Return on Investment: Analysis of Benefits of the Implementation of Elastomeric Wedges as Vibration Control on the Apache (AH-64D) Aircraft

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***Abstract*—Analysis of the material and operational costs shows that the use of self-adhering elastomeric trailing edge wedges on the Apache (AH-64D) helicopter in main rotor (MR) blade tracking operations will significantly reduce the number of blades damaged by tab bending that must be repaired at the depot level. Wedge implementation will also allow for a decrease in the number of test flights and maintenance man hours associated with those flights. Additionally, the wedges will lower aircraft vibration levels. This paper describes the benefits of the implementation of MR wedges on the AH-64D. A 10-year return on investment (ROI) is calculated for projected peacetime flying hours and for the current flying rate. Dollar values and flight hour optempo have been removed to comply with the operations security process. These values have been replaced with percentages.**

Key words—material costs; operational costs; wedges; AH-64D helicopter; main rotor blade; blade tracking; tab bending; return on investment (ROI)

I. INTRODUCTION

In 2010, the Vibration Control project began with one goal being to improve the MR blade tracking feature used in helicopter main rotor smoothing. Routinely scheduled maintenance events use rotor smoothing (RS), also known as rotor track and balance (RT&B), to make corrective adjustments to pitch links, blade weights, and trim tabs with the use of Modern Signal Processing Unit (MSPU) equipment and procedures. The purpose of these adjustments is to improve the track of main rotor blades and determine their sensitivities, which reduces vibrations at the fundamental (once-per-revolution) rotor frequency. Main Rotor (MR) wedge application, as an alternative to bending tabs, is one way to reduce vibration. Helicopter main rotor wedges can be thought of as a more complex version of a balancing kit that can be purchased for a ceiling fan with wobbling blades. Reducing these vibrations increases the "smoothness" of aircraft flight. Current maintenance procedures prescribe bending metal tabs, which extend off the trailing edge of the main rotor blade, to a specified angle [1-3]. Tabs are bent using a tab bending tool, also known as a trim tab tool. A diagram displaying the tab bending operation can be seen in Figure 1, where KTAS stands for "knots, true airspeed", sometimes written KTS.

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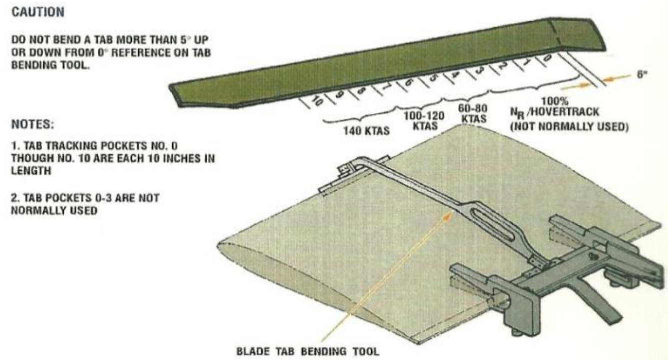


Figure 1. Diagram of Main Rotor Blade Tab Bending Tool Operation [4]

A. Current Procedure: Trim Tab Bending

The trim tabs are effective at achieving acceptable vibration and satisfactory blade track but put excessive burden on maintainers by requiring several maintenance test flights for adjustments. The trim tab tool only fits in one pocket at a tab so rotor balancing can get to be time intensive. Furthermore, trim tab adjustment can damage the blade, requiring blade replacement. In flight, the highest strain levels of any blade location are experienced along the trailing edge of the main rotor blade [3]. Bending the tab causes further strain along the bend, resulting in compromised material strength and leads to trim tab washout, which means that the blade can no longer hold the angle required for rotor smoothing. A certain skill is necessary when using the tab bending tool, a skill that is not taught to every maintainer. An inexperienced maintainer could easily exceed the maximum bend limit of 5° if not properly trained, resulting in blade damage beyond reparable limits. Consequently, RT&B actions could be delayed by an absence of trained maintainers. A limited quantity of trim tab tools is provided to each unit; therefore, maintenance could also be hindered by a lack of tool availability. Additionally, the trim tab tool is user subjective. Since tool operation is not an exact science, two individuals may view the angle differently. The MR wedges will be implemented to recreate the trim tab's success in reducing vibration while decreasing maintenance time and main rotor blade demand.

B. Alternative Procedure: Wedges

The tracking wedges have a peel and stick adhesive backing and are made of Ethylene Propylene Diene Monomer (EPDM) elastomer, which was chosen for its high resistance to chemical and environmental exposure. Wedge kits include a piece of Scotchbrite pad, two alcohol wipes, and one 10.0-inch long, 1.25-inch wide wedge with a thickness angle taper of 6° [3]. A photograph of wedges installed on a main rotor blade can be seen in Figure 2.

