IMPROVED ROTOR SMOOTHING FOR THE U.S. ARMY CH-47D

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Rotor smoothing for U.S. Army rotorcraft must provide both a time efficient and cost effective means for reducing once-per-revolution vibrations. Through anecdotal experience, rotor smoothing systems have proven to be relatively efficient for both UH-60 and AH-64 rotorcraft; however, these same systems have not been as efficient for the CH-47. Improving the rotor smoothing coefficients for the CH-47 will reduce both the time and cost needed to bring the rotorcraft to an appropriate performance level. This paper outlines the effort for improving the rotor smoothing process for the CH-47.

Introduction

Rotor smoothing, or rotor track and balance, is a routine maintenance task consisting of a calculated system of adjustments to pitch links, blade weights, and trim tabs. These adjustments are designed to reduce vibrations at the fundamental (once-per-revolution) rotor frequency. A reduction in rotor vibration adds a significant amount of “smoothness” to the aircraft flight. The procedure for rotor smoothing is typically performed in multiple flight modes including flat pitch ground running at 100% (FPG100), hover, and several pre-defined steady, level flight air-speeds. The smallest adjustment can change both the dynamic balance as well as the aerodynamic response of each individual blade. The Aeromechanics Division of the Aviation Engineering Directorate is the organization cognizant over the rotor smoothing of Army rotorcraft. Since the fleet-wide fielding of the Aviation Vibration Analyzer (AVA) in the early 1990’s, AED has noted more difficulty in rotor smoothing the Chinook than either the Blackhawk or the Apache. This inefficiency was suspected to be caused by inaccurate sensitivity coefficients associated with the CH-47 adjustments. Current sensitivity coefficients for the CH-47 are based upon a relatively small sampling of aircraft, unlike the UH-60 and AH-64 whose coefficients are based upon a more extensive sampling. In addition, the coefficients may have changed as the airframes and blades have accrued flight hours and various repairs. Increasing the sampling on current aircraft produces more accurate coefficients and, thus, should reduce the number of flights required to reach satisfactory vibration levels during rotor smoothing.

Rotor Smoothing Process

Vibration monitoring systems collect vibration and blade track data and then recommend adjustments for each rotor blade. These adjustments (i.e., pitch link, weight, and trim tab) have historically been calculated using linear models in which the adjustments are assigned experimentally determined sensitivity coefficients. These coefficients reflect an adjustment’s effect on the magnitude and phase of vibrations as well as the effect on the blade tracking height. In reality, there are many possible solutions for any RT&B scenario; therefore, the best solution is typically found as the “best fit” using a linear model [1-5].

Test flights

The rotor smoothing process is typically composed of three phases:

- Initial flight test and gathering of vibration data
- Adjustment(s) to blade(s)
- Flight test and gathering of vibration data

During the initial flight test, data is gathered and used as a base for the subsequent flight. Adjustments are then made according to predictions provided by the rotor smoothing system. Following the adjustments, another test flight is made. This pattern allows for the gathering of three types of information: vibration data before any corrections, the correction/adjustment itself, and vibration data collected after the correction [1].

While tracking data is also gathered during the rotor smoothing process, it is not the primary goal of rotor smoothing. Adjustment solutions for a given rotor are optimized for several variables, including track split, number of moves (adjustments) required, and vibration levels over the entirety of the test envelope. For this optimizing process, track split plays only a small part in choosing a balancing solution [2].

During the test flights, data is collected in a number of different flight regimes which typically include flat pitch on ground (FPG100), hover, and several predefined air speeds. The AVA, for instance, collects data for the following CH-47 flight regimes:

- FPG100
- Hover
- 100 Knots
- 130 Knots

Collecting data for all these regimes enables the rotor to be smoothed over the entire flight envelope rather than at a single flight regime.

Linear Model

Most rotor smoothing systems rely on a combination of experimental data and linear models. There has been increased interest in neural networks as an improved method for calculating and predicting adjustments; however, these networks have closely modeled linear relationships. A recent study showed that neural networks can almost always be accurately described with a set of linear coefficients [6]. In reality, the linear model is an oversimplification of the actual rotor system because many parametric relations are possible. As an oversimplification, however, it is only inaccurate at extremes and is otherwise sufficient as an acceptable approximation. Using a significant number of test flights (20-30), the error associated with the linear coefficients can be reduced to 20-30% [1,2,7]. The linear coefficients a_{ijk} can be defined as:

$$a_{ijk} = \Delta v_{jk} / A_i \qquad (1)$$

where Δv_{jk} is the change in measured vibrations for flight state j and sensor k and where A_i is the adjustment type. Similarly, linear models are currently being used in predicting track split response [6]. Linear blade tracking coefficients b_{ijk} can be defined as:

$$b_{ijm} = \Delta t_{jm} / A_i \qquad (2)$$

where Δt_{lm} is the change in measured blade tracking height for flight state j and rotor m and where A_i is the adjustment type.

