Rotor Blade Static Balance
– Art or Science?

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Preface

The co-development of the world's most proliferated rotor blade static balance fixture has been tremendously interesting, educational, rewarding, but at the same time frustrating. Technology has enabled the development of static balance solutions that can be utilized effectively at all levels of maintenance. While operators and intermediate maintainers praise the benefits, OEMs and depot operators have been much more reserved in their appraisal. It has been this reservation that has caused the greatest frustration.

The purpose of this paper was initially to document the pros and cons of the new technology as compared to the old. Simple science and new technology gives anyone with the ability to read, the ability to balance any rotor blade. The old technology has worked effectively for decades, however, it is tedious, time consuming, and generally requires the experience of a seasoned artisan. The OEMs and the depots have raised their concern that the new technology is not as accurate and repeatable as the old techniques. While it is true that the new technology has failed to meet the old expectation, it is clear in this author's mind that the same level of scrutiny has not been placed on proving that the old technology even meets the current perception of performance.

It was decided to put the matter into perspective with vibration, which is the only reality in the final analysis. As a result, the pro and con purpose was abandoned as it was recognized how little impact the differences mean in terms of vibration. It is now the hope, expressed in this paper, that all readers will recognize the necessity and effectiveness of static balance of rotor systems prior to dynamic tuning. It is the subject of other papers and brochures to convince all operators of the cost effectiveness of utilizing today's technologies.

The Goal of all balancing is to reduce vibration

Final rotor blade track and balance is almost always performed dynamically. This process accommodates any cause for imbalance in the entire rotating system. Due to the high cost of operating a helicopter, and the limited authority available to the dynamic tuner, maintenance test flights and test flight hours can generally be reduced by performing off-aircraft, static balance of the rotor blades. Static balancing provides the dynamic balance technician with a set of rotor blades at the onset of dynamic tuning which are matched in terms of balance characteristics.

Until recently, this capability has only existed within OEMs and depot facilities.

Rotor Blade Static Balance – Art or Science?

Dynamic balancing is always the final solution

Static balancing procedures do not replace dynamic tuning procedures, but augment the dynamic tuning process. Dynamic balancing accommodates any cause for imbalance in the entire rotating system.

Dynamic tuning is expensive to perform

Dynamic tuning requires the operation of the helicopter which is expensive. Costs vary from several hundred dollars to several thousand dollars per hour to operate.

Dynamic tuning is needlessly time consuming if span balance is not close

The rotor system must be physically balanced before the blades can be tracked. Most rotor systems do not have enough dynamic weight authority to allow adequate adjustment when blade repairs or blade exchanges are made. Countless man-hours and calendar time are consumed in attempting to find a solution when the right fix is not possible.

The chart below shows the amount of weight that is available for dynamic weight adjustments for a sampling of aircraft:

Aircraft Model	Max Dynamic Weight (lbs)	Distance from CoR (in)	Dynamic Authority
CH-47D	1.0625	359.75	382 in-lbs
AH-64D	2.5	42.0	105 in-lbs
UH-60	5.0	23.4	117 in-lbs
UH-1H	5.0	28.0	140 in-lbs
Lynx MK3	250 grams	155 cm	39 kg-cm

Table 1 – Dynamic Weight Authority for Various Blades

Why the automotive analogy of tire spin balancing and bubble balancing is not complete

The automotive industry abandoned the bubble balance when the spin balancers were introduced. It is always possible to balance an auto wheel, providing the wheel is not bent, because of the relatively large amount of lead weight that can be added to the rim.

The aviation community was led to believe that static balance of rotor blades would no longer be necessary with the advent of the dynamic tuning capability. It was believed that the static balance step was unnecessary, thus saving money through its omission in the overall track and balance process. Only OEMs and depot facilities continued to perform static balance.

The difference in the aviation application is that precious little weight is available to adjust in most applications. The mechanic is often forced into trying to solve a rotor track and balance problem with the wrong resource, i.e. trim tab or pitch change instead of balance weight adjustment. This precipitates track problems and/or transfers a lateral vibration problem into a vertical vibration problem.

The Goal of static balancing is to reduce the expense of the dynamic balance process

Static balancing is quick, easy, and inexpensive with new tools. Flight time, man-hours, and downtime are all reduced, minimizing expense and maximizing fleet readiness.