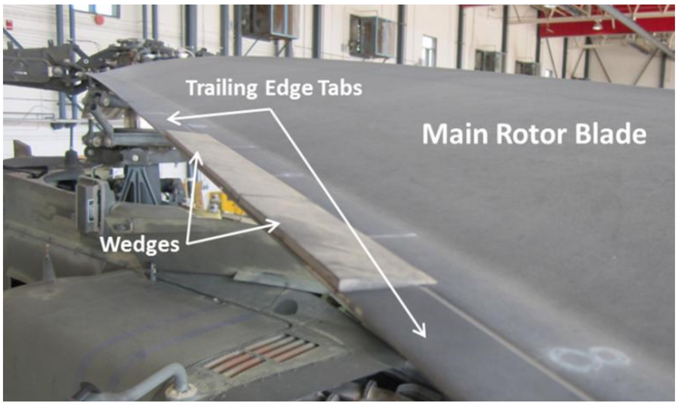


Figure 2. Photograph of Wedges on an AH-64D Apache Main Rotor Blade *(Courtesy of 1-151 ARB)*

The addition of discrete main rotor wedges to the trailing edge of the main rotor blades allows for the same change in lift and pitching moment characteristics of the airfoils as experienced by trim tab deflection. Another immediate benefit is that flight test mechanics have found the MR wedge installation to be quicker, easier, and more precise as compared to bending trim tabs [3]. Moreover, trim tab washout will be eliminated since the blades are no longer required to be bent to a specific angle.

MR wedge installation is guided by the instruction of the MSPU system. A simple correlation is established for the appropriate amount of wedge based on MR trim tab bend requirements from the MSPU system [3]. The wedge equivalence to tab bends is listed in [3] and an overall correlation from that document for wedges and tab bends is shown in Table 1.

Table 1. Tab Bend and Wedge Equivalence [3]

Tab Bend (deg.)	Equivalent Wedge Length (in.)	Total Wedge Length, Pockets 4-10 (in.)	Total Wedge Length, Pockets 6-10 (in.)	Total Wedge Length, Pockets 8-10 (in.)
0.5	1.0	7	5	3
1.0	2.0	14	10	6
1.5	3.0	21	15	9
2.0	4.0	28	20	12
2.5	5.0	35	25	15
3.0	6.0	42	30	18
3.5	7.0	49	35	21
4.0	8.0	56	40	24
4.5	9.0	63	45	27
5.0	10.0	70	50	30

A 3.0° bend in pockets 4-10 would mean that each individual pocket would need to be bent 3.0°; since the tab bending tool fits only in one pocket at a time, this task will be time consuming. With wedges, that same 3.0° bend simply means that 42 inches of wedge must be applied on the blade in pockets 4-10. The wedge AWR explains, "The shaded areas represent conditions for which there may not be enough real estate for the wedges. If the adjacent pockets are available, wedges may be added to the pockets immediately inboard or outboard."

II. Analysis

Material and operational costs are examined to ultimately determine the return on investment after 10 years with the implementation of the main rotor elastomeric trailing edge wedges. The projected annual savings, or benefits, determined in the following analyses are taken as a cost avoidance in that these are costs that will not be spent on maintenance, but on training or missions. The material cost avoidance explores the costs associated with main rotor blade demand, while the operational cost avoidance considers the maintenance-related costs. The return on investment incorporates the benefits from both the material and operational cost avoidances.

A. Material Cost Avoidance

Material costs are developed from Aviation and Missile Command (AMCOM) Integrated Material Management Center (IMMC) and Aviation and Missile Research Development and Engineering Center (AMRDEC) total return and demand data for MR blades.

1) *MR Blade Material Demands FY09 – FY11:* The analysis begins by acquiring the total demand for AH-64D main rotor blades from FY09 to FY11 which is used to then obtain an average MR blade demand. The values in Table 2 are taken as a percentage of the average annual MR blade demand. The total demand data for FY09 (60.35%) is significantly lower than the total demand data for FY10 and FY11 (132.81% and 106.84%, respectively). Due to a changeover in AMCOM Logistics Modernization Program (LMP) procurement systems, the demand for the entire FY09 year was not able to be accessed; the demands are only from 14 May 2009 to 20 Sep 2009. These values are not used to create a predicted annual demand due to an abnormal spike in demand during that time. The resulting values from this absence in data just provide a more conservative value than what would have been determined otherwise.

Table 2. AH-64D Main Rotor Blade Demands for FY09 - FY11 in AMCOM LMP[a]

Main Rotor Blade National Stock Number (NSN)[b]	FY09 Total MR Blade Demand[c]	FY10 Total MR Blade Demand[c]	FY11 Total MR Blade Demand[c]
MR Blade 1	60%	138%	102%
MR Blade 2	56%	75%	169%
MR Blade 3	72%	116%	112%
MR Blade 4	45%	85%	170%
Total:	**60%**	**133%**	**107%**

[a] Values taken as a % of the average annual MR blade demand
[b] CSM Woody Sullivan; Department of the Army (DA) Form 2408
[c] Sara D. Finigan; AMCOM IMMC Item Manager for MR Blade

2) *MR Blade Field Returns to Depot:* Based on historical maintenance data, it is implied that trailing edge failures are related to tab bending. According to the team leader for the Aviation Engineering Directorate (AED) Maintenance Division at Corpus Christi, TX, the number of blades that are

rejected for damage to the trailing edge beyond reparable limits is equivalent to 35.64% of the average annual MR blade demand. Figure 3 is a graphical representation of the MR blades that will be affected by wedge implementation. The number of MR blades with trailing edge failures will decrease with the use of wedges and it is what the material costs focus on.