Coefficient Improvement Process

Data collection for the coefficient improvement process was taken with the new AVA single tracker in its standard configuration. Flight tests were made covering a variety of different flight regimes as mentioned previously. The data collected was then processed and the results were analyzed.

AVA Equipment

Standard configuration for the AVA single tracker during rotor track and balance involves the installation of forward and aft accelerometer boxes as seen in Figures 1 and 2 [8].

Figure 1. Aft Accelerometer Block

Figure 2. Forward Accelerometer Block

After the blocks are placed within the forward and aft rotor pylons, the Data Acquisition Unit (DAU) is assembled and connected with the breakout cable to the blade track bulkhead receptacle. The Universal Tracking Device (UTD) is then set up with the sunshield attached (for daytime flight), and the cable from the UTD is fed through the fuel vent hole. An alternative wiring option for the UTD cable is to feed it through the left side gunner's window. In many cases the full AVA system is configured on an aircraft in coordination with a unit's other maintenance needs. Adjustments for the blades are computed by the Control and Display Unit (CADU) using data acquired during flight.

While the AVA was used in this effort for the majority of the data acquisition, several other vibration monitoring systems were also used to collect data (MSPU and IVHMS). Although there were differing systems, they all used similar instruments located on the same parts of the aircraft. Each system also collected data for the same set of flight regimes. These similarities ensured that the data collected from each of the differing systems was comparable and compatible for the purposes of this study.

Figure 3. UTD with sunshield

Figure 4. Suggested UTD cable route

Data Collection

Data was collected in the same manner that it would be for a typical rotor smoothing process. This procedure includes the following three test modes:

- Flight test, with data collected at FPG100, hover, 100K and 130K (FPG100 and hover regimes included track height and all four included rotor vibrations)
- Single adjustment to aircraft rotor (pitch link, weight, or trim tab)
- Flight test, with data collected at FPG100, hover, 100K and 130K (FPG100 and hover regimes included track height and all four included rotor vibrations)

Recording flight data immediately before and after each adjustment ensured that any change in vibration between flights was completely attributed to the adjustment made. Furthermore, the applied adjustment was as large as possible to reduce non-vibration adjustment effects while not making the aircraft uncomfortable to fly. Track data included absolute blade tip height for both forward and aft rotors. Vibration data was composed of vertical and horizontal vibrations for both forward and aft rotors in each flight stage.

Data Analysis

In order to process the data collected from the flights, the measured vibration levels from flights immediately before and after an adjustment were compared. The change in vibration levels, both magnitude and phase, was completely attributed to the effect of the adjustment. That change can be calculated as:

$$r_{ijk} = \sqrt{\begin{aligned}&\left(r_{(n+1)jk}\cos\left(\phi_{(n+1)jk}\right) - r_{njk}\cos\left(\phi_{njk}\right)\right)^2\\ &+\left(r_{(n+1)jk}\sin\left(\phi_{(n+1)jk}\right) - r_{njk}\sin\left(\phi_{njk}\right)\right)^2\end{aligned}} \quad (3)$$

$$\phi_{ijk} = \arctan\left(\frac{r_{(n+1)jk}\cos\left(\phi_{(n+1)jk}\right) - r_{njk}\cos\left(\phi_{njk}\right)}{r_{(n+1)jk}\sin\left(\phi_{(n+1)jk}\right) - r_{njk}\sin\left(\phi_{njk}\right)}\right) \quad (4)$$

where r is the change in magnitude of vibrations and ϕ is the change in phase for flights n and n+1 at flight state j, sensor k, and adjustment i. The sines and cosines may appear to be incorrect at first glance; however, due to the standard rotor smoothing polar chart orientation of the angles subject to the blade of the aircraft, as shown in Figure 5, it is necessary that the sines and cosines be inverted.

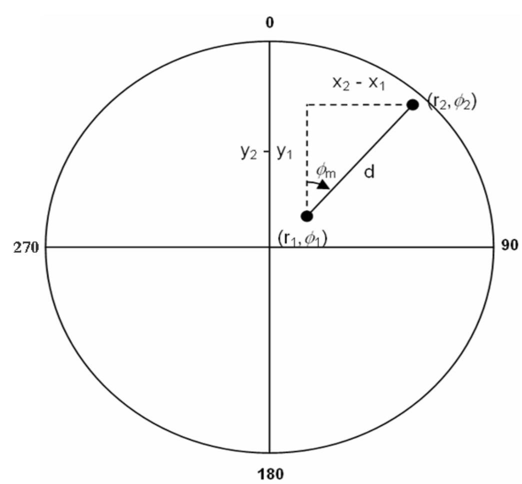

Figure 5. Angle orientation

The change in vibration ($r \angle \phi$) is then adjusted to reflect positive moves. For example, if the adjustment between flights were a positive move of 3, the change in vibration would not be corrected. If the adjustment between flights were a move of -3, the phase angle p would be corrected by 180˚. Blade angle is then adjusted yet again to force each coefficient to be the equivalent of a change to the master blade (green for CH-47). For an adjustment to the yellow blade, 120˚ was added and for an adjustment to the red blade, 240˚ was added. Once again, 360˚ was either added or subtracted to keep the final phase angle between 0˚ and 360˚.