Span balance is the single biggest factor in rotor smoothing

Span static imbalance is the single greatest cause of vibration in a rotor system, and static imbalance is the quickest and easiest to resolve with the proper tool.

The span moment (first moment) must be equal in all directions about the center of rotation

The teeter-totter example describes moments in balance. The diagram below exemplifies the simple rules of statics that applies to balancing a rotor system. A moment is simply the product of a given weight and the distance that weight is placed from the fulcrum. The moments on each side of a fulcrum must be equal.

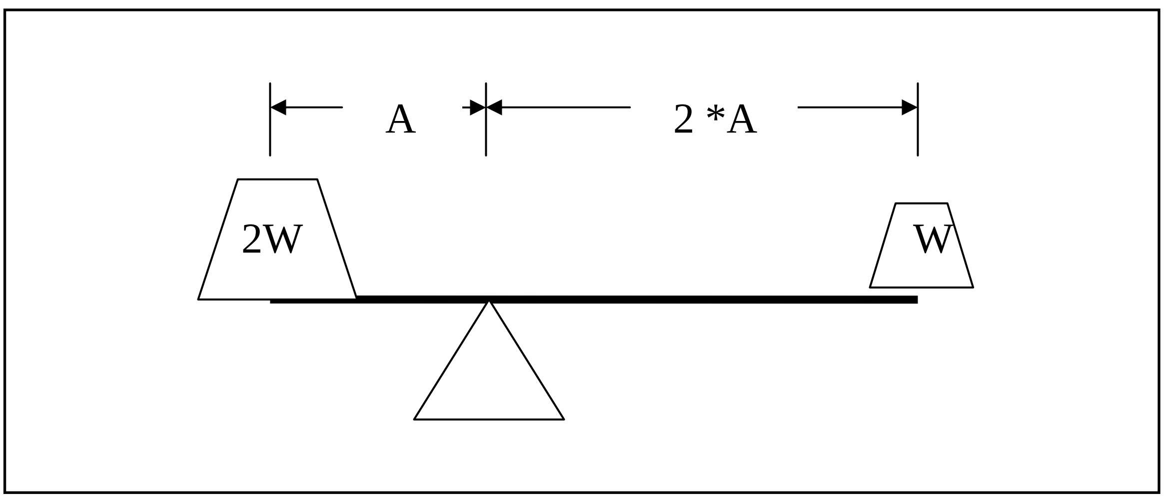

Figure 1 – Teeter-Totter- Balanced Moments

Manufactures and Depots have coveted the static balance process as "black magic"

All rotor blades are designed with adjustable weight packages so that all blades can be shipped from the factory with the exact same span moment. Figure 2 shows the tip of an

Rotor Blade Static Balance – Art or Science?

AH-64 Apache main rotor blade. The tip cap is removed and the weight packages are resting on top of the blade where they would be inserted upon assembly.