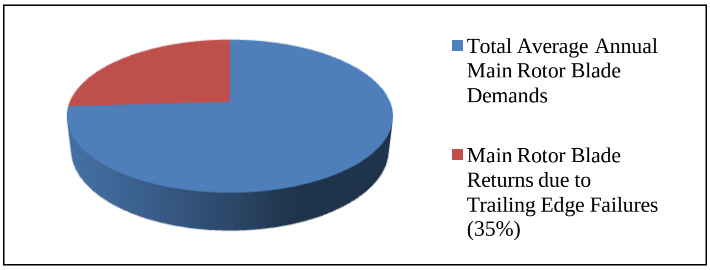


Figure 3. Pie Chart of Annual Main Rotor Blade Demands and Trailing Edge Failures

3) *Material Costs Prior to Wedge Implementation:* Using the average annual MR blade demand, the unit price for the MR blade, and the percentage of MR blade returns due to trailing edge failures, the material costs prior to wedge implementation can be calculated. For this analysis, 35% is used for the MR blade returns that are due to trailing edge failures in order to obtain a more conservative value.

4) *Material Costs After Wedge Implementation:* Total flight hours for FY09, FY10, and FY11 are averaged together to find the current annual flight hour rate. In order to determine the material costs after wedge implementation, a peacetime estimate of flight hours is considered. It is anticipated that the United States will not always be at war and this should be reflected in the analysis. Values used in the subsequent calculations are taken as a peacetime-reduced percentage of the previously mentioned rate. Table 3 lists these projected rates as a percentage of the current rate.

Table 3. Projected Peacetime-Reduced Flight Hours as a Percentage of Current Flight Hours

Percentage of Reduction
42%
50%
63%
75%
100%

It is expected that, with the change from tab bending to wedges, fewer blades will be returned due to trailing edge failures, resulting in a reduced demand. An estimated reduced demand rate of 25% is anticipated, another conservative value. The reduced demand rate means that 75% of that value will remain and will continue to be demanded. This rate is applied to the annual cost of MR blades due to trailing edge failures along with the calculated ratios given in Table 3. The resulting value is the annual cost of MR blade returns due to trailing edge failures after wedge implementation.

The annual cost of blade returns due to trailing edge failures after wedge implementation is proportional to the projected peacetime flight hours. This means that as flight hours increase, the likelihood of having a trailing edge failure on a MR blade increases as well.

5) *Material Cost Avoidance Benefit & Projected Cash Flow:* The material cost avoidance benefit is the difference between the current cost and the new forecasted cost. The benefits decrease as flight time increases. A graphical representation of that is shown in Figure 4.

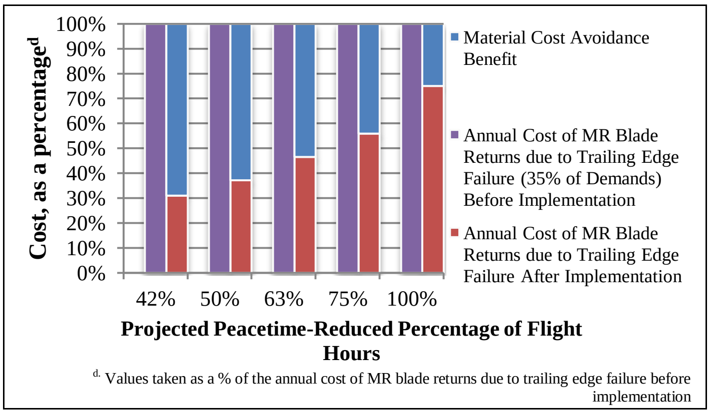


Figure 4. Bar Graph Displaying Material Cost Avoidance Benefit

The next step is to use the cost avoidance benefit to calculate the benefits achieved over a 10-year period of time. Since the data collected is from FY09 through FY11, it is estimated that the benefits will not begin until two years after the last set of data acquired. This means that the benefits begin in FY13. The total benefit will not be seen in its entirety during FY13 but will be seen progressively. An incremental benefit of approximately 16.67% per year was chosen so that by FY18, a 100% benefit is achieved. These calculations also take into account a 3% inflation rate, which was compounded for single flow, also beginning in FY13. The inflation equation is shown in (1) where P is the present single sum, F is the future single sum, i is the interest per period in percent, and N is the period (beginning in FY13) [5]. The projected cash flow over 10 years is illustrated on a graph in Figure 5. The lines on the graph appear to be nonlinear toward the end. This is due to the full benefit being achieved in both FY18 and FY19, so inflation is the only difference between the two.