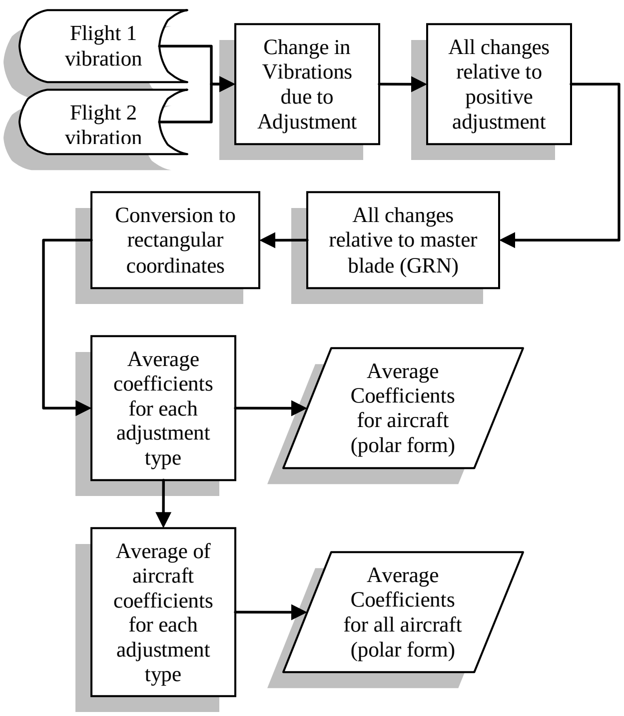

Figure 6. Flow chart for data analysis

The magnitude r is then divided by the magnitude of the adjustment, and the equations are converted into rectangular form to facilitate easier calculation. Hence:

$$x_{ijk} = r_{ijk} \sin(\phi_{ijk}) \qquad (5)$$

$$y_{ijk} = r_{ijk} \cos(\phi_{ijk}) \qquad (6)$$

where x and y are the rectangular coordinates for the change in vibration of $r \angle \phi$. These rectangular coordinates are then averaged for each individual helicopter:

$$\bar{x} = avg(x_{ijk}) \qquad (7)$$

$$\bar{y} = avg(y_{ijk}) \qquad (8)$$

where i is the adjustment for flight state j and sensor k. Next, the rectangular coordinates are reconverted into polar coordinates to be compared on a polar plot. Averages can then be formed by taking these coordinate points from each aircraft.

Results

Plotting the resulting data in polar form provided an effective means for discerning data trends and patterns. (See Appendix) The resulting coefficients show that both forward and aft tab adjustments should increase by approximately 34% as shown in Tables 10 and 11. This means that what was a 3° tab recommendation should really be 4°. Likewise, the new coefficients show that weight adjustments should increase by approximately 17%. What was a 6 plate recommendation, in this case, should really be 7 plates. This can easily be seen in Figures 7-9 below. Figure 7 depicts an actual set of rotorcraft vibrations while Figures 8 and 9 illustrate both the old and new adjustment recommendations.

State	Sensor	Meas. Mag (ips)	Goal
Hover	Fwd Vert	0.09	0.25
Hover	Fwd Lat	0.49	0.25
Hover	Aft Vert	0.03	0.25
Hover	Aft Lat	0.25	0.25
100K	Fwd Vert	0.77	0.25
100K	Fwd Lat	0.40	0.25
100K	Aft Vert	0.16	0.25
100K	Aft Lat	0.23	0.25
130K	Fwd Vert	0.96	0.25
130K	Fwd Lat	0.55	0.25
130K	Aft Vert	0.15	0.25
130K	Aft Lat	0.17	0.25

Figure 7. Measured Vibrations

	GRN Blade	YEL Blade	RED Blade
Fwd Wt	+1	-	-
Fwd PL	-	-	-
Fwd Tab	-3.0	-2.0	-
Aft Wt	-	+1	-
Aft PL	-	-	-
Aft Tab	-	-	-

Figure 8. Old Adjustment Recommendations

	GRN Blade	YEL Blade	RED Blade
Fwd Wt	+1	-	-
Fwd PL	-	-	-
Fwd Tab	-4.0	-2.5	-
Aft Wt	-	+2	-
Aft PL	-	-	-
Aft Tab	-	-	-

Figure 9. New Adjustment Recommendations

		FWD WT		FWD PL		FWD TAB		AFT WT		AFT PL		AFT TAB	
		(IPS/wt)	(deg)	(IPS/ntch)	(deg)	(IPS/deg)	(deg)	(IPS/wt)	(deg)	(IPS/ntch)	(deg)	(IPS/deg)	(deg)
Hover	FWD VERT			0.022	12			0.057	227	0.031	121		
	FWD LAT	**0.119**	327	**0.098**	223	**0.111**	207						
	AFT VERT	0.030	61	0.030	290					0.042	128		
	AFT LAT							**0.105**	325	**0.073**	215	**0.094**	208
100 KTS	FWD VERT			**0.064**	78	**0.236**	71			0.035	183	0.100	195
	FWD LAT	**0.119**	329	**0.052**	220	0.090	180						
	AFT VERT			0.046	276	0.154	272			**0.050**	54	**0.134**	54
	AFT LAT							**0.116**	332	**0.039**	204	0.037	199
130 KTS	FWD VERT			**0.080**	70	**0.300**	60			0.050	187	0.117	190
	FWD LAT	**0.125**	332	**0.080**	216	0.135	190						
	AFT VERT			0.051	271	0.180	274			**0.061**	50	**0.170**	50
	AFT LAT							**0.114**	330	**0.046**	204	0.060	193

