Weight and Balance Measurement and Control for Helicopter Rotor Blades

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The extract data displayed in this paper was collected over a two-year time frame. Most of the data were obtained in the presence of government and contractor personnel. Complete data sets that support the data reflected can be made available.

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The USBF development was partially funded by a Manufacturing Technology program spearheaded by the Corpus Christi Army Depot. Government funding, private funding, soldier involvement, and corporate cooperation facilitated the development of a good piece of equipment at great benefit to Army Aviation.
I. Blade History

Early helicopter rotor blades were fabricated from wood, dope and fabric. These blades were sufficient to take flight loads when new, but deteriorated within a relatively short time. Environmental weathering of these structures and dry rotting of the wood were prevalent. A common joke was, “You are OK as long as the termites continue to hold hands!”

Metal blades were the next technology iteration that solved the wood blade problems. Common design features included an extruded aluminum spar, aluminum honeycomb covered by aluminum skin after bodies. Stainless steels were utilized at the leading edge for erosion control. These blades were superior to the wood blades in most all respects. Eventually corrosion became the primary reason for removal from service. Unfortunately there were some in-flight fatigue failures, due to manufacturing anomalies and environmental effects. During the Vietnam War, these blades served admirably. The blades were capable of sustaining damage and still getting the crew home. The one critical area where damage tolerance needed improvement was in the spar area. Damage here propagated very quickly and some losses were suffered.

As a partial result of the Vietnam experience, so called composite blades were developed during the 70’s. Use of composite materials technology allowed for redundant load path structures and tailoring of blade layout, allowing for new aerodynamic shapes and airfoils. All blades have been, by strict definition, composite blades but the term today refers to those blades made at least partially from fiberglass epoxy type materials. Blades of this type utilize either glass fiber or titanium for spar construction with a Nomex Honeycomb (Trademark) core after-body with glass skins. These blades are damage tolerant and very reparable in the field. It is this last fact, the reparability that has lead to much of the field’s track and balance problems.

I. The Manufacturers Balance Process

Typically, after a rotor blade is manufactured, the blade is statically balanced span-wise. Some manufacturers balance both span-wise and chord-wise. The objective of span balancing is to get the span moment (the product of blade weight times the distance from the mast center of rotation to the blade center of gravity) to be equal to the specification target. Blade designers always document this value, although historically, have not used the numerical value for balance purposes. Generally, manufacturers select a blade that is used as a master blade. The master blade span moment gets measured as closely as possible and it is this value that is documented.

The master blade is used to comparatively balance production blades. When overhaul sites are established, a master blade is required. Usually the prime contractor is paid to make a duplicate(s) of the master for the new sites. Some manufacturers go an extra step in their process of producing blades. After static balancing, some manufacturers utilize a whirl tower and a whirl tower master to further refine blade track and balance characteristics. Blades that go to a tower do not have weight added or subtracted at the
tower. The static span balance assures the lateral balance. The purpose of the tower is to set trim tabs and dynamic chord. Weights, generally at the tip of the blade, are moved forward or aft, to dynamically tune the blade to the referenced master whirl blade.

During evolution of rotor blade design, whirl towers were found to be useful in the development process.

Out in the field, blade track and balance evolved from tracking by using a “flag” (a long pole with bunting at the top that had to be stuck into the blades rotating path) and guessing which blade was light, to dynamic tracking and balance computers.

II. Span Moment Tolerances

Span moment tolerances required by the blade manufacturers vary between $\pm 1/4$ in-lbs in span-wise moment on old UH-1 blades to $\pm 10$ in-lbs on newer OH-58D blades. The tight tolerances are believed to be essentially the stated repeatability of the then in vogue, comparative balance available. The looser tolerances are probably recognition of what is achievable in a digital world.