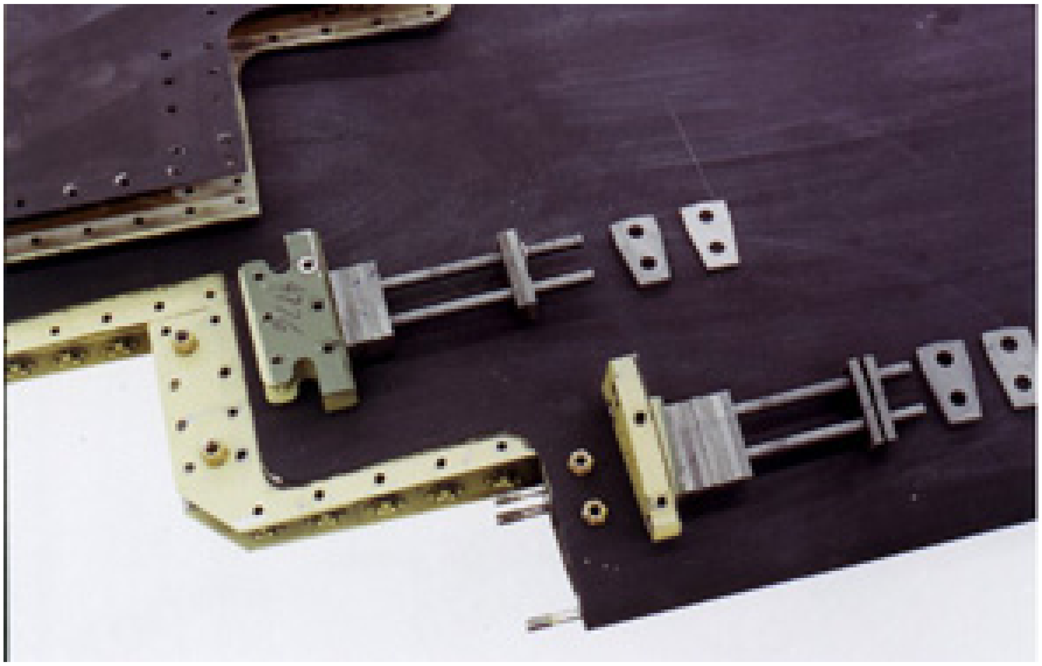

Figure 2 – Apache AH-64 Main Rotor Blade Weight Packages

It has been cautioned that if a weight should be slung, the result would be catastrophic. The reality is that current maintenance procedures allow for the disassembly and reassembly of most weight packages. The maintenance techniques associated with weight package adjustments are conventional. The absence of an adequate tool for static balancing was the limiting factor in preventing balance adjustments at maintenance facilities other than the OEMs and depot facilities.

Current static balance processes have required an artisan to perform

Many current static balance tools employ bolting a master blade to one side of a fulcrum and bolting the necessary weight to balance the master blade on the other side of the fulcrum. Then the master blade is removed and the specimen blade is bolted to the fixture replacing the master blade. Weights are added or removed to exactly balance with the dead weights on the other side of the fulcrum.

Other current systems employ a long table that is suspended by an arbor as depicted in the following diagram. A master blade is precisely positioned on the table and adjustable weights are positioned on the opposite side of the arbor in both the span and chord orientations until the arbor rings appear to be exactly centered to the operator. Then the master blade is removed and a specimen is installed. Now, instead of adjusting the weights on the table, the weight packages from the blade are precisely located on the top surface of the blade with special fittings as depicted in the lower portion of the following graphic. The operator will use trial and error with various weight adjustments, at the various weight package locations, to center the concentric rings on the arbor.

