Coefficient Development for Linear Rotor Smoothing on the MH-6 Main Rotor

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Abstract

The main rotor of any helicopter is subject to unwanted 1/rev vibrations due to mass and aerodynamic unbalances in the rotor blades. The MH-6 helicopter currently uses the Vibration Management Enhancement Program (VMEP) to measure vibration levels in the main rotor and recommend adjustments needed to reduce the vibration magnitude to an acceptable level. The VMEP uses a neural network (NN) to recommend adjustments to the maintenance test pilot. However, the VMEP consistently recommends incorrect adjustments for the three trim tab pockets on each blade. These errors require the maintenance pilot to perform more flights in order to bring the rotor vibrations to a minimum. The development of linear coefficients corresponding to trim tab adjustments has been proposed as the solution to the problem. By taking vibration measurements before and after a single adjustment has been made, the effect of that adjustment on rotor vibration can be determined. Coefficients can be developed for vibration changes into the form of IPS/degree tab bend in a specified direction on the rotor's polar chart.

Introduction

Rotor track and balance is extremely important for small helicopters such as the MH-6. Reasons to reduce vibration levels include pilot comfort as well as reduced stress on the support structures of the aircraft. Significant track splits on a smaller rotor are quite noticeable and unsettling if left uncorrected. The primary method of adjusting the track and balance of the MH-6 main rotor consists of adjustments made to trim tabs located along the trailing edges of the rotor blades. The effect of adjustments to these tabs will be the focus of the improvements on the track and balance process.

MH-6 Main Rotor

The MH-6 main rotor has a total of six blades equally spaced at intervals of sixty degrees. Each blade is identified with a different color, blue (BLU) being the master blade. For the purpose of rotor track and balancing, there are three tab pockets located span-wise along the trailing edge of each blade. These tabs can be deflected upwards or downwards depending on the vibration. This effectively changes the camber of the blade at that station, which in turn affects the aerodynamic performance of the blade. Pitch links for each blade can also be adjusted to change the entire angle of attack of the blade. However, the improvements on the vibration reduction process will only focus on tab bends. The tab pockets available for adjustment are illustrated in Figure 1. For main rotor track and balance, the pockets are grouped as three larger tabs: TP 93-105, TP105-117, and TP 124-142.

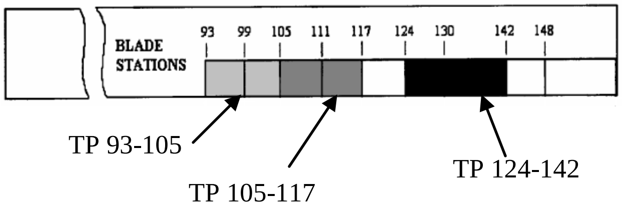


Figure 1. MH-6 Main Rotor Blade Trim Tab Stations

Since the MH-6 main rotor has six blades, there are eighteen adjustment options for vibration reduction using tabs alone and twenty-four options if pitch links are included. The limiting number of adjustments for high vibration levels is a combination of three tab bends or pitch link turns. From a statistical standpoint, there are $\frac{24!}{(3!)(24-3)!} = 2024$ possible adjustment combinations if three out of the twenty-four adjustments are made. For this reason it is extremely important to develop an accurate prediction program in order to minimize the amount of time test pilots spend tuning the aircraft.

Data Collection Procedure

In order to isolate the effects of a tab adjustment on aircraft vibration, flight conditions were recorded before each adjustment was applied. Both lateral and vertical accelerations were recorded by accelerometers measuring along each axis. Time domain vibrations were converted to frequency domain with the aid of a tachometer and the application of time synchronous averaging. This allowed for a polar chart to be made of the main rotor vibrations. Both magnitude and phase angle were recorded for the vibrations. Blade track was also recorded by the tachometer and an optical sensor. After the initial flight, one adjustment was applied to one tab on a single blade. Afterward, the helicopter completed another flight and records of vibration levels and tracking were logged again. This process was repeated for three adjustments per tab on one blade of the aircraft. Overall, three aircraft were tested, giving a total of nine data points per tab for each flight regime. The vibration and track data were collected for each of the following flight regimes:

- Idle
- FPG 100
- Hover
- 60 Knots
- 80 Knots
- 100 Knots
- 120 Knots

Vibration Coefficient Development

The change in vibration from one flight to the next was calculated in polar coordinates. The magnitude and phase can be determined by:

$$\Delta v_{ijk} = \sqrt{\begin{array}{l}\left[v_{(n+1)jk}\cos(\phi_{(n+1)jk}) - v_{njk}\cos(\phi_{njk})\right]^2 \\ + \left[v_{(n+1)jk}\sin(\phi_{(n+1)jk}) - v_{njk}\sin(\phi_{njk})\right]^2\end{array}}$$

E.1

$$\Delta\phi_{ijk} = \tan^{-1}\left(\frac{\left[v_{(n+1)jk}\cos(\phi_{(n+1)jk}) - v_{njk}\cos(\phi_{njk})\right]}{\left[v_{(n+1)jk}\sin(\phi_{(n+1)jk}) - v_{njk}\sin(\phi_{njk})\right]}\right)$$

E.2

where v is the magnitude of the vibration, φ is the phase angle of the vibration, i is the adjustment made between flights n and $n+1$, j is the flight mode, and k is the sensor orientation.