If a comparative balance is good to $\pm 1/4$ in-lbs. and the working master is developed from the golden master using the comparative tool, is the working master accurate to a $\pm 1/4$ or a $\pm 1/2$ in-lb? Working masters for depot use are even more removed. How much do they vary during the year or two before mandatory re-calibration?

With the advent of the Avion digital machine, insights into these numbers are now available. Figures 1-4 reflect requirements versus measured values on various master blades and new production or overhauled blades. Many variations from the expected are observed. These variations have probably been with us forever and have not always been a real problem in the past. On less repairable blades, the dynamic authority was sufficient and variation was easily handled. Now the variation in blade span moments is such that the dynamic authority is not sufficient and the field is forced into swapping rotor blades until blades with similar span moments are, by chance, paired opposite each other. As many units in the field can now attest to, the other solution is to statically balance the blades using the Avion USBF (Universal Static Balance Fixture).

III. Master Blades

The AH-64 Apache

During the development / qualification process, the Avion USBF was taken to the various prime contractors facilities to “calibrate” with their masters. The first visit was made to the MDH (McDonnell Douglas Helicopter – now Boeing) facility in Mesa, Arizona. The master blade (serial number RBM-196) was used to obtain numerous data points. The readings varied from the 24,300 in.-lb. requirement by 13 to 19 in.-lbs. on the light side.
The 13 was one reading with the other data points clustered at the 18 and 19 end of the spectrum.

The manufacturer of the Apache blade for the Prime Contractor is Composite Structures of Monrovia, California. Three master blades were made available at their facility. Figure 1. below reflects the data for each of these master blades. Figure 1 also incorporates the master blade data from MDH and CTI.

<table>
<thead>
<tr>
<th>SPAN MOMENT SPECIFICATION  24,300 in-lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSD</td>
</tr>
<tr>
<td>GRAND MASTER</td>
</tr>
<tr>
<td>WORKING MASTER</td>
</tr>
<tr>
<td>CONTROL MASTER</td>
</tr>
<tr>
<td>MDH</td>
</tr>
<tr>
<td>MASTER</td>
</tr>
<tr>
<td>DELTA'S</td>
</tr>
<tr>
<td>TOTAL RANGE</td>
</tr>
<tr>
<td>CTI</td>
</tr>
<tr>
<td>MASTER</td>
</tr>
</tbody>
</table>

Figure 1

The MDH master blade agrees very favorably with the CSD (Composite Structures) master blades. CSD provided the master blade and calibration service to MDH. The total range in figure 1 above reflects a 11 in-lb delta between the lowest Avion reading on the lowest span moment blade versus the highest span moment reading on the highest span moment blade. The average difference in these four CSD produce master blades is 4.2 in-lbs. These blades are very close to each other; however, they seem to be “lighter” than specification requirements (24,300) by approximately 20 in-lbs.

The CTI master blade was developed independently of CSD. Without access to the CSD standard, CTI had to develop their master blade to the specification! The CTI master blade was measured at much closer to spec values, but was on the high side.

It is clear (Fig. 1) that the Avion USBF machine is measuring to a repeatability of plus or minus three in-lbs on any given Apache blade. With regards to answering the question; “Is the USBF accurate in evaluating the Apache blade?” the following reasoning helps! The fact that two sets of independently developed master blades were measured to either side of target value brings one to logically conclude that the Avion USBF might be closer to the target than either set of master blades.
More importantly, if blades balanced from either set of master blades are adequate, then blades balanced with the Avion USBF will be somewhere in-between and will also be adequate.

**Boeing Master Blades**

The CH-47D master blade was measured at Boeing’s facility in Ridley Park, Pennsylvania. The master blade was found to be about 10 in-lbs low. The USBF was shown to be capable of repeating Chinook blade readings to within ± 6 in-lbs.

The Avion USBF was used by Boeing to check Boeing production blades. Boeing, using their current pivot balance and master blade technology had balanced these blades. Their balance process produced new production and newly overhauled blades that varied as much as ± 72 in-lbs. Boeing’s conclusion after using the Avion equipment was that the USBF was accurate and repeatable. Figure 2 below reflects the Chinook master blade findings.