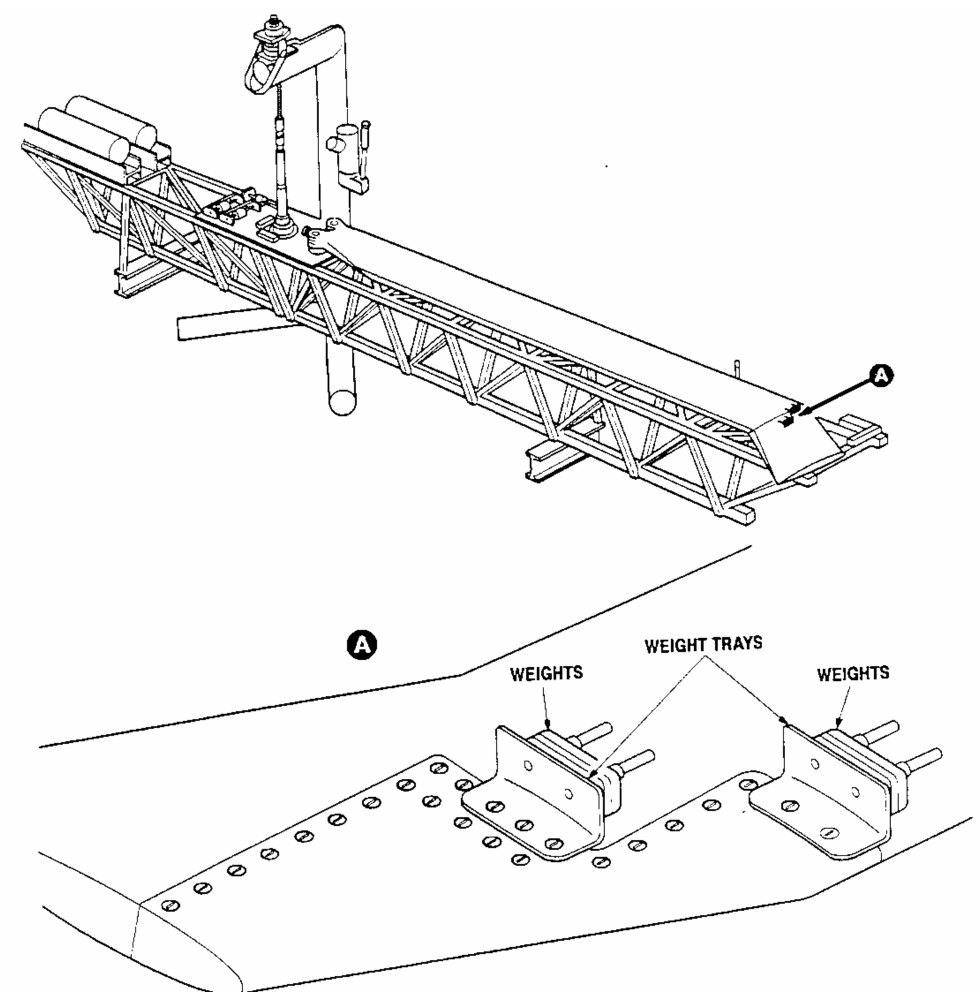

Figure3 – Traditional Arbor Type Static Balance Fixture

New, digital systems take the art out of the process and utilize simple science

Very sensitive, computer controlled, three point digital scales eliminate the time consuming fixturing and the logistics associated with utilizing master blades and calibration weights. The static characteristics of the master blade are known by the computer and digitally stored as a “virtual master blade”.

Figure 4 – Universal Static Balance Fixture (USBF)

How do Statics relate to Dynamics?

Dynamic tuning is presented in terms of acceleration

Vibration is represented in terms of acceleration. Acceleration is measured in "inches per second per second." Because the rotor systems are rotating objects, the dynamicist typically defines vibration in terms of inches per second or "IPS" by simply removing the reference to the revolutions per second of the rotating object.

The threshold of acceptable vibration for most helicopter components is generally 0.2 ips.

Static balancing is presented in terms of moment

Static balance is represented in terms of the first moment, or a weight times the arm. In the United States the common unit of measurement for the first moment, which can occur in the span or chord orientation, is expressed in "inch-pounds." This is very similar to the torque convention of pound-inches. A moment is simply an expression of torque.

How does one compare to the other?

Dynamic tuning equipment is programmed with coefficients that describe the vibration change that will result by adding one gram of weight to a predefined location. These coefficients are generally described conveniently in ips / gram. By knowing where the dynamic weight package is located in a rotor blade, the conversion from ips to in-lbs is simple. The following chart describes the relationship between ips and in-lbs for the AH-64 Apache main rotor blade.

Model	coefficient	units	ips / lb	dynamic	lbs per	resultant
				arm (ins)	1 in-lb	ips / in-lb
			(note 1)		(note 2)	(note 3)
AH64	0.0003	ips / gram	0.13608	42	0.02381	0.0032
Note 1: ips/lb = (ips/gram) x (453.6 grams/lb)						
Note 2: Moment = Weight x Arm, therefore, 1 in-lb / 42 ins =0.02381 lbs per 1 in-lb						
Note 3: (0.13608 ips/lb) x (0.02381 lb/in-lb) = 0.0032 ips/in-lb						

Table 2 – ips to in-lb conversion for the AH-64 MRB

The same technique can be applied to any rotor or propeller blade. The chart below displays the relationship between the vibration expressed in IPS and the static balance characteristic expressed in inch-pounds for several other systems:

Model	resultant
	ips / in-lb
AH64	0.0032
UH60	0.0062
AH1S	0.0089
CH47	0.0031
UH1H	0.0146
OH58D	0.0427
AH64 t/r inboard	0.3612
AH64 t/r outboard	0.6300
UH60 t/r	0.4360
LYNX3TR	1.6404
C-130	0.0893

Table 3 – ips per in-lb for various blades

Is This Technology Accurate and Repeatable?

