer. The MTBR has historically been expressed in terms of engine operating hours, however, some engine manufacturers now recommend a cycle limit. For the Turmo IVB engine a limit of 5000 h has been used, whereas a limit of 13,000 cycles for similar engines is now being set. In practice, engines are overhauled after a power

Table 3 Specific erosion calculation for a Turmo IVB engine fitted with a single mode intake equipped with Donaldson vortex tubes for the characterized flight envelope

Flight regime, i	Hours of flight	Dust concentration, mg/m^3	Dust mass entering engine M, kg	Equivalent dust type	Effective particle size, ϕ_{eff} μm	Specific erosion $\Sigma M_i \phi_{i\text{eff}}$, kg μm
Hover	250	50	11.25	MIL-E	7.00	78.8
NOE	1000	15	13.50	SAE	4.93	66.6
30 m	1250	6	6.75	SAE	4.93	33.3
300 m	2500	2	4.50	SAE	4.93	22.2
Σ:	5000	—	36	—	—	200.8

deterioration of approximately 5–10%. A limit of 5% is used for analysis purposes.

The number of cycles per mission is calculated by taking account of significant power variations that might occur between engine start and stop. These power variations, called partial cycles, are then added together and added to the complete cycle (1 for one mission flown). From this information the MTBR limit in hours can be calculated and used as the FEL. For this analysis however, it is irrelevant how this value is obtained, and the MTBR will be assumed to be 5000 h.

Therefore, the specific erosion and power deterioration resulting after the 5000 h are calculated. Using the Turmo IVB engine fitted with a Donaldson vortex tube filtration system ($\eta_{\text{mass}} = 0.95$ and $\eta_{\text{erosion}} = 157$ based on SAE coarse dust) with an average airflow rate of 5 m³/s, the total specific erosion resulting from the use of the vortex tube, which is derived from Eq. (5) and defined in Eq. (10), can be calculated, and the power deterioration can be obtained and compared with the MTBO limit of 5%:

$$E_s = \frac{\Delta W}{kV^\alpha} = \sum_{i=1}^{n} M_i \phi_{i\text{eff}} \tag{10}$$

The specific erosion for the chosen filtration system is calculated in Table 3. It is assumed that the unsteady phase extends the engine life by initially increasing the engine power somewhat and then returning it to 100%. Possible errors resulting from this assumption should be relatively small, as the entire unsteady phase was shown to be approximately 10% of the total erosion process when SAE coarse test dust was ingested (Fig. 1).

The resulting loss in engine power can be calculated by subtracting the unsteady phase relative erosion from the steady phase relative erosion, and then multiplying the result by the engine erosion factor kV^α [experimentally determined to be -0.145 for the Turmo engine using Eq. (5)]. The power deterioration for this case is calculated to be

$$\begin{aligned} \Delta W &= (E_{s\,\text{tube}} - E_{s\,\text{unsteady}})kV^\alpha \\ &= (200.8 - 4 \times 38.737)0.145 \\ &= 6.64\% \end{aligned} \tag{11}$$

which is 1.64% more than the MTBO limit of 5%. It is more convenient to simply calculate the MTBO resulting from each filtration system to enable comparison. The MTBO resulting from the Donaldson vortex tube (lower than 5000 h) can be calculated by subtracting the unsteady phase specific erosion from the right-hand term in Eq. (10). Reorganizing the middle and right-hand terms and writing the ingested dust mass in terms of air volume flow rates, time fractions, dust concentrations, and mass-based filtration efficiencies, results in an equation giving the MTBO for the evaluated filtration system:

$$T_{\text{tube}} = \frac{E_{s\,\text{required}}}{E_{s\,\text{tube}}/T} = \frac{(\Delta W/kV^\alpha) + (M\phi_{\text{eff}})_{\text{unsteady}}}{\sum_i Q_i t_i \lambda_i (1 - \eta_{\text{mass}})_i \phi_{\text{it eff}}} \tag{12}$$

where

$$\phi_{\text{it eff}} = \int_{\phi_{\text{it min}}}^{\phi_{\text{it max}}} f_{\text{it}}(\phi)\phi \, d\phi$$

The numerator in Eq. (12) would be the total specific erosion required to attain the given level of power deterioration (5% in this case). The denominator represents the specific erosion per unit time T due to the use of the vortex tube. Hence, the MTBO resulting from the Donaldson vortex tube can be calculated from Eq. (12):

$$T_{\text{tube}} = 4718 \text{ h} \tag{13}$$

It is clear that the objective of a 5000-h MTBO for this flight envelope specification cannot be achieved fully by the Donaldson vortex tube. It is therefore necessary to calculate the FEL as well as η_{erosion} for each vortex tube type for the given flight envelope to enable reliable comparisons. Since a combination of different dust types is used, the erosion reduction factor given by Eq. (8) ($\eta_{\text{erosion}} = 157$ for the Donaldson vortex tube when based on SAE coarse test dust alone), has to be adapted:

$$\eta_{\text{erosion}} = \frac{T_{\text{tube}}}{T_{\text{dust}}} = \frac{E_{s\,\text{dust}}/T}{E_{s\,\text{tube}}/T} = \frac{\sum_i Q_i t_i \lambda_i \phi_{\text{id eff}}}{\sum_i Q_i t_i \lambda_i (1 - \eta_{\text{mass}})_i \phi_{\text{it eff}}} \tag{14}$$

where

$$\phi_{\text{id eff}} = \int_{\phi_{\text{id min}}}^{\phi_{\text{id mass}}} f_{\text{id}}(\phi)\phi \, d\phi$$

$$\phi_{\text{it eff}} = \int_{\phi_{\text{it min}}}^{\phi_{\text{it max}}} f_{\text{it}}(\phi)\phi \, d\phi$$