$$F = P(F/P, i\%, N) = P(1+i)^N \quad (1)$$

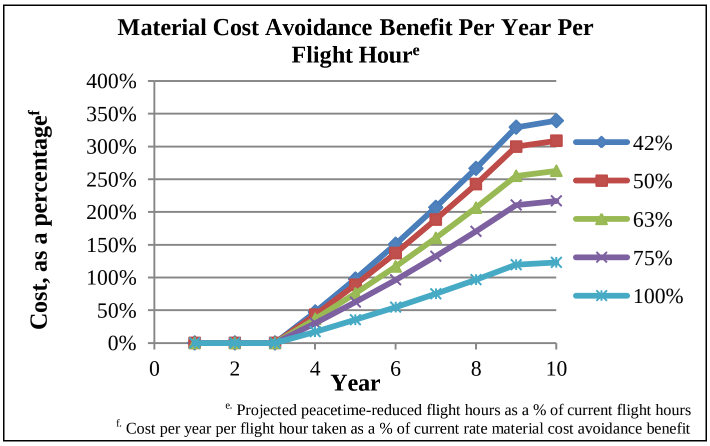


Figure 5. Annual Percentage of Material Cost Avoidance Benefit Achieved

B. Operational Cost Avoidance

Operational costs are determined by using phase maintenance to determine how much it costs to perform rotor smoothing events before and after wedge implementation. Based on pilot experience, a reduction in maintenance test flight time is observed. The additional cost of wedge packets is considered here.

1) Rotor Smoothing Events for Fleet: It is difficult to determine the exact number of rotor smoothing events per year since they must sometimes be performed during unscheduled maintenance events. Phase maintenance is used to create a baseline allowing a comparison between the before and after costs. Phase maintenance, when related to aircraft, is a system of scheduled maintenance events. For the AH-64D, phases occur every 500 flight hours. Rotor smoothing events are guaranteed at every 125-hour interval within the phase; this is illustrated in Figure 6. T/B stands for "Track/Balance".

The calculations to determine the number of annual rotor smoothing events is done on an incremental inspection basis. This means that the number of rotor smoothing events per month for aircraft is determined for the 500-, 375-, 250-, and 125-flight hour incremental inspections separately. Those values are added up to determine the total number of rotor smoothing events per month for the fleet. Once that number is multiplied by 12 months/year, the annual number of rotor smoothing events for the fleet is determined. The results of the calculations are proportional to the projected peacetime flight hours. This means that with higher annual flight rates, the total number of RS events will increase.

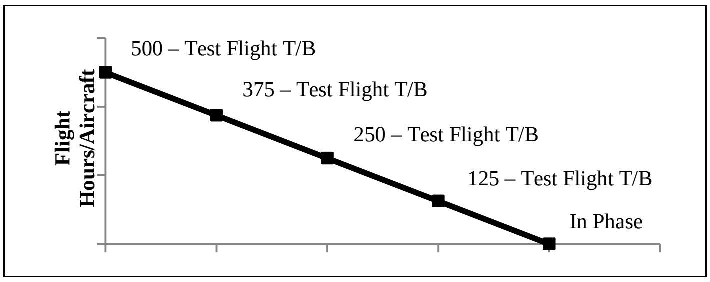


Figure 6. Phase Cycle for the AH-64D

2) *Operational Costs Prior to Wedge Implementation:* Test flight patterns (TFP) are used in rotor smoothing events. A flight test pattern is a pre-determined path, or pattern, that is flown by the maintenance test pilot (MTP). In this case, TFP are performed at the beginning of a rotor smoothing event and after each set of adjustments made to the blades in order to confirm those adjustments. TFP take approximately 15 minutes to complete, or 0.25 hours. On average, 3 TFP are done every rotor smoothing event when tab bending is used to track and balance the main rotor blades—one initial flight and two flights to confirm adjustments. This would be about 45 minutes every RS event. The operating cost of the AH-64D is used in this calculation. This cost is unburdened, which means that it does not include maintenance man hours. Using the values mentioned above along with the annual rotor smoothing events for the fleet, the annual cost of rotor smoothing events for the fleet prior to wedge implementation is able to be calculated.

3) Operational Costs After Wedge Implementation: With the implementation of wedges, it is predicted that the number of TFP will be reduced from 3 to 2 per rotor smoothing event. This can be expected because, as it was stated previously, wedges allow for a more precise adjustment as compared to trim tabs, so less TFP are required. Instead of 45 minutes of flight time during these events, there will now be only 30 minutes of flight time. The calculated values result in a 33% reduction in costs.

Since tab bending will no longer be used, the analysis must also take into account the cost of the wedges as an additional cost. Approximately 3 wedge packets are used during each rotor smoothing event, which is multiplied by the cost of the packet to acquire the cost of wedge packets per RS event. Instead of being replaced at every 125-flight hour interval within the phase, or four times every phase, the wedges are replaced every 250 flight hours, or twice every phase. This means that the annual rotor smoothing events for fleet value can be reduced to half of the original number when determining the annual cost of wedge packets for the fleet; the resulting values are equivalent to almost 9% of the operational costs after wedge implementation.

Although the cost of the wedge packets is a material cost, it is used in the operational cost calculations because it is dependent on the amount of rotor smoothing events per year. Adding the annual cost of rotor smoothing events after wedge implementation to the annual cost of the wedge packets for the fleet will yield the annual cost after wedge implementation.