Accuracy

The introduction of the digital static balance fixture has caused great controversy with OEMs and depot facilities. Until this time, most static balancing has incorporated the comparative balance method. Master blades were set aside and used to "calibrate" static balance fixtures. It was intended that all blades would be made to have the same static characteristics by making them all look like the "Working Master Blade" which was made to look like the "Secondary Master Blade" which was made to look like the "Primary Master Blade at the OEM. No one actually cared what the actual span and chord moment values were, because all blades were compared to "The Master Blade" through the ancestry just described. With the introduction of the digital balance fixture, suddenly it was obvious what the "digital" values were for the span and chord moments. Many times the OEMs and depots would qualify the result by saying that the value displayed is simply what the balance fixture believes the blade to be, which is not necessarily what the blade really is!

The approval process for use within the US Army required the measurement of numerous "flyable blades" to determine if the new fixture was reporting the correct values. It was during this process that the variability in the current comparative balance method became obvious. Master blades were measured quite differently from the expected engineering values. New and overhauled blades had values quite different from the specification. Occasionally master blades and operational blades were measured to within specification.

The following table provides an example of the variation. One new blade and three freshly overhauled Black Hawk blades were measured at Savannah, GA.

–	New Blade	35,361 in-lbs
–	IAI Overhaul	35,345 in-lbs
–	IAI Overhaul	35,361 in-lbs
–	CCAD Overhaul	35,442 in-lbs
	Range in measurements	97 in-lbs
	Manufacturers Spec.	35,418 in-lbs +/- 6 in-lbs

Table 4 – Example of Comparative Balance Method Results

Which value of the above blades is correct? Is the tool that made the measurements wrong, or are these blades all out of spec?

The result has been that the accuracy of the digital fixture has not been accepted by many OEMs and depot facilities because there is no way of testing the accuracy, other than empirically. Unfortunately, there has been too much variability in specimens to say which specimen is actually right!

Repeatability

The repeatability of the digital system is easy to test. It takes only 4 minutes to make a blade measurement and the answer is displayed digitally on the operator console. It is easy to measure the same blade numerous times, day after day, and determine the repeatability. The following chart displays the repeatability of one such digital fixture for various rotor and propeller blades.

Model	repeatability
	(+/- in-lb)
AH64	3
UH60	4
AH1S	3.5
CH47	19
UH1H	3
OH58D	2
AH64 t/r inboard	0.3
AH64 t/r outboard	0.3
UH60 t/r	0.3
LYNX3TR	0.05
C-130	0.3

Table 5 – Demonstrated Repeatability of USBF for Various Blades

Accuracy and Repeatability in terms of IPS

It is important to note that the only balance ultimately important is the dynamic balance result from the dynamic track and balance process. Because there is controversy over static balance accuracy and repeatability, looking at the static balance accuracy and repeatability in the dynamic balance terms, or ips, will put the controversy into better perspective.

The accuracy of the individual blade measurements for a ship set of blades is not important in itself, as long as all of the blades in the ship set are virtually the same. Accuracy is important in sustaining the store of spare blades so that all blades are interchangeable, thus eliminating the necessity to static balance all of the blades in a ship set whenever one or more blades are repaired or replaced. Even though there have been “Master Blades” utilized that do not meet the engineering static balance specification, that has been OK when all of the blades in a ship set were made to look close enough, or virtually the same as the master blade to allow dynamic tuning success.

Because accuracy is difficult to define, and it is not actually as important as the repeatability for producing a low vibration solution, it is prudent to look at repeatability first.

The repeatability of a static balance fixture is expressed in terms of the resolution of the fixture for a given rotor blade. This resolution is expressed in inch-pounds and will vary for different rotor blade models. Multiplying the demonstrated repeatability of the balance fixture by the factors that were developed previously, the repeatability of the balance fixture can be presented in terms of ips, which is the measure better understood by the pilot and maintainer.

The following chart expands the AH-64 example and derives the repeatability of the static balance fixture in terms of ips:

Model	coefficient	units	ips / lb	dynamic arm (ins)	lbs per 1 in-lb	resultant ips / in-lb	USBF repeatability	repeatability in ips
			(note 1)		(note 2)	(note 3)	(+/- in-lb)	(note 4)
AH64	0.0003	ips / gram	0.13608	42	0.02381	0.0032	3	0.0097
Note 1: ips/lb = (ips/gram) x (453.6 grams/lb)								
Note 2: Moment = Weight x Arm, therefore, 1 in-lb / 42 ins =0.02381 lbs per 1 in-lb								
Note 3: (0.13608 ips/lb) x (0.02381 lb/in-lb) = 0.0032 ips/in-lb								
Note 4: (0.0032 ips / in-lb) x (3 in-lb) = 0.097 ips								