<table>
<thead>
<tr>
<th>CH-47D</th>
<th>SPAN MOM</th>
<th>LOW</th>
<th>AVG</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASTER</td>
<td>65369</td>
<td>65353.6</td>
<td>65359.4</td>
<td>65364.6</td>
</tr>
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<td>DELTA FROM SPEC</td>
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<td>9.6</td>
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<table>
<thead>
<tr>
<th>CH46</th>
<th>SPAN MOM</th>
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<th>AVG</th>
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</tr>
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<tbody>
<tr>
<td>MASTER</td>
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<td>26694.1</td>
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<td>26695</td>
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<tr>
<td>GOLD MASTER</td>
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<tr>
<td>DELTA BETWEEN MASTERS</td>
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<tr>
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<td>26626</td>
<td>26628</td>
<td>26630</td>
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<td>21</td>
<td>23</td>
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</tbody>
</table>

**Figure 2**

When the CH-46 fiberglass rotor blade masters were evaluated, they were found to be 80 plus in-lbs over spec value. After checking key USBF data files and dimensions and finding no errors, Boeings two point scales were used to resolve the difference. The two point scales provided a third set of values. This data was in closer agreement to the USBF values. Boeing concluded that there was a problem with their master blades. Boeing volunteered that production blades should be evaluated as they were balanced on the pivot balance and should be good. In fact, new production blades were found to be within 23 in-lbs of specification.
Sikorsky Master / Production Blades

Sikorsky master blades for the UH-60, SH-60, and CH-53E were evaluated at the Sikorsky blade balance shop. All of the master blades were found to be under the specification targets. When you look at the specifications, especially for the SH-60 and CH-53E, you might conclude that the values are approximate values. These values are used by other engineering disciplines for their calculations, but are not very precise for digital balance purposes. When master blades are used, exact span moment values are not necessary. What is necessary, is that all blades be close to each other in actual span moment. Master blades accommodate this requirement. This same argument is supported by the Apache data above. CTI’s master blade was developed independently and without benefit of existing master blades. Faced with developing a master blade to a digital specification, CTI used standards other than an existing master blade and consequentially developed a blade much closer to the specification value. If given a master blade as the standard, rest assured that CTI’s developed master blade would have been statistically equivalent.

<table>
<thead>
<tr>
<th>UH-60</th>
<th>SPAN MOM</th>
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<td>35,384.30</td>
<td>35,387.50</td>
<td>35,391.90</td>
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<th>AVG</th>
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<tr>
<td>Overhaul (IAI)</td>
<td>35,418</td>
<td>35,361</td>
<td>35,361</td>
<td>35,361</td>
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<tr>
<td>Overhaul (IAI)</td>
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<td>35,345</td>
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<td>Overhaul CCAD</td>
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<td>35,442.50</td>
<td>35,445</td>
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<td>New Sikorsky</td>
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<tr>
<td>Delta’s</td>
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<td>95</td>
<td>97.5</td>
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<table>
<thead>
<tr>
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<tr>
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<tr>
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<tr>
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<td>56</td>
<td>51.7</td>
<td>48.3</td>
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</table>

Figure 3

A new production blade and three newly overhauled, never flown blades were obtained for evaluation. The span moments were analyzed and it was concluded that the four blades would probably not dynamically balance properly with each other. Figure 3 above documents the as found condition of these blades. Two contractor overhauled blades and
the new production blade would have flown together, but the CCAD (Corpus Christi Army Depot) overhauled blade would most likely have been a problem. Interestingly, the CCAD blade was closer to specification than the other three. In the field however, this CCAD blade would have been seen as the “bad” blade. (The reasoning that produced the above conclusion is provided later on in this document; in the paragraph labeled “Dynamic Authority”.)