Table 10. Old Coefficients

		FWD WT		FWD PL		FWD TAB		AFT WT		AFT PL		AFT TAB	
		(IPS/wt)	(deg)	(IPS/ntch)	(deg)	(IPS/deg)	(deg)	(IPS/wt)	(deg)	(IPS/ntch)	(deg)	(IPS/deg)	(deg)
Hover	FWD VERT			0.010	43			0.031	223	0.035	94	0.034	85
	FWD LAT	**0.104**	324	**0.086**	214	**0.099**	214	0.015	179	0.009	12		
	AFT VERT	0.021	50	0.016	281	0.015	285			0.029	210		
	AFT LAT	0.012	133	0.021	13			**0.090**	322	**0.075**	212	**0.046**	204
100 KTS	FWD VERT	0.033	244	**0.058**	65	**0.187**	62	0.029	228	0.023	210	0.025	174
	FWD LAT	**0.103**	323	**0.048**	211	0.060	202						
	AFT VERT	0.033	46	0.032	240	0.097	247			**0.051**	60	**0.094**	49
	AFT LAT	0.016	137					**0.089**	322	**0.042**	195	0.030	176
130 KTS	FWD VERT	0.029	199	**0.076**	63	**0.224**	59	0.028	201	0.039	198	0.058	194
	FWD LAT	**0.107**	321	**0.071**	208	0.104	197	0.012	32			0.032	129
	AFT VERT	0.043	25	0.043	239	0.129	248	0.011	327	**0.069**	51	**0.127**	44
	AFT LAT	0.014	124			0.022	345	**0.092**	317	**0.056**	195	0.055	196

Table 11. New Coefficients

Pitch links, on the other hand, show no significant difference between both the old and new coefficients. It is also interesting to note that there are no significant changes in phase angle for any of the adjustment types. This signifies that the RED/YEL/GRN blade to adjust is the same as it would be using the old coefficients. Analysis of the new coefficients further showed that adjustments to the aft rotor have a significant affect on the forward rotor and vice versa. In an attempt to account for these rotor-to-rotor effects, there are more coefficients present for each adjustment type than were previously present. Originally, 30 of the 72 coefficients had been ignored; however, it was determined that many of these coefficients were important. Consequently, the new coefficient chart only ignores 14 of the 72 coefficients. Those coefficients that are ignored are less than 10% of the largest coefficient for that adjustment type and can, therefore, be considered negligible.

While possibly not as pertinent as the primary results, this test did yield several secondary results. It was noted, for example, that the effect of pitch link adjustments are less consistent than either weight or tab adjustments. The large variations in IPS/notch and phase for pitch links corresponds with the "best practices" approach. This approach suggests that pitch link adjustments should be used primarily for ground and hover track while tab and weight adjustments should be used for hover and flight vibration smoothing as evidenced in Figures 8 and 9. It was further found that weight adjustments yielded the most consistent results when measured from aircraft to aircraft. Tab adjustments, however, proved to have the largest effect per single adjustment resulting in larger coefficients than the other adjustments. Forward tabs in general appear twice as effective as aft tabs, which is likely due to less turbulent air at the forward rotor.

Tracking data proved to be as inconsistent as pitch link adjustments. Many of the coefficients contained signs opposite of what were initially expected. All of the tracking coefficients also contained relatively high standard deviations. In fact, in most cases the standard deviations were greater than the averages themselves.

Conclusions

Expecting an exact vibration coefficient for every available adjustment is not feasible. As observed during this project, every aircraft has its own unique qualities. In most cases, the differences between aircraft are small. Perhaps the most significant difference, however, is the difference between the blades. Part of the difficulty in the collection of consistent data during this project was due to the fact that some aircraft had relatively new blades while others had severely worn blades. While this caused difficulties in the collection process, it was to be expected. This is why RT&B data was collected from nine different aircraft in five different states using three different HUMS systems:

AVA, VMEP, and IVHMS. The use of multiple aircraft in differing climates using varying software enabled the collected data to be as accurate and representative as possible. The resulting data was averaged to create the final measured coefficients. These measured coefficients are similar to the current coefficients; yet, there is enough difference to improve RT&B by implementing them into the current software. Once implemented, these newly measured coefficients are expected to reduce the number of flight hours required to perform RT&B on the CH-47 fleet. In doing so, the U.S. Army will be able to reduce costs associated with RT&B by reducing man-hours, fuel costs, and wear-and-tear of time-based components. Furthermore, in shortening the time required to perform RT&B, there will be an increase in aircraft availability fleet-wide. In conclusion, integrating the newly calculated coefficients will aid in making RT&B both a more time efficient and cost effective means of reducing vibrations on the CH-47.