Table 6 – Conversion of Repeatability from In-Lbs to ips for AH-64 MRB

This same conversion has been applied to the other sample blades presented earlier in the following chart:

Model	resultant ips / in-lb	USBF repeatability (+/- in-lb)	repeatability in ips
AH64	0.0032	3	0.010
UH60	0.0062	4	0.025
AH1S	0.0089	3.5	0.031
CH47	0.0031	19	0.060
UH1H	0.0146	3	0.044
OH58D	0.0427	2	0.085
AH64 t/r inboard	0.3612	0.3	0.108
AH64 t/r outboard	0.6300	0.3	0.189
UH60 t/r	0.4360	0.3	0.131
lynx3tr	1.6404	0.05	0.082
C-130	0.0893	0.3	0.027

Table 7 – Repeatability Expressed in In-Lbs and ips for Various Blades

Another way to look at the impact and importance of static balance is to relate the maximum acceptable vibration level of 0.2 ips to an equivalent static imbalance in terms of moment and described in in-lbs.

It is a simple matter to divide the "ips/in-lb" factor derived previously into the maximum acceptable vibration level of 0.2 ips. The following chart presents those results:

Model	resultant ips / in-lb	repeatability (+/- in-lb)	repeatability in ips	in-lb per 0.2 ips
AH64	0.0032	3	0.0097	61.73
UH60	0.0062	4	0.0246	32.50
AH1S	0.0089	3.5	0.0310	22.60
CH47	0.0031	19	0.0596	63.71
UH1H	0.0146	3	0.0437	13.72
OH58D	0.0427	2	0.0854	4.68
AH64 t/r inboard	0.3612	0.3	0.1084	0.55
AH64 t/r outboard	0.6300	0.3	0.1890	0.32
UH60 t/r	0.4360	0.3	0.1308	0.46
lynx3tr	1.6404	0.05	0.0820	0.12
C-130	0.0893	0.30	0.0268	2.24

Table 8 – In-Lbs Occurring at 0.2 ips for Various Blades

It is obvious from the chart that the demonstrated repeatability of the static balance fixture equates to a fraction of the final acceptable vibration level after dynamic tuning. Knowing that the rotor and propeller blades are the single greatest contributor to system imbalance, it is easy to see why the dynamic tuning process is so greatly simplified after the blades have all been statically balanced. The dynamic tuner is now able to fine-tune the system because the most egregious cause for imbalance has already been eliminated.

Our deferred look into accuracy can now be put into perspective. By using the ips to in-lb conversion, and putting that into perspective with the 0.2 ips acceptable limit, the table above also provides insight to accuracy and "what is good enough."

Using the AH-64 as an example, the chart shows that one in-lb is equivalent to 0.0032 ips. The chart also shows that 61.73 in-lbs equates to the threshold for acceptable final vibration of 0.2 ips. Therefore, any discussion of "inaccuracy" in excess of two or three times the demonstrated repeatability for most blades appears unproductive. Striving for an understanding of accuracy beyond these levels becomes more theoretical and academic than practical.

Real World Facts

Universal Static Balance Fixtures (USBFs) have been deployed around the world for about seven years. Data has been captured on thousands of rotor blade static measurements. Data from two of the U. S. Army's primary aircraft are displayed in the following series of charts.

This first chart displays the results of initial measurements of over 1100 different AH-64 main rotor blades. The manufacturer's specification for span moment is 24,300 in-lbs. As the chart shows, blades ranged in value from 24,000 in-lbs to 24,500 in-lbs.

The equivalent of 0.2 ips has been superimposed as control limits on this chart to show just what 0.2 ips looks like in relation to the static balance argument for the population of Apache blades measured. In the case of the Apache, the equivalent of 0.2 ips is 62 in-lbs.