Bell Helicopter Blades

The only master blades available for Bell Helicopter aircraft were the master blades at CCAD, shown below. Again, there is significant deviation from specification. An overhauled blade balanced by processes utilizing the master blade produced, not surprisingly, a similar blade. The AH-1W production blade was found to be 14 in-lbs closer to the specification than the master blade. Although the comparative balance tool is quoted to be accurate enough to maintain a plus or minus 1/2 in-lb tolerance, the fact is, the process in this case produce a product with a much wider tolerance. It should be emphasized that the above blade would have flown with similarly balanced blades and may have been “good enough”.

<table>
<thead>
<tr>
<th></th>
<th>SPAN MOM SPEC</th>
<th>LOW</th>
<th>AVG</th>
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<tr>
<td>AH-1W</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MASTER (CCAD)</td>
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<td>59,740.10</td>
<td>59,743.20</td>
<td>59,746.40</td>
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<tr>
<td>DELTA FROM SPEC</td>
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<td>79</td>
<td>82.22</td>
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<td>DELTA FROM SPEC</td>
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<table>
<thead>
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<tr>
<td>UH-1N</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>MASTER BLADE (CCAD)</td>
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<td>32,018.00</td>
<td>32,018.60</td>
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</tr>
<tr>
<td>DELTA FROM SPEC</td>
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<td>139.5</td>
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<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>UH-1H</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MASTER BLADE (CCAD) 2522</td>
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<td>DELTA FROM SPEC</td>
<td>-0.5</td>
<td>18.4</td>
<td>16.6</td>
<td>14.4</td>
</tr>
</tbody>
</table>

Figure 4

V. Dynamic Authority

When statically balance blades are installed on a rotor hub, the whole spinning mass is again balanced using computerized dynamic balance tools. In the old days before the
dynamic tools became available, tight blade specs and very little blade repair allowed the field to fix a lateral vibration by guessing which blade was at fault and then adding mass. If the lateral got worse, you deduced that you had guessed wrong. If it got better, you might have added additional mass, with a flight test after every move. It was an art! Today, the Army uses the AVA (Aviation Vibration Analyzer) tool that tells the user how much weight to add where, as well as predicting track and vibration solutions.

Figure 5 depicts the span moment weight authority available to the field for dynamic balance of the rotor hub and blades. For instance, the 117 inch-pounds for the UH-60 means that if you had a perfectly balanced hub with four perfectly balanced blades installed on it and then were to add the maximum allowed weight to one blade, you would have a 117 inch pound unbalanced moment. The 117 inch-pound adjustment is provided to the field to make up for the hub, blades, and eventual blade mass properties changes that happen over time.

One of the reasons the field has track and balance problems is because the new composite blades are so repairable; repairs are being accomplished that would have otherwise gone to depot. Economic pressures have forced the field commanders to attempt repair versus sending in to depot, which has exacerbated this problem. The weights authorized to be adjusted for dynamic balance purposes are just not large enough to counter act the factors that are changing the span moments of the blades. These factors include large repairs, moisture, erosion and painting. At depot, tip caps are removed and larger weight packages are revealed, that allow greater control than normally allowed in the field.

<table>
<thead>
<tr>
<th>Dynamic Authority inch pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uh-60</td>
</tr>
<tr>
<td>AH-64</td>
</tr>
<tr>
<td>CH-47D</td>
</tr>
<tr>
<td>OH-58D</td>
</tr>
</tbody>
</table>