Recommendations

Having obtained improved RT&B coefficients, it is recommended that these coefficients be integrated into both the AVA and MSPU software. Once the software is updated, it can then be released to the AED Aeromechanics website for download by Army Aviation personnel. Upon updating the CH-47, it is recommended that several more tests be completed to ensure that the improved coefficients are, indeed, effective in reducing the number of flight hours required for RT&B. This will also allow the opportunity to provide technical field assistance to Army Aviation units on how to more effectively smooth there aircraft. Lastly, data collection flights should also be performed on the CH-47F and MH-47G variants to quantify the effect of their increased weight and fuselage stiffness on the rotor smoothing coefficients.

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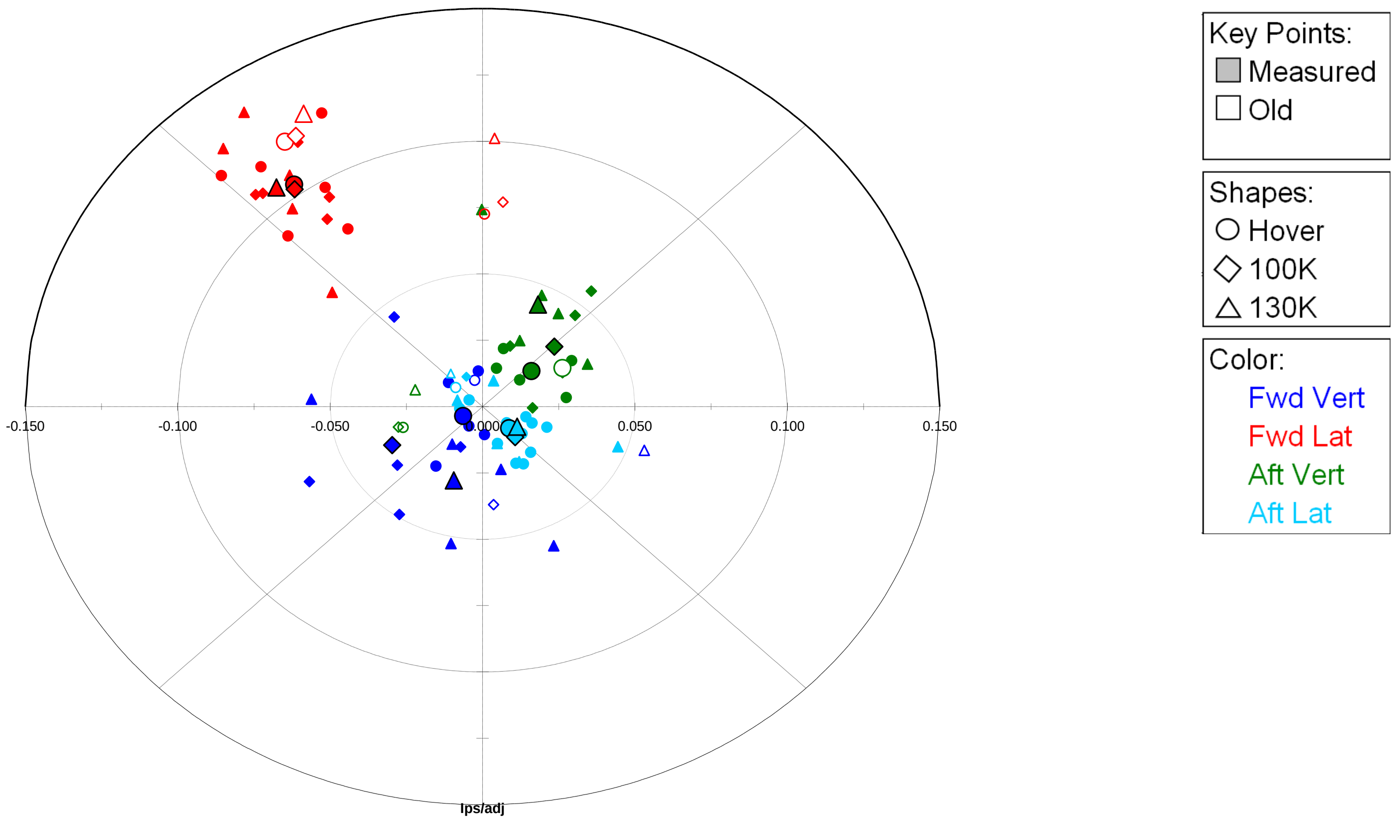
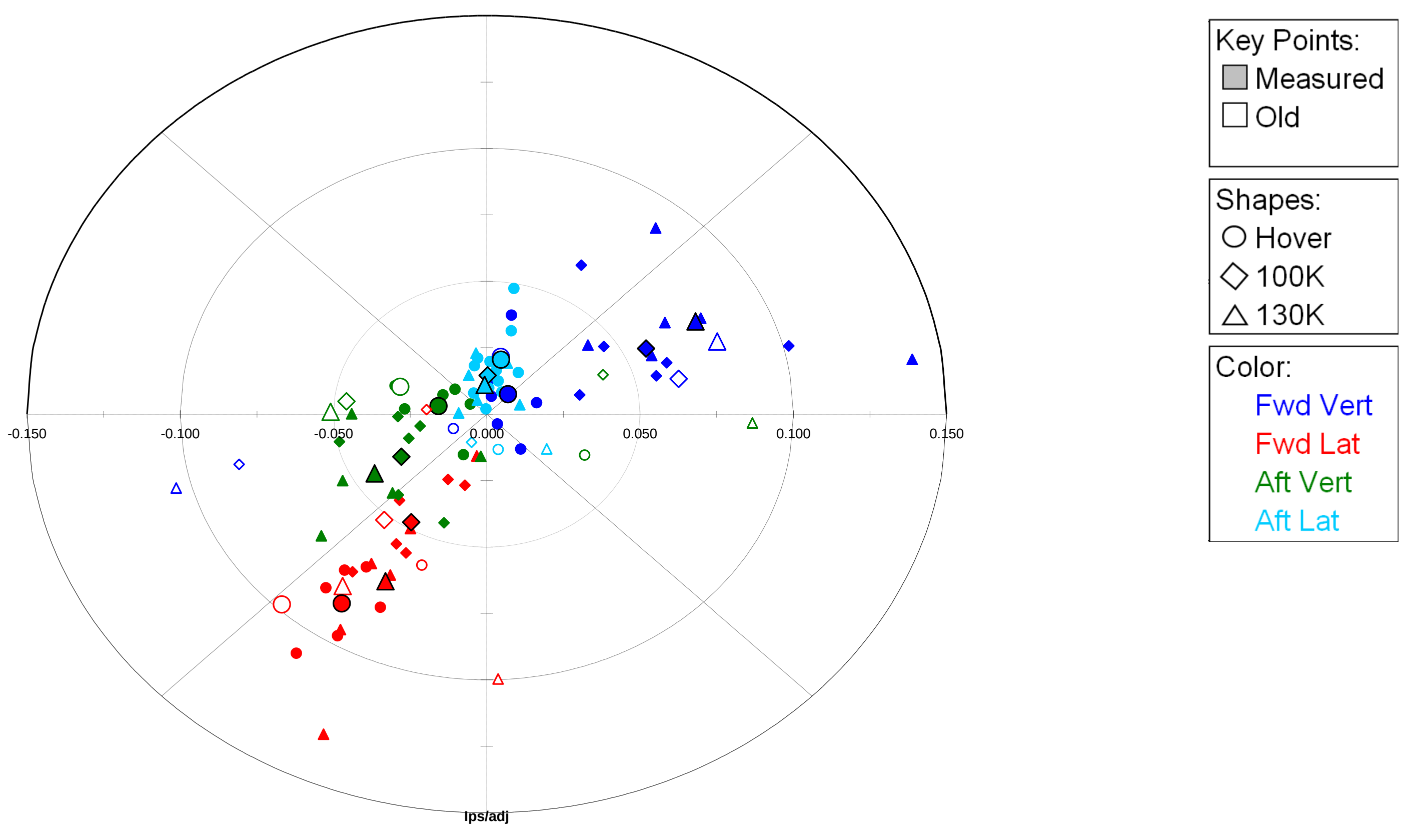
Appendix