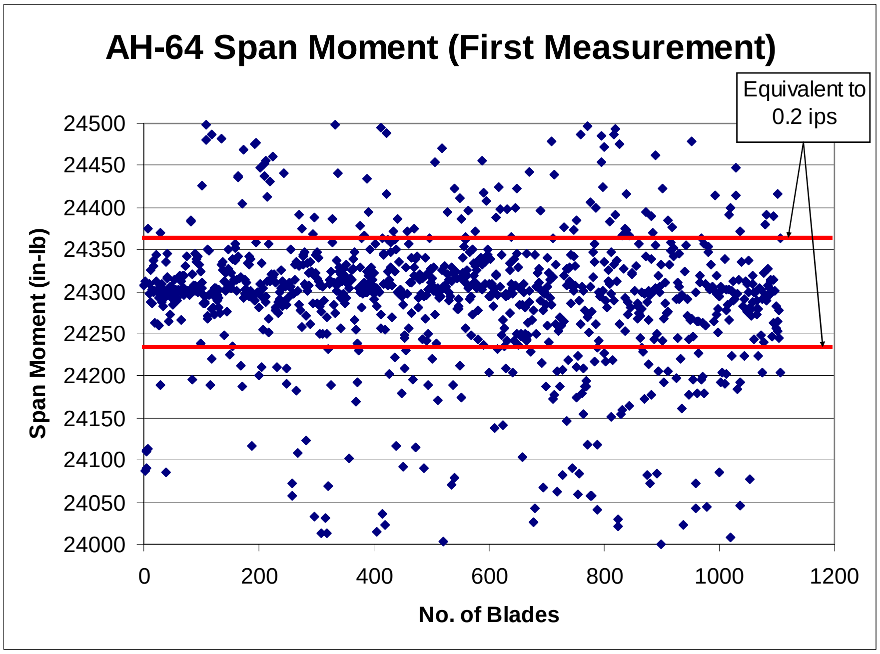

Figure 5 – AH-64 MRB Span Moments with 0.2 ips Control Limits

This is a powerful chart. First, it impresses the viewer with the dramatic reality of how drastically the rotor blade static balance characteristics change over time and with use. Secondly, it clearly answers the question as to why rotor tuning can take so long to complete. The dynamic tuner only has 105 in-lbs worth of weights to adjust on the Apache. Dynamic balance is impossible if the span moments of opposing blades differ by more than 105 in-lb. Thirdly, efforts to statically balance this rotor blade to an accuracy less than 3 in-lbs has greatly diminishing benefit. The resolution of this balance fixture for the AH-64 main rotor blade is 3 in-lbs. In terms of vibration, that amounts to just 0.0097 ips!

The next chart depicts first measurement results for the population of Black Hawk main rotor blades reported. Here, the 0.2 ips equivalent happens to be equal to 32.5 in-lbs and has been superimposed on the chart. The manufacturer’s specification for span moment is 35,418 in-lbs. The range of moments for the Black Hawk is approximately 600 in-lbs. Because the dynamic authority for the Black Hawk is limited to 117 in-lbs, the Black Hawk maintainer has the same problem as the Apache maintenance officer. When the opposing blades differ by more than 117 in-lbs, dynamic balance cannot be achieved.