Figure 5

Another reason for some of the problems resides in the depots. Multiple overhaul sites, using master blade technology require precise master blade duplication and maintenance! For a multiple number of reasons, this has not always been happening. The table in figure 3 shows four blades with zero time since overhaul and / or since new. All of these blades were required to be statically balanced using master blades. All of these blades were balanced to the same specification. All of these blades were shown to be significantly out of tolerance. If the CCAD blade were to be installed opposite the second Israeli Aircraft Industries blade, there would be a 105 in-lb difference between them. On an UH-60 Blackhawk, you can add weights to the lighter span moment blade to counteract the other blade. The UH-60 blade accommodates enough weight during
dynamic balancing to generate a 117 in-lb moment (Figure 5 above). If the hub were perfectly balanced this example hub and blade combination would dynamically balance acceptably. However, perusing hub drawing tolerances reveal that the hub may consume about 30 in-lbs. of the 117 in-lb. capability. It’s obvious that this hub, although well within engineering tolerances, when paired with the referenced blades, would probably not be adequately balanced dynamically.

VI. Field Operating Limitations

There are no real limitations to what can operate in the field! Blackhawk blades are operating at 400 inch-pounds over specifications. The way this is accomplished is, span moment heavy blades get matched up with other span moment heavy blades. The cost to this approach is high. The actual blade span moments of blades are unknown, so matching blades is a process of random chance. A number of blades might be tried before a suitable match is found. Maintenance test flights are required for each trial before a determination of suitability can be made.

The older the fleet of blades and the more repairable the blades the wider the variation in span moments. The wider the variation in the population of blades, the harder and more costly the search for a suitable match becomes. The Chinook is a good example. The Chinook meets all of the criteria for being hard to match up. Chinook blades on operating aircraft have been found to have span moment deviations to specs as large as the equivalent of plus and minus two pounds at the tip. Plus or minus 700 plus in-lbs. of imbalance on an aircraft rotor system is attention getting to say the least.

If a Chinook were successfully flying with blades at one end of this extreme and a single blade had to be replaced with a brand new blade, the aircraft could not be tracked and balanced within limits. There is not enough dynamic balance weight authority to make up for this situation. When this type of situation occurs, the Army’s dynamic balance tool will look at the data and then try and make corrections to the one blade that is not flying like the rest. The only blade meeting span moment specifications is the one that is deemed to be bad. The field gets unfairly so, but nevertheless, irate with the Boeing product.

With the advent of the fielding of the Avion USBF, this kind of problem has been largely eliminated, at least in those locations where the machine is available.

The tightness of span moment at depot is important, but the maintenance of that span moment in the field is critical. Coming out of depot there is considerable leeway available if the span moment is maintained over time. For instance, going back to the UH-60 example again, the field acceptable span moment using the USBF is set at 35,418 plus or minus 30 in-lbs. The UH-60 has a dynamic authority of 117 in-lbs. so if one blade is 30 in-lbs low and the opposing blade were 30 in-lbs high, there would still be 57 in-lbs of excess dynamic authority left to make up for any hub imbalance. There is a high probability that all of a population of blades meeting these criteria would be interchangeable and successfully balanced. Setting this higher field limits attempts to
keep Blackhawk tip caps from being removed more than necessary. Getting tip caps off is a tough job. If the blade exceeds the plus or minus 30 in-lbs, then the tip cap comes off and the blade is re-balanced back to specification.

**This field procedure and attendant tolerance is in recognition of what is really important. Dynamic balance and low vibration is important! Static span moment values are important only when they go out side of the tolerances that start making the dynamic balance process difficult or impossible.**

**VII. Dynamic Chord Problem**

Both Boeing and Sikorsky utilize whirl towers at their respective facilities. The typical procedure is for the blades to first be statically balanced and then they go to the tower. At the tower, the objective is to make the production blades fly with the whirl tower master blade. Mass is generally not added nor subtracted from the blade. The span moments are assumed to be on specification so the only adjustments made to the blade is the bending of trim tabs and the moving of weight forward and aft to affect dynamic chord balance. Trim tabs allow for slight aerodynamic differences in blades. Moving weights chord-wise change the chordal response to moment of inertia changes with changes in lift.