4) *Operational Cost Avoidance Benefit & Projected Cash Flow:* The operational cost avoidance benefit is calculated the same way as the material cost avoidance benefit: the difference between the current cost and the new forecasted cost. The operational cost avoidance benefit increases as flight time increases, which is unlike the trend seen in the material cost avoidance benefit. This is because there is a 27% cost avoidance across the board. It can be compared to shopping a sale at a department store. If everything in the store is 30% off, the customer will have a greater "savings" when buying a $100 item as compared to buying a $50 item. The same concept is experienced in this situation. A graphical representation of the operational cost avoidance benefit values is shown in Figure 7.

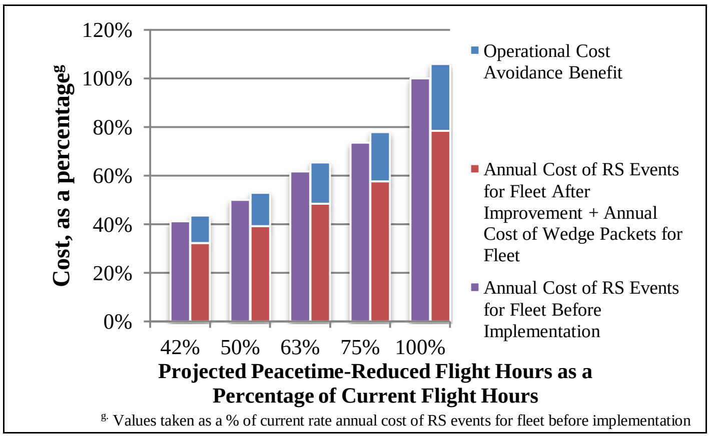


Figure 7. Bar Graph Displaying Operational Cost Avoidance Benefit

As before, the cost avoidance benefit is used to calculate the benefits achieved over a 10-year period of time. For consistency, the benefits will not begin until FY13, just as they did with the material cost avoidance benefit. The total benefit will not be seen in its entirety during FY13 but will be seen progressively. An incremental benefit of approximately 16.67% per year was chosen so that by FY18, a 100% benefit would be achieved. These calculations also take into account a 3% inflation rate, which was compounded for single flow, also beginning in FY13. The projected cash flow over 10 years is illustrated on a graph in Figure 8. The lines on the graph appear to be nonlinear toward the end. This is due to the full benefit being achieved in both FY18 and FY19, so inflation is the only difference between the two.

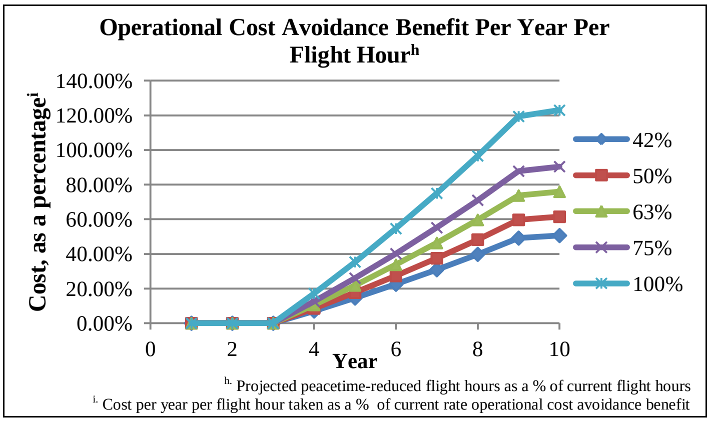


Figure 8. Annual Percentage of Operational Cost Avoidance Benefit Achieved

C. Total Cost Avoidance

By adding the material cost avoidance benefit and the operational cost avoidance benefit, the total cost avoidance benefit is obtained. Figure 9 displays the total cost avoidance benefits for each projected peacetime flight hours broken down by material and operational cost avoidance benefits. The graph shows that overall the trend is that benefit decreases with increasing flight time. It also shows that the majority of the benefit comes from the costs that will no longer be spent on blade demands due to the trailing edge failures.

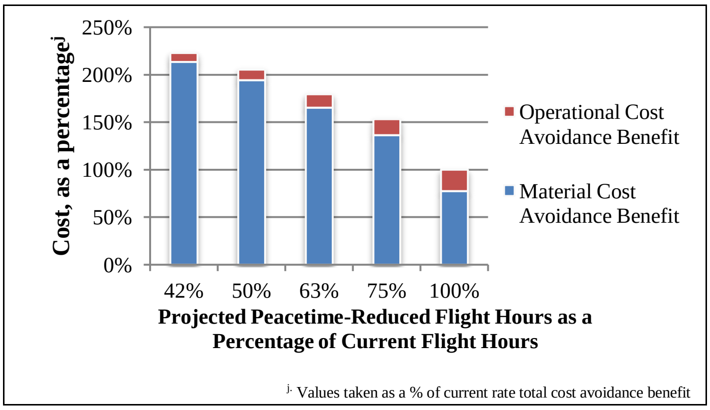


Figure 9. Total Cost Avoidance Benefit Graph

D. Return on Investment (ROI)

A return on investment is a way to evaluate the efficiency of an investment; the result is expressed as a percentage or ratio. In this case, it is used to predict the return, or cost avoidance, that will be gained in the future. The formula for determining the ROI is given below in (2).

