Effect of Aero-Engine Washing on Turbine Gas Temperature Margin

DOHYEONG LIM, HYUKJUN KWON and DOOYOUL LEE

ABSTRACT

This study investigates the effects of engine washing on T700 engine performance and material deterioration. To assess performance improvement, turbine gas temperature margin data from six Sikorsky S-70 aircraft were analyzed using linear mixed model. The statistical test yielded a p-value below 0.05, rejecting the null hypothesis that there is no significant difference in the mean turbine gas temperature margin before and after engine washing. Regarding material impact, alternate immersion and potentiodynamic test indicated that residual chloride and sulfate ions in the washing water can increase corrosion risk. Additionally, exposure experiments confirmed that the wetting of metals post-washing could also trigger corrosion. Considering these conflicting effects, a Bayesian decision model was applied to determine the economic feasibility of engine washing strategies. The results indicate that engine washing is economically advantageous. Furthermore, considering both risk cost and washing cost, the analysis suggests that an optimal washing interval is 190 hours. The results of this study are expected to contribute to establishing an optimal engine corrosion management plan.

INTRODUCTION

Recently, the Sikorsky S-70 helicopter made a precautionary landing during takeoff due to a rapid increase in turbine gas temperature (TGT) and the activation of the engine-out warning light. An investigation revealed that foreign objects ingested into the engine had damaged the blades surface coating and passivation layer. This damage allowed corrosive elements to penetrate leading to localized pitting corrosion and subsequent fatigue cracking that resulted in the fracture of two compressor blades. Considering this incident, this study aims to evaluate the effects of engine washing on both engine performance and material deterioration, and to propose guidelines for an engine maintenance strategy that can prevent similar incidents in the future.

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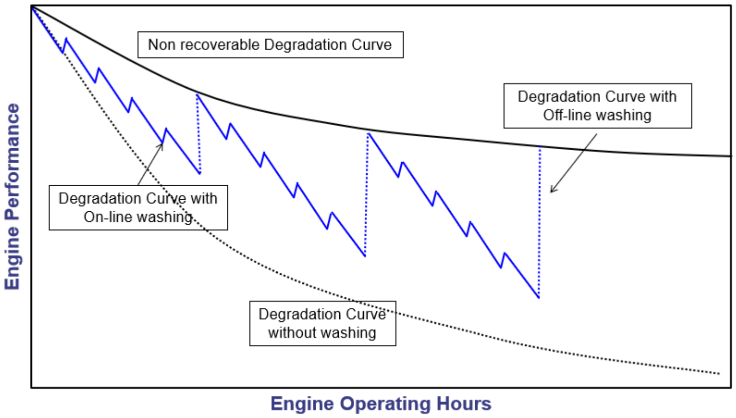

Figure 1. Engine Performance Degradation Curve.

When compressor is corroded or contaminated by airborne pollutants and foreign matter, the gas turbine's performance can degrade by about 70–80% [1]. For this reason, periodic compressor washing is essential for maintaining performance by removing contaminants from the blades.

According to the U.S. Air Force technical order T.O. 1-1-691 [2], removing salt deposits, corrosive contaminants, and electrolytes is crucial for preventing corrosion. Figure 1 illustrates the performance degradation curve of a gas turbine engine and shows the impact of periodic washing. In general, engine performance follows a continuous downward trend over time [3]. However, regular washing (both on-line and off-line) prolongs the period during which the engine can sustain higher performance relative to the original degradation curve. (See Figure 1.)

In terms of materials, tap water used for engine washing contains chlorides, sulfides, and other compounds that can accelerate corrosion if they remain on engine surfaces under atmospheric conditions [4]. Accordingly, the use of distilled water for engine washing has been proposed [3]. However, the deployment of equipment to produce sufficient distilled water at all military bases is almost infeasible.

The performance improvement and corrosion risk are in conflict which complicates operators' decisions about washing intervals and overall engine management. Therefore, Engine washing effects must be verified and an optimal strategy should be established to maintain engine performance and minimize the risk of corrosion.

This study quantitatively assessed whether engine washing has a significant impact on engine performance by using collected TGT margin data from Sikorsky helicopters. In addition, by reviewing prior research, we analyzed the effects of using tap water in engine washing on material corrosion. Based on these findings, a Bayesian decision model was developed to evaluate the relevant cost factors and to propose an engine management strategy that achieves maximum cost-effectiveness.

Material deterioration

Various methods are used to prevent metal corrosion, such as surface painting, plating and washing. [2] Among these, compressor washing which removes corrosion-inducing substances is primarily used to prevent corrosion in aircraft engine systems. However, tap water typically used for washing contains chlorine as a purifier.

Consequently, chloride ions may remain on the metal surfaces after washing which can increase the risk of corrosion [5].