For instance, a blade at the tower is flat tracked to the master using pitch links and trim tabs. Then pitch is increased and weights are moved to keep the production blades tracking with the master. If, for instance the production blade climbed above the master with the application of pitch, weight would be moved forward to try and bring that blade down. This is an oversimplified explanation of the procedure, but detailed enough for our purpose here. The over all goal is to try and get equal lift produced by the master and production blades at equal angles of attack.

This is all well and good. However, in real life this is what happens. The newly accepted rotor blade is sent out to the field as a replacement blade. The first thing that happens after installing the new blade is the aircraft is run up and flat pitch track checked. If this blade that simulates the whirl tower master does not track with the other two on the Chinook, the pitch links and possibly trim tabs get adjusted. When pitch is pulled and the aircraft leaves the ground, the AVA looks at track, lateral and vertical vibration levels and attempts to solve the dynamic situation. The blade that changes the most is usually the blade just off the whirl tower. Remember that it’s easier to change one blade than the two that have been successfully flying together. If all looks good or is made good during hover, then forward flight airspeed sweeps are made. Additional adjustments can be directed by the AVA to further fine-tune the blades to fly harmoniously with changes in airspeed. The bottom line is, after all of this commotion, there is little chance that the new blade still emulates the whirl tower master blade.

Occasionally, after span balancing a Chinook blade in the field, the aircraft goes from ground to a hover condition, and sees a split in blade track. One blade climbs or dives compared to the others. This may be a dynamic chord problem. The technical solution
would call for moving weights chord-wise, just like on the whirl tower, until the split is resolved. There are some legitimate concerns that the AVA may not have the required resolution in track to make a small adjustment in the field. On the other hand, if the track is large enough in deviation that it is noticed, then at least an improvement may be possible with chord weight movement. The adjustment might not be as fine-tuned an adjustment as possible on a tower, but an adjustment is at least possible to push the blade in the right direction.

The relationship of static chord to dynamic chord was addressed by a recent Boeing study. Boeing utilized an Avion USBF to address whether or not there was a correlation between static chord center-of-gravity and the dynamic chord. The USBF was used to get static chord center of gravity data, both before and after whirl tower. Although Boeing has not delivered their official findings, Avion analysis of the data did not detect a correlation. There has been hope by some that the Avion USBF could somehow take the place of the whirl tower. Whirl towers are very expensive and represent a funnel through which all production must flow, which also adds to the overhaul cost.

Unluckily, static chord measurements do not predict dynamic chord reactions.

A case can still be made however, for doing away with whirling blades for field use. By recognizing that with the USBF in the field (taking care of the static span balance portion of the process) and with the AVA in the field, all aircraft become whirl towers. You loose very little in terms of not having a whirl tower master blade model when, as it has already been shown, the master blade imitation is not maintained after installation anyway.

It should be noted that for production, a whirl tower is invaluable due to the fact that all of the blades that are installed on the production aircraft come from the whirl tower. When all blades that are installed come from the whirl tower, their dynamic characteristics are very similar which will reduce the time for track and balance in the production facility.

VIII. Field Experience

The field experience with the USBF has been outstanding. Complete populations of CH-47 blades at locations such as Ft. Rucker and Ft. Campbell have been made, once again, interchangeable. Maintenance flight time for track and balance has been cut dramatically. AH-64 units are starting to reap similar benefits as a result of fielding 20 USBFs to Apache units in 1999. Where contractor personnel control USBFs, UH-60s and OH-58Ds are being balance with excellent results and savings.

There is a required paradigm change, but tremendous savings are the reward!
Conclusions

No matter how tight depots control production span moments, maintaining span moments in the field is critical.

If span moments are maintained in the field, extremely tight depot tolerances are unnecessary.

A virtual master blade can maintain span moment tolerances better than comparative balance / master blade technology. This is especially true when managing multiple depots for any given blade.

The Avion USBF is quite adequate for depot use.

It may be possible to adjust chord weights in the field to affect the dynamic chord of a blade.