In order to process and correlate the effects of tab bends for specific tab pockets, the adjustments had to be translated to a positive unit move for the master blade. Therefore, if the tab bend was negative, the phase angle of the resulting vibration change was reversed 180 degrees. Also, if the blade the adjustment was made on was not the master blade, a corresponding phase shift was applied. For example, if the adjustment was made to the YEL blade, 60 degrees was added to the phase angle of the resulting change in vibration. If the adjustment was made to the GRN blade, 120 degrees was added to the phase angle. A map of the blade stations on the main rotor can be noted in Figure 2 which gives a visual explanation of this transformation.

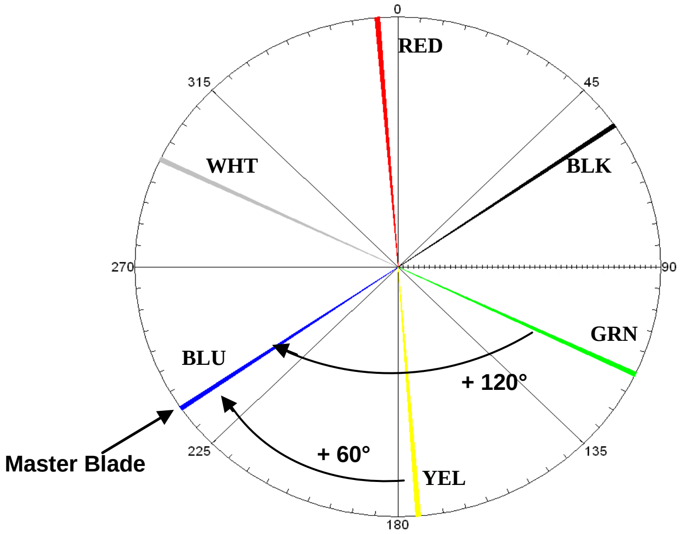


Figure 2. Blade Stations of Main Rotor

Finally, the magnitude of each vibration reaction was divided by the magnitude of the tab bend corresponding to that reaction. By this method, the units of the coefficients are change in IPS per degree tab bend (IPS/deg). Each tab adjustment has a mirrored adjustment on the blade 180 degrees out of phase with its respective blade which will result in the same vibration changes. For example, a TP 93-105 adjustment of +1° on the BLU blade will affect vibrations the same as a TP 93-105 adjustment of -1° on the BLK blade.

Track Coefficient Development

The track coefficients, however, do not share the symmetry of the vibration coefficients. A tab adjustment on a specific blade will primarily affect only the track of that same blade. In order to develop track adjustment coefficients corresponding to trim tab bends, absolute track changes were initially analyzed. When it became apparent that there was no correlation between changes in absolute track from flights framing a tab adjustment, the relative track data was analyzed. It was hypothesized that external conditions such as wind direction or gross weight would affect absolute track height but not relative track height. In order to obtain the relative track for a flight, the average blade track height for the flight is subtracted from each individual blade height. When relative track height changes associated with a tab bend were analyzed, a clear pattern emerged. The blade on which a positive tab bend was applied to increased in relative track height while the other blades simultaneously decreased in relative track height by 20% the magnitude of the adjusted blade's response. This reaction is synonymous with all blades remaining stationary except the blade with the applied adjustment. The blade on which the tab bend was performed will actually change 120% of its apparent magnitude from relative track height. A mathematical explanation follows:

$$\overline{H}_{ac} = \frac{1}{6}\sum_{b=1}^{6} H_{abc}$$

E.3

Where H is the absolute track height, $\overline{H}$ is the average absolute track height, a is the adjustment made, b is the blade number, and c is the flight regime.

$$h_{abc} = H_{abc} - \overline{H}_{ac}$$

E.4

$$\Delta h_{abc} = h_{(n+1)bc} - h_{nbc}$$

E.5

Where h is the relative track height, Δh is change in relative track height, and n is the flight number preceding adjustment a.