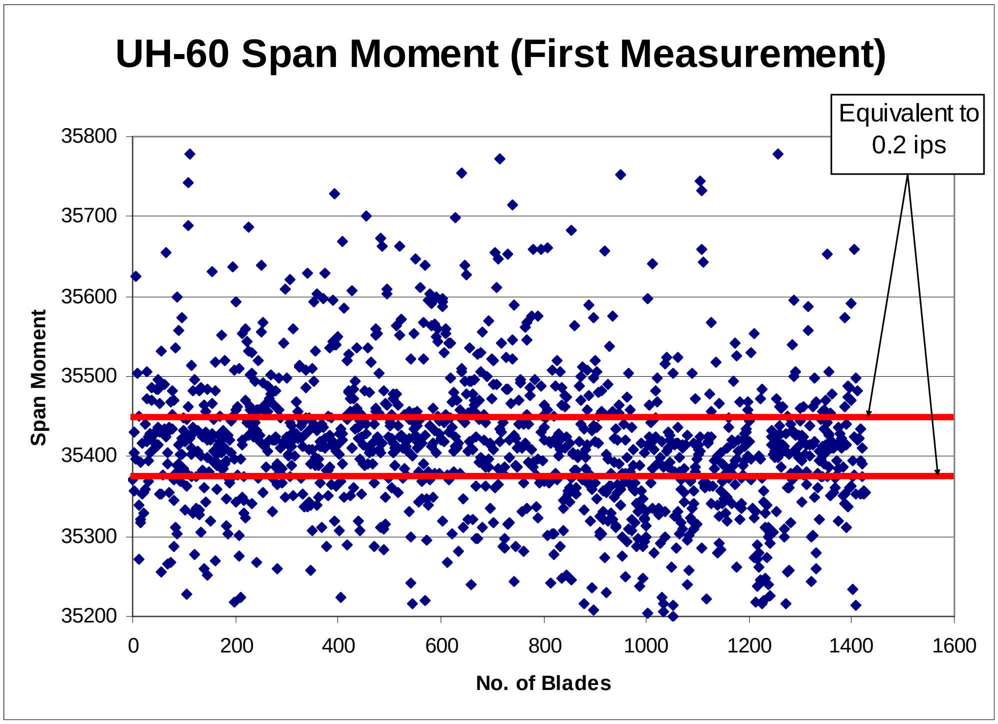

Figure 6 – UH-60 MRB Span Moments with 0.2 ips Control Limits

A Change in Paradigm

State of the art tools are now available that take the "art" out of rotor blade static balance and utilize science to make it simple, safe, easy, and inexpensive to perform. Before the deployment of static balance equipment to the operator, blades were removed and swapped with other blades until a combination was found that would fly together. With the deployment of the USBF to all levels of maintenance, rotor blade swapping has been eliminated, returns to the OEM and depot facilities, for balance reasons, have been eliminated, and all blades are being forced back to the manufacturer's specification for static balance, making all of the blades interchangeable.

Current OEM and depot processes are being utilized that were developed decades ago. OEMs and depot facilities are reluctant to change and some claim that the digital technology is not as accurate and repeatable as the conventional, comparative balance method using master blades. While this could be so, it can be argued that the conventional methods have never been put to the same scrutiny as the digital alternatives have been, thus diminishing that claim. The point of this paper is to provide evidence that eliminates the necessity to prove one to be equal to the other, and puts the digital balance results into perspective with the dynamic goals of rotor tuning, the only goals that matter in the final analysis.

A change in paradigm from the comparative balance method to the "virtual master blade" method provided with digital technology is necessary to reduce costs to the operators. Literally thousands of master blades are shipped all over the world as the backbone of the conventional static balance process. All of the costs associated with master blade maintenance and shipping can be eliminated with the adoption of the "virtual master blades" through the use of the digital static balance fixture.

Conclusion

Digital static balance technology delivers results quickly, consistently, reliably, inexpensively. Many blades can be balanced on a digital balancer in the time it takes to balance one blade using conventional methods. The reduction in maintenance man-hours to balance the blades, the reduction in man-hours to dynamically balance the blades, the reduction of operational flight hours to dynamically balance the blades, and the reduction in expenses to support the static balance infrastructure (no master blades) all add up to a tremendous cost reduction in maintenance downtime and expense.

The United States Army now employs dozens of Universal Static Balance Fixtures within all levels of maintenance, depot, intermediate and unit. The United States Army has saved millions of dollars in reduced rotor blade returns to the manufacturers and depot repair facilities. The United States Army has saved millions of dollars in reduced maintenance test flight expenses by cutting associated activity in half.

Similar savings are available to commercial operators with the cooperation of the FAA and/or the Original Equipment Manufacturers (OEMs).

Rotor blades are an expensive asset and maintenance of those assets is critical to helicopter performance. Maintenance facilities stand to collectively save millions of dollars by adopting the "virtual master blade" in place of the conventional techniques requiring master blades.

Joseph T. Buckel – Vice President / Senior Engineer, Avion, Inc.

Joseph has managed numerous information system development initiatives that include Automated Information Technologies (AIT), Contact Memory Button (CMB) technologies, and the WEB for the purpose of managing and understanding aviation maintenance, support, and cost. These efforts provided the insight to problems that led to the product development of static balance fixtures. Joseph is the co-developer of the Universal Static Balance Fixture (USBF), and the Virtual Master Blade (VMB), both of which are test fixtures for the static balancing of helicopter main and tail rotor blades respectively. Current activities include the adaptation of this technology to propeller blades.

Joseph is an honor graduate of Parks College and holds FAA Airframe and Powerplant Mechanics and Commercial Pilot Licenses. Joseph co-founded Avion, Inc. in 1992.