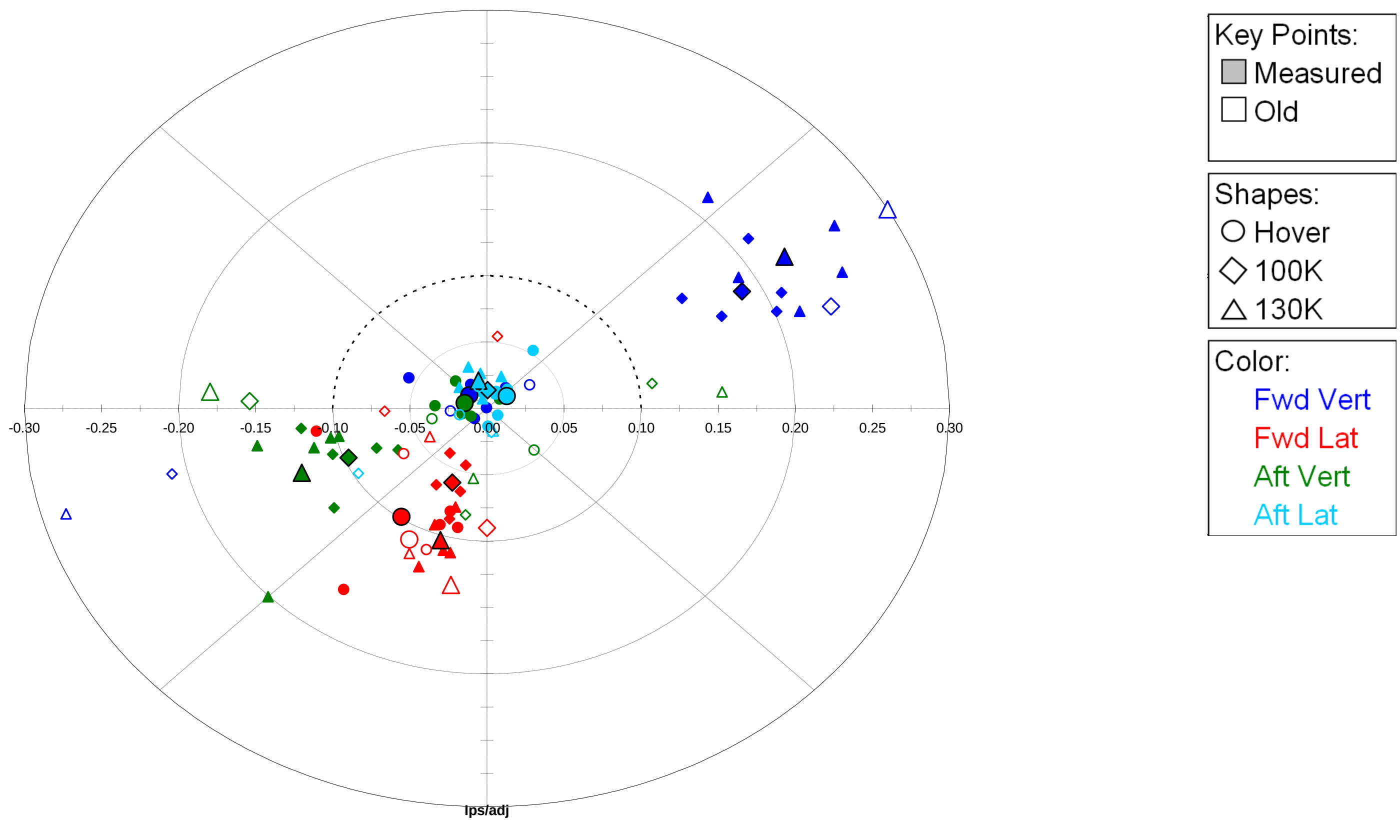
Forward Weight Adjustment



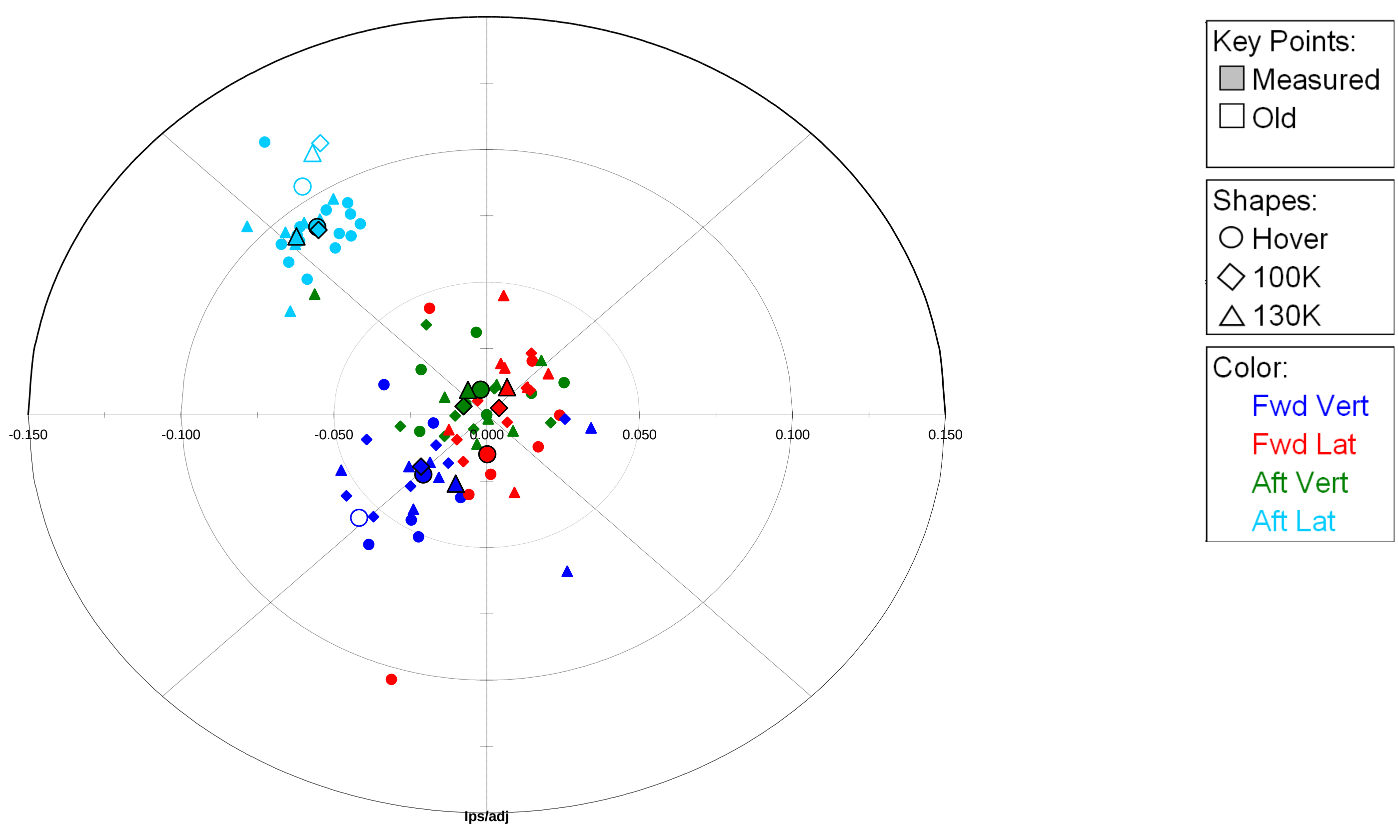
Forward Pitch Link Adjustment