$$ROI = \frac{Benefit - Expense}{Expense} \tag{2}$$

The expense is taken as the total investment in the Vibration Control project. The first investment is given in FY10. The second investment is given in FY11 and is equivalent to 53% of the first investment. The final investment is given in FY12 and is equal to 24% of the first investment. These costs are known as sunk costs because they have already been incurred and cannot be recovered. The benefit is determined by using the total cost avoidance. Table 4 displays the return on investment values determined for each assumed flight hour/month. Figure 10 illustrates how much of the ROI that is achieved per year

Table 4. Return on Investment

Projected Peacetime-Reduced Flight Hours	Return on Investment (ROI)
42%	2300.42%
50%	2114.69%
63%	1832.50%
75%	1550.31%
100%	978.09%

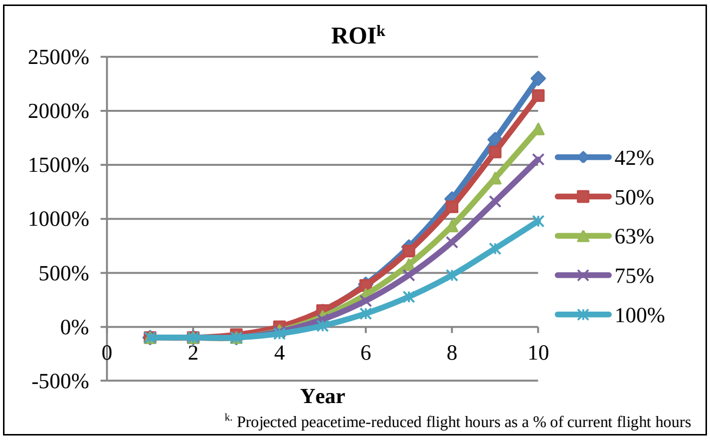
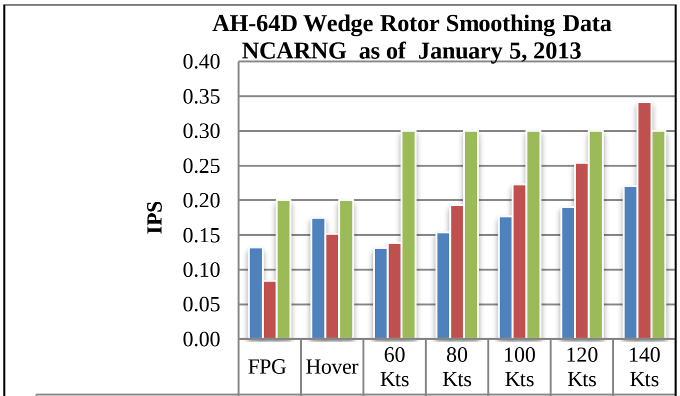


Figure 10. Percentage of Return on Investment Achieved Per Year using Material and Operational Cost Avoidance

III. ADDITIONAL BENEFITS

This analysis has demonstrated that elastomeric tracking wedges provide a substantial amount of benefits. Reducing the time spent on maintenance test flight patterns also reduces the maintenance man hours involved in a rotor smoothing event. This value is difficult to calculate because the time spent balancing rotor blades can be vastly different between aircraft. This holds true more so for trim tab bending as compared to wedges.

Figure 11 is a chart comparing rotor smoothing vibration levels from North Carolina Army National Guard (NCARNG) and the AH-64D fleet against the Army's goal. The NCARNG fleet uses only wedges for rotor smoothing and the rest of the Army's fleet uses tab bending for rotor smoothing. The data collected is from January 2012 through January 2013. FPG stands for "flight pitch ground" which means there is no pitch in the blades while on the ground. The vibration is measured in inches per second (IPS). The first thing to recognize about the chart is that all wedge levels are below the goal. At FPG and Hover, the wedge vibration average is higher than the fleet average. This is not significant because the majority of flight time is spent from 60Kts to 100Kts, where the wedge average is lower than the fleet average. Overall, it is safe to say that the use of wedges results in lower vibration levels as compared to vibration levels experienced by aircraft using tab bending.



	FPG	Hover	60 Kts	80 Kts	100 Kts	120 Kts	140 Kts
NC Wedge Average	0.13	0.17	0.13	0.15	0.18	0.19	0.22
Fleet Average	0.08	0.15	0.14	0.19	0.22	0.25	0.34
Goal	0.20	0.20	0.30	0.30	0.30	0.30	0.30

Figure 11. NCARNG AH-64D Wedge Rotor Smoothing Data, provided by Stanley H. Graves

According to the AWR for the MSPU [6], "rotor smoothing adjustments recommended by the MSPU system…may be made without necessitating an additional maintenance test flight. Relief from the maintenance test flight requirement only applies if MSPU measured vibration levels are 0.50 ips or less and the displayed Main Rotor Smoothing status is green or green with an upward arrow." When looking at the figure above, it can be seen that all of the vibration levels from wedge aircraft are far below 0.50 ips. This means that the number of maintenance test flights can be further reduced with the use of elastomeric wedges instead of bending tabs.

A. Examples of Second Order Effects from Lower Vibration Levels

Lower vibration levels can result in a multitude of second order effects. The results/benefits found in the following examples can be applied to the vibration effects expected from the AH-64D.