As indicated in Eq. (14), the erosion reduction factor can be expressed as a ratio of MTBO times calculated by Eq. (12), which is also equal to the ratio of specific erosions or specific erosions per unit time resulting from the unfiltered and filtered dust streams, respectively. For the Donaldson vortex tube, the erosion reduction factor is calculated as follows, using the various approaches:

$$\begin{aligned} \eta_{\text{erosion}} &= \frac{4718 \text{ h}}{22.7 \text{ h}} = \frac{41{,}566 \text{ kg } \mu\text{m}}{200.8 \text{ kg } \mu\text{m}} \\ &= \frac{2.317 \times 10^{-3} \text{ kg } \mu\text{m/s}}{1.1154 \times 10^{-5} \text{ kg } \mu\text{m/s}} \\ &= 207 \end{aligned} \tag{15}$$

It is clear that the value of η_{erosion} can change significantly with changes in the flight envelope and ambient dust compositions. The required specific erosion to attain the 5000-h objective can be calculated by using the numerator in Eq. (12). This value can then be compared with the specific erosion resulting from the ingestion of the ambient dust when no filtration is done, giving a measure of the required improvement in erosion to achieve the FEL. Alternatively, the FEL is given by the ratio of the intended MTBR (5000 h) and the MTBO resulting when no filtration is done, giving a measure of the required improvement in engine life. The third possibility is to compare the specific erosions per unit time as given by Eq. (14). The required specific erosion [which is the numerator in Eq. (12)], is defined by

$$E_{s\,\text{required}} = (\Delta W/kV^\alpha) + (M\phi_{\text{eff}})_{\text{unsteady}} \tag{16}$$

and for the case at hand is calculated to be

$$\begin{aligned} E_{s\,\text{required}} &= (-5/-0.145) + (4 \times 38.737) \\ &= 189.43 \text{ kg } \mu\text{m} \end{aligned} \tag{17}$$

The FEL can thus be calculated using the three approaches discussed above.

Substitution of values obtained in Eqs. (15) and (17) results in the FEL for the specified flight envelope and environmental

Table 4 Comparison of calculated MTBO and statistical MTBO values for a 78% efficient Puma SA 330 filtered intake for different configurations

Filtration performance and mode	Calculated MTBO, h	Statistical MTBO, h	Deviation from mean, %
No filtration	22.7	25–32	20.7
78% dual mode (filter can be bypassed)	176.0	175–200	6.1
78% single mode (filter always operational)	458.0	380–450	10.4

dust compositions:

$$\eta_{\text{FEL}} = \frac{\text{MTBR}}{T_{\text{dust}}} = \frac{E_{s\,\text{dust}}}{E_{s\,\text{required}}} = \frac{\text{MTBR} \sum_i Q_i t_i \lambda_i \phi_{\text{id eff}}}{(\Delta W/kV^{\alpha}) + (M\phi_{\text{eff}})_{\text{unsteady}}} \tag{18}$$

$$\eta_{\text{FEL}} = \frac{5000\text{ h}}{22.7\text{ h}} = \frac{41{,}566\text{ kg }\mu\text{m}}{189.43\text{ kg }\mu\text{m}}$$

$$= \frac{2.309 \times 10^{-3}\text{ kg }\mu\text{m/s}}{1.052 \times 10^{-5}\text{ kg }\mu\text{m/s}}$$

$$= 220 \tag{19}$$

Comparison of Engine Life Predictions with Actual Flight Statistics

Statistical engine MTBO data obtained from the report by Möhlmann and Chertkow[25] regarding the Puma SA 330 helicopter is compared with calculated MTBO values for the flight envelope given in Table 4 for a 78% filtration efficient (by mass) system. Effective particle sizes for the 78% efficient filtration system were found to be 17 μm for MIL-E-5007E dust, and 11 μm for SAE coarse test dust.

Although helicopters fitted with improved filtered air intakes are evaluated, no information for the high-performance region (90% and above) is currently available. It seems from the available information that the proposed correlations predict engine MTBOs with reasonable accuracy. It is to be expected that the error will be significantly higher for the first case where no filtration was used, since deviations of only a few hours translate to large errors.

Conclusions

Using an analytical method based on the characteristics of sparse dust concentrations, combined with knowledge of the dust composition encountered in each phase of the flight mission, it was shown that it is possible to predict the expected life of a helicopter turbine engine.

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