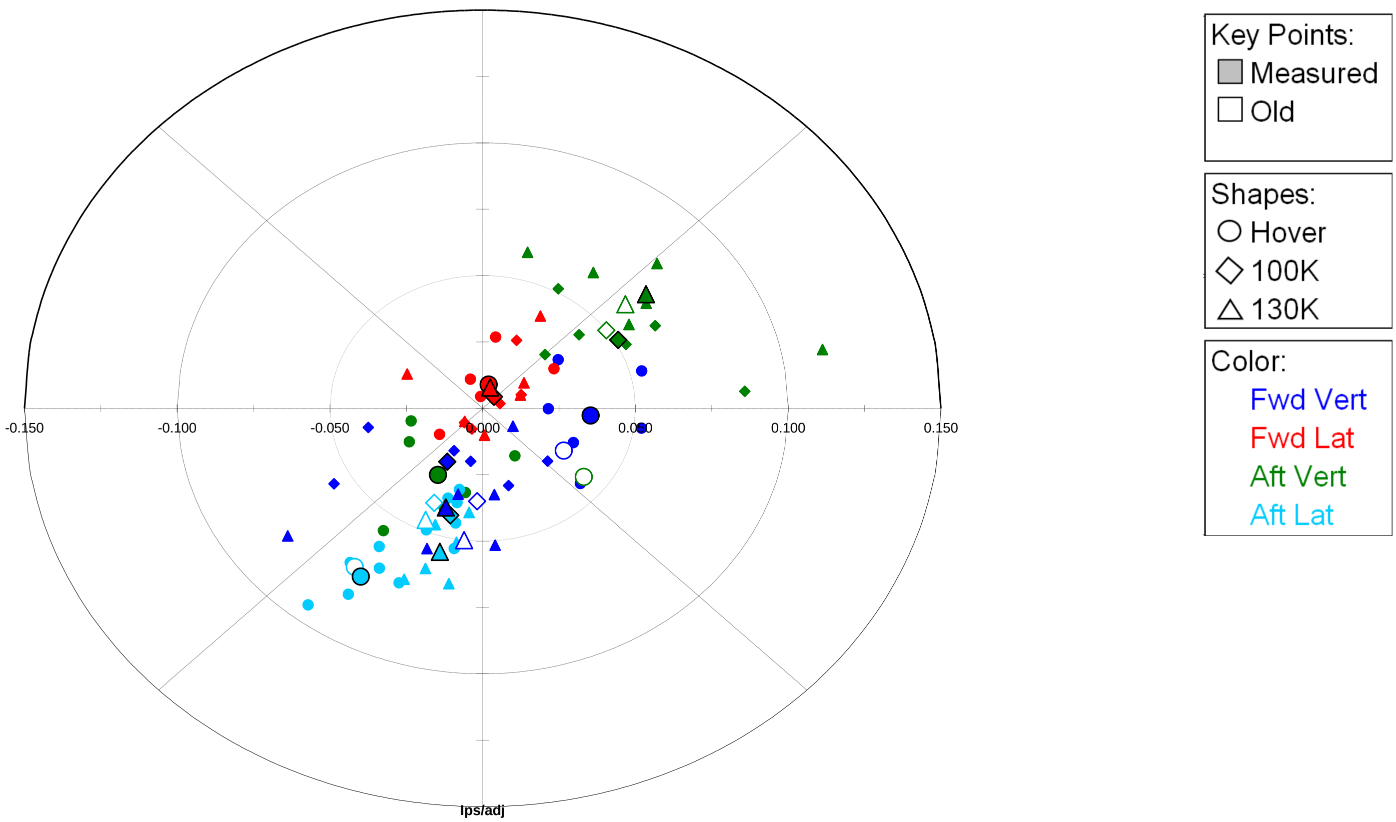
Forward Tab Adjustment



Aft Weight Adjustment



Aft Pitch Link Adjustment



Aft Tab Adjustment