1) Rotor Mounted Bifilar Vibration Absorber Study (1970): Angelo C. Veca [7] wrote about the vibration effects on helicopter subsystem reliability, maintainability, and life-cycle costs. The study examines two groups of United States Air Force (USAF) H-3 helicopters: one equipped with a rotor-mounted bifilar vibration absorber and one without the absorber. The bifilar vibration absorber reduces helicopter vibration induced by the rotor. The evidence in this report indicates that a decreasing vibratory stress level results in a decreasing failure rate. With an average vibration level reduction of 54.3%, "the overall H-3 helicopter failure rate and corrective maintenance are reduced by 48% and 38.5%, respectively. Correspondingly, life-cycle costs show a significant reduction of approximately 10% for the overall aircraft." It goes on to state, "The improved reliability resulting from the reduced vibratory stress environment results in less corrective maintenance being expended on the CH-3 aircraft. This results in less downtime on the aircraft, thereby improving availability and contributing to the reduction in the operating cost of the aircraft." Figure 12 is a chart from the report displaying a comparison of the total average failure rate and maintenance man-hours per 1000 flight hours (MMH/KFH) for the top 13 aircraft subsystems.

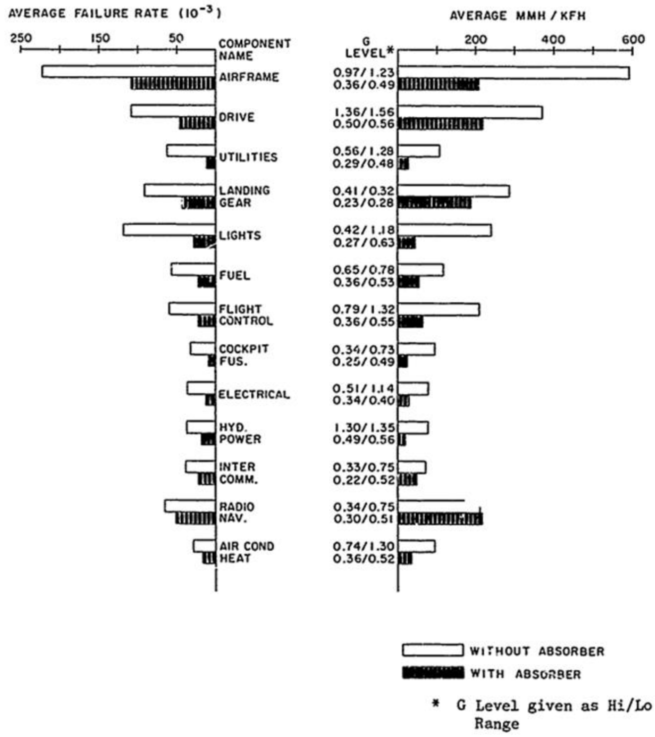


Figure 12. Comparison of Total Average Failure Rate and MMH/KFH for Top 13 Aircraft Subsystems [7]

2) UH-60 Vibration Surveys (1988): Vibration surveys on the UH-60 aircraft were conducted in 1988 by U.S. Army Aviation and Surface Material Command's (AVSCOM, which is AMCOM today) Aeromechanics. A sample of 9 aircraft from Fort Rucker and 12 aircraft at Fort Campbell were surveyed. The results showed that the vibration levels for the aircraft at Fort Campbell were twice that of Fort Rucker's and are given in Table 5. Additionally, unscheduled maintenance removal and replacement rates were studied. This study found that Fort Rucker maintained UH-60 aircraft had one-half the removal and replacement rates of regular Army UH-60 aircraft [8]. The equipment categories that were surveyed are the following: instruments, avionics, flight controls, and electrical systems.

Table 5. UH-60 1P/4P Survey & Removal and Replacement Rate Results [8]

	Average Vibration Levels at 140 Kts		Unscheduled Maintenance Removal & Replacement Rates
	1P	4P	
Fort Rucker (Sample of 9 aircraft)	0.2 IPS	0.3 IPS	23 per 1000 flight hours
Fort Campbell (Sample of 12 aircraft)	0.4 IPS	0.55 IPS	51 per 1000 flight hours

3) Navy P-3 Orion Propeller Dynamic Balancing: In 1986, the propellers of 50 P-3 aircraft were dynamically balanced. Prior to balancing, the average vibration was 0.4 ips. After balancing, the average vibration level dropped to 0.15 ips. For six months prior to and six months following the propeller balancing, the Navy tracked the maintenance records of the 50 aircraft for nine selected systems. The Mean Flight Hours Between Failure (MFHBF) for the aircraft with balanced propellers doubled that of the unbalanced propellers. The results can be seen in Figure 13 [9]. Lower vibration levels lead to an increase in MFHBF for every single system that was monitored, with MFHBF increases ranging from approximately 20 to 190 hours.