Lim et al. [5] quantitatively analyzed how using tap water for washing influences metal corrosion. In their experiment, four types of immersion solutions were prepared with varying chloride and sulfate ion concentrations excluding pH. Test specimens were prepared using common aircraft metals. A series of wet-dry cyclic tests, acid washing procedures, and electrochemical measurements were conducted to evaluate parameters such as corrosion rate and corrosion potential. The concentrations of chloride and sulfate ions were chosen based on water quality data from treatment facilities near each base.

Although the weight loss varied with the chloride/sulfate ratio and the specimen type, the results consistently showed that residual chloride and sulfate ions after washing increase both the corrosion rate and the total mass loss. Notably, total mass loss was highest in solutions containing both chloride and sulfate ions, compared to solutions containing only one of these ion types. In addition, at the beginning of corrosion in solutions containing both chloride and sulfate ions, the corrosion rate increased rapidly. However, as corrosion progressed, competitive adsorption reactions occurred. When the chloride concentration was high, the corrosion rate unchanged according to the potentiodynamic test results. Furthermore, according to the weight loss measurements, the overall weight loss was mitigated.

Kwon et al. [4] directly observed the effects of aircraft washing under operational atmospheric conditions. They attached corrosion monitoring devices comprising aluminum alloy, carbon steel, and silver test plates to an aircraft's fuselage and wings, then analyzed corrosion under identical environmental conditions with and without washing. Experimental results showed that surfaces on the washed aircraft experienced more corrosion than those on an unwashed aircraft under identical environmental conditions. This increased corrosion was attributed to the metal surfaces remaining wet for longer because they did not dry completely after washing.

METHOD

Engine washing methods

Gas turbine engine washing is typically classified into on-line washing and off-line washing. While off-line washing allows for the complete cleaning of all compressor stages, it requires a prolonged shutdown period to decrease internal temperature. In contrast, on-line washing involves the injection of ambient-temperature water into the compressor inlet for a short duration while the turbine operates under load. In the army's rotary-wing aircraft, the engine washing process is performed on-line washing which is conducted when the engine operating time reaches 100 hours or when the TGT margin exceeds the hit baseline.

TGT margin

The TGT sensor measures the temperature of the gas exiting the combustion chamber and entering the turbine section to ensure engine components do not exceed allowable temperature limits. The TGT margin means the difference between the actual TGT and the manufacturer's maximum allowable TGT. Removing contaminants from the compressor blades improves airflow and fuel efficiency. As a result, the gas expansion (pressure) energy can be enhanced without raising the thermal energy. In other words, the same TGT level can generate higher output, and it means that the TGT margin improves.

Bayesian decision analysis

Bayesian decision theory uses Bayes' theorem to make optimal decisions under uncertainty. A Bayesian network consists of nodes that represent probabilistic variables and edges indicating their relationships among them, thereby illustrating probabilistic causality. This network enables to build a decision model that estimates the probabilities of success or failure for specific actions and evaluates the associated costs, determining the optimal decision.

$$\boldsymbol{a_{opt}(z) = arg_{\dots}\ min\ E_{c|z|}\ [C_T(a, C)]} \tag{1}$$

In Equation (1), $a_{opt}(z)$ represents the optimal action for an observation z that refers to the action that minimizes the expected total cost. $E_{c|z|}$ denotes the expected value of the system state's conditional probability, given the observation z. $C_T(a, C)$ is the total cost function, which depends on both the selected action a and the system's actual state C. Bayesian decision theory aims to identify the decision that minimizes the expected cost [6].

RESULT AND DISCUSSION

Descriptive statistics

The descriptive statistics for TGT margin data before and after engine washing are shown in Table I. Overall, the mean TGT margin decreased. The standard deviation also declined, indicating a modest reduction in variability except for Aircraft No. 5.

TABLE I. DESCRIPTIVE STATISTICS

Flight	Cleaning Date	Cleaning	Mean	Standard Deviation	Min	Max	Sample
No. 1	'22.8.12.	Before	-4.6153	5.4243	-12	3	13
		After	-9.6154	4.5007	-15	0	13
No. 2	'23.11.2.	Before	-1.1053	5.2903	-11	12	19
		After	-7.5263	3.6722	-15	6	19
No. 3	'23.3.29.	Before	1.5625	3.4635	-3	4	16
		After	-6.2500	3.0659	-11	-2	16
No. 4	'22.8.9.	Before	-9.2500	5.0475	-19	30	12
		After	-13.6667	4.9052	-22	22	12
No. 5	'22.12.16.	Before	-15.0667	3.4942	-21	-7	15
		After	-15.2000	4.4593	-25	-12	15
No. 6	'22.6.21.	Before	-29.4545	5.1451	-38	10	11
		After	-30.5455	4.5025	-36	-6	11