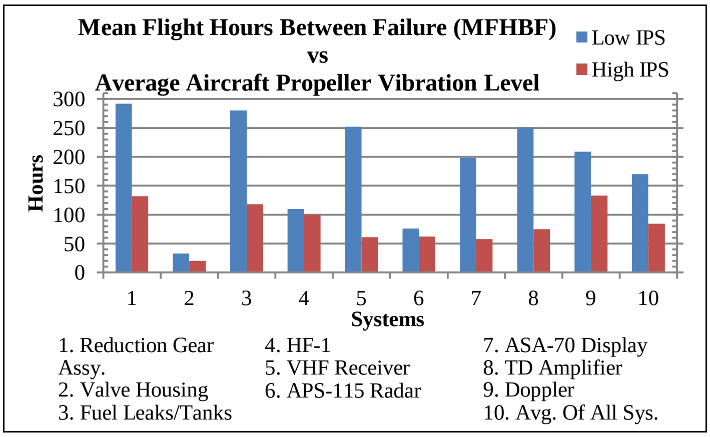


Figure 13. Mean Flight Hours Between Failure (MFHBF) vs. Average Aircraft Propeller Vibration Level [9]

IV. Future Work

Wedge equipped and non-wedge equipped aircraft vibration levels will continue to be monitored. Along with the vibration levels, fuel consumption can be tracked to see what relations may exist between the two. Reduced vibration will lead to fewer structural fatigue related faults which can be discovered by observing internal mechanical and electrical components. An increase in mean time between failure and a reduction in removal and replacement rates is expected as well. The MR blades can be tracked to observe extended component life and likewise, a reduction in demand. MR trailing edge failures can be monitored to see just how many exist after the introduction of wedges to maintenance protocol.

V. Conclusion

It is safe to say that elastomeric wedges used on AH-64D main rotor blades are an improvement in rotor smoothing events over bending the trailing edge metal trim tabs. First of all, wedges are quicker, easier, and more accurate than bending tabs, for installation and use over time. This means that maintenance delay due to limited tooling or an absence of trained maintainers will be eliminated. The wedges provide the same change in lift and pitching moment characteristics as tab bending. Trim tab washout is not an issue with wedges since the metal tab is no longer being bent to hold an angle.

Due to the tracking accuracy of the wedges, the maintenance test flight patterns flown during rotor smoothing events decrease by, on average, one test flight pattern per event, which results in a 33% reduction in operational test flight pattern hours during phase maintenance across the entire fleet. The elastomer that the wedges are made from have a high resistance to chemical and environmental exposure, which means that wedges only need to be applied every 250-flight hours within the phase instead of every 125-flight hours. Even with the addition of wedges as a cost, a 27% reduction in operational costs before wedge implementation exists. This value increases as flight time increases.

It has been demonstrated that the use of tracking wedges will decrease the overall MR blade demand by reducing the amount of trailing edge failures experienced by main rotor blades. The material cost avoidance increases as flight time decreases. The majority of the total cost avoidance benefit comes from the blades that will no longer be returned and demanded due to trailing edge failures.

The use of elastomeric wedges result in lower levels of vibration which leads to the following benefits: less corrective maintenance actions (and thus, MMH required), reduced downtime, lowered component failure rate, a reduction in removal and replacement rates, increased mean time between failure, increased reliability, increased availability, and increased maintainability. Three of four Condition Based Maintenance (CBM) objectives are affected: the soldier and maintenance burden is reduced, operational support cost is reduced, and aircraft availability is increased.

The analysis of both the material and operational benefits that are achieved from the use of elastomeric wedges as a form of vibration control result in a 10-year return on investment of between 9.8:1 and 23:1 for the current rate of flight and a range of projected peacetime flight hours.

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References

[1] N. A. Miller, "A Comparison of Main Rotor Smoothing Adjustments Using Linear and Neural Network Algorithms," Master's thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, 2006.

[2] J. C. Hasty, J. A. Keller and S. M. Krick, "Improved Rotor Smoothing for the U.S. Army CH-47D," AHS International Technical Specialists Meeting on Condition-Based Maintenance, Huntsville, AL, Feburary 2008.

[3] W. D. Lewis, "Airworthiness Release (AWR) for Operation of Apache AH-64D Helicopters with Self-Adhering Elastomeric Trailing Edge Wedges Installed on Main Rotor Blades (TTS 70805B)," Department of the Armt: Aviation and Missile Research, Development, and Engineering Center, Redstone Arsenal, AL, 10 May 2010.

[4] AH-64D Smart Book, The Hangar Inc. the Aviator's Shoppe.

[5] W. G. Sullivan, E. M. Wicks and J. T. Luxhoj, Engineering Economy, 12 ed., Upper Saddle River, New Jersey: Pearson Education, Inc., 2003.

[6] W. D. Lewis, Airworthiness Release (AWR) for the Modernized Signal Processing Unit (MSPU) on the AH-64D Apache Helicopter (TTS #77094), Redstone Arsenal, AL: Department of the Army: Aviation and Missile Research, Development, and Engineering Center, 11 Dec 2009.

[7] A. C. Veca, Vibration Effects on Helicopter Reliability and Maintainability, Fort Eustis, VA: U.S. Army Air Mobility Research and Development Laboratory, April 1973.

[8] S. T. Crews, Helicopter Vibration and its Effect on Operating Costs and Maintenance Requirements, Huntsville, AL: AMCOM, 1991.

[9] L. M. Dew, Propeller Dynamic Balancing's Effect on Maintenance Manhours Per Flight Hour for the P-3 Orion, 10 Mar 1992.