Hypothesis testing

The statistical hypothesis test is defined as follows:

H_0**: There is no statistically significant difference in mean TGT margin data before and after engine washing.**
H_1**:** H_0 **is rejected, indicating a statistically significant difference.**

As a result of data analysis, the engine was identified as an intrinsic factor associated with each aircraft. Therefore, a statistical test was conducted using a linear mixed model (LMM), which considers both fixed effects (the presence or absence of washing) and random effects (variability among aircraft and engines) enabling a more nuanced analysis [7]. This approach isolates the effect of engine washing while controlling the inherent characteristics of each aircraft and engine.

$$\boldsymbol{TGT\ Margin_{ij} = \beta_0 + \beta_1 \cdot Washing_{ij} + \beta_i(Aircraft) + \beta_j(Engine) + \epsilon_{ij}} \tag{2}$$

The basic structure of the LMM is given in Equation (2). β_0 represents the intercept (baseline TGT margin), β_1 indicates the fixed effect associated with engine washing. β_i, β_j represent the random effects for aircraft and engines, respectively. ϵ_{ij} denotes the residual error term. The negative value for β_1 indicates an improvement in TGT margin after washing.

The LMM results showed that the TGT margin after washing decreased by 4.115, with a p-value below 0.05. This confirms that the improvement in TGT margin through engine washing is statistically significant. Accordingly, the null hypothesis was rejected.

Decision analysis results

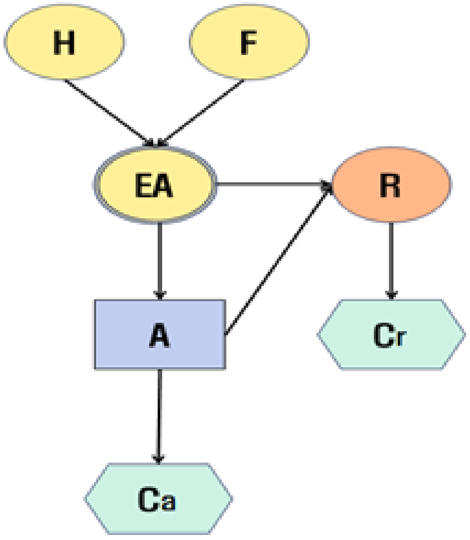

Figure 2. Influence diagram for engine cleaning.

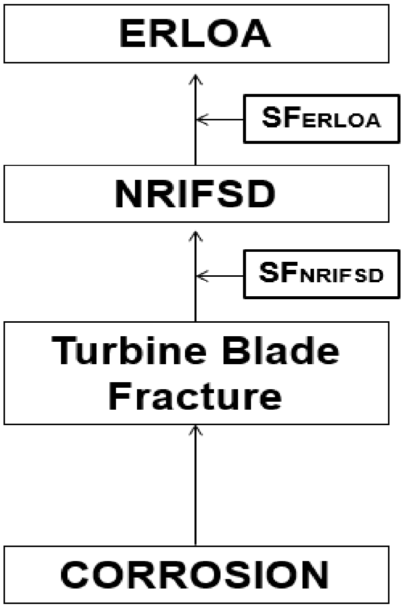

Figure 3. Fault Tree.

A Bayesian decision model was constructed. (See Figure 2.) It shows that the engine anomaly node (EA) is connected to the risk occurrence probability node (R) and the decision node (A), which determines whether washing is performed. The nodes (R) and (Cr) derive their values from the probabilities of a Non-Recoverable In-flight Engine Shutdown (NRIFSD) and an Engine-Related Loss of Aircraft (ERLOA), based on the fault tree structure.

In reference to the S-70 incident, the initial event (corrosion) resulted in an in-flight engine shutdown, which may ultimately lead to total aircraft loss. Accordingly, the fault tree was modeled in a serial configuration (See Figure 3). The NRIFSD and ERLOA values were calculated by multiplying the number of fault events by the corresponding severity factors, SF_{NRIFSD} and SF_{ERLOA}. The number of fault events was derived from the probability of failure due to corrosion. In this case, since one instance of turbine blade fracture due to corrosion directly led to one NRIFSD event, the severity factor SF_{NRIFSD} was set to 1.0 (100%). As ERLOA did not actually occur, a conservative value of 0.036 (3.6%) commonly used by the manufacturer was applied for SF_{ERLOA} [8]. Based on these results, the risk cost for NRIFSD was calculated by multiplying the probability by the engine replacement cost, while the risk cost for ERLOA was obtained by multiplying the probability by the aircraft loss cost. Among the two, NRIFSD had the higher risk cost (9,006,000 KRW) and was selected.

In the Bayesian network, the NRIFSD probability (0.0114) was assigned to node (R) as the risk-event probability under the 'no washing' scenario and the corresponding risk cost was assigned to node (Cr). For the ‘washing performed’ scenario, 10^{-7} input to node (R) was derived from a single-flight probability of failure (SFPOF) value commonly referenced in aircraft structural risk assessments [9]. The total engine washing cost assigned to node (Ca), including cleaning products and fuel consumption, amounts to 11,125,500 KRW. The analysis shows that engine washing provides a cost benefit under the given assumptions.

The optimal engine washing interval was then determined by considering both the risk cost and the washing cost, based on the following assumptions.

1. The Weibull shape parameter (β) remain constant. This reflects the premise that the fundamental failure mechanism does not change with different washing intervals. This assumption is commonly adopted to allow statistical comparison across different lifetime datasets [10].

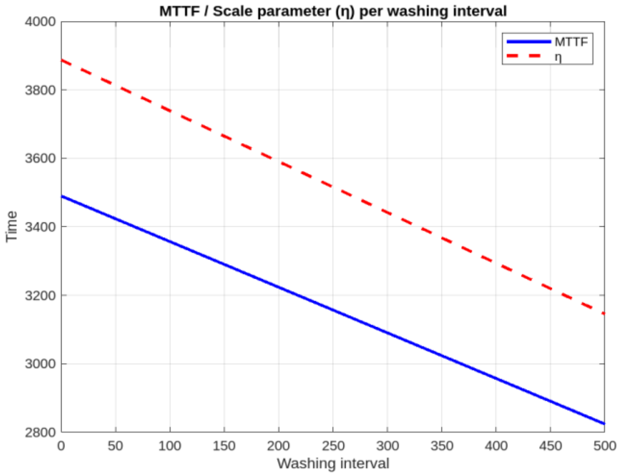

Figure 4. MTTF and Scale parameter with washing interval.

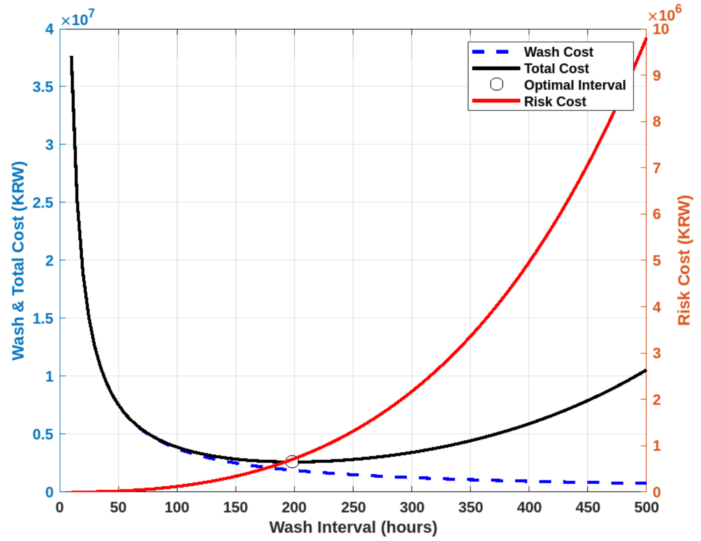

Figure 5. The optimal washing interval minimizing the total cost.

2. The mean time to failure (MTTF) decreased linearly as washing intervals increase. Enyia et al. [11] observed that longer washing intervals lead to a linear increase in performance degradation. If β remains constant and the failure threshold is fixed, this implies that MTTF decreases linearly. (See Figure 4.) In other words, less frequent washing shortens the engine's lifespan [12].

Based on these assumptions, the risk cost was calculated using the Weibull cumulative distribution function. By comparing the resulting risk cost with the washing cost over the T700 engine's 3,000-hour overhaul cycle, the optimal and most cost-effective washing interval that minimizes the total cost was identified as 190 hours. (See Figure 5.)

CONCLUSION

This study presented a comprehensive analysis of the effects of aircraft engine washing on TGT margin, considering both performance and material perspectives. From a performance standpoint, engine washing resulted in a statistically significant improvement in TGT margin, primarily due to the removal of internal contaminants that enhance combustion efficiency. From a materials perspective, however, residual chloride and sulfate ions remaining after washing were found to accelerate corrosion especially when metal surfaces are not fully dried under humid conditions.

Based on these findings, Bayesian decision model was developed to establish a cost-effective engine maintenance strategy. This model demonstrated that engine washing is more economically beneficial than not washing. And the optimal washing interval of 190 hours was derived as the point minimizing the total cost, which includes both risk and washing costs.

Overall, this study emphasizes the importance of balancing performance enhancement with the risks of material corrosion. By verifying the cost-effectiveness of engine washing and deriving an optimal interval that accounts for corrosion-related costs, this work provides practical guidance for engine management planning.

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