From Equations 3, 4, and 5:

$$\Delta h_{abc} = \left(H_{(n+1)bc} - H_{nbc}\right) + \frac{1}{6}\sum_{b=1}^{6}\left[H_{nbc} - H_{(n+1)bc}\right]$$

E.6

Since the PC-GBS only works calculations with relative track data, the change in absolute average track can be neglected. The ground base station also assumes that only the target blade which the adjustment was applied to will experience a change in track from one flight to the next. Under this assumption Equation 6 becomes:

$$\Delta h_{atc} = \frac{5}{6}\left[H_{(n+1)tc} - H_{ntc}\right] \tag{E.7}$$

or

$$\left[H_{(n+1)tc} - H_{ntc}\right] = \frac{6}{5}\Delta h_{atc} \tag{E.8}$$

where *t* denotes the target blade. This explains why the final coefficients entered into the PC-GBS for relative track are 120% of the initially calculated value. Figures 3 and 4 give a visual representation of the process. Note that the heavy dashed line is the average of the blades which did not receive a tab adjustment.

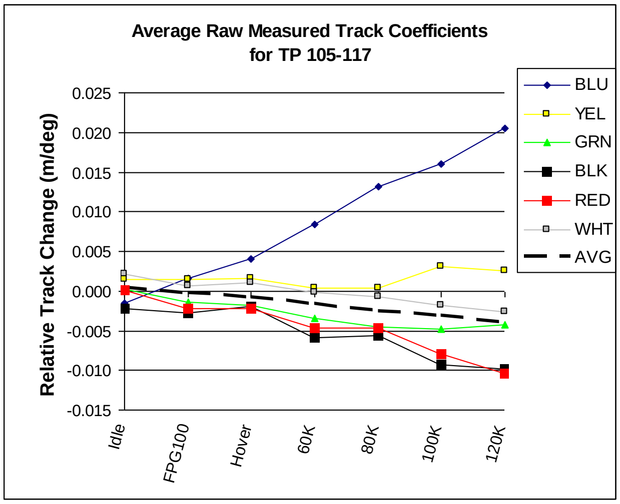


Figure 3. Track coefficients prior to adjustment

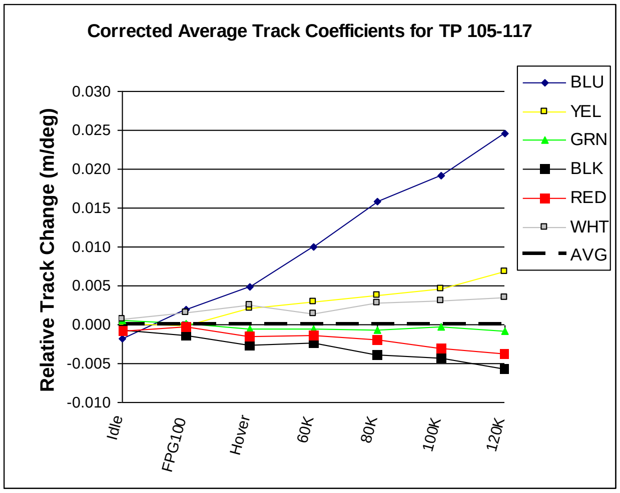


Figure 4. Corrected track coefficients

This process was used to determine a master blade coefficient for a positive trim tab bend applied to the master blade. All relative track height changes were divided by the number of degrees of the trim tab adjustment, resulting in coefficients with units of meters per degree tab bend (m/deg).

Neural Net Equivalent Coefficients

A study by Miller [1] determined the VMEP neural net behaves in an essentially linear manner. For this reason, it was desirable to obtain linear coefficients yielding results equivalent to the neural net's predictions. This would allow a comparison between the two rotor smoothing techniques. To determine the effective coefficients of the neural net, the change in vibration data that the VMEP NN predicted for a certain tab bend was recorded. The coefficients were then developed in the same way that the new LRS coefficients had been determined for actual flight data. It was also confirmed that the neural net does indeed act in a linear manner when predicting new vibration levels.

Results

The newly developed LRS coefficients (see Appendix) differed greatly from the equivalent coefficients of the VMEP NN. The new coefficients were consistently between 33-50% the magnitude of those derived from the neural network. This difference would result in the corrections suggested by the VMEP NN to be constantly undershooting the desired change in vibration levels. This leads to more maintenance test flights (MTF) and decreases aircraft availability. Also, adjustments to TP 105-117 yielded VMEP NN predicted vibration changes over 40 degrees out of phase with those of the new LRS coefficients. This means that the neural network was recommending tab adjustments to the wrong blade, which could potentially worsen vibrations in the main rotor. Track height change due to tab adjustment was also found to be only 33% as sensitive as the neural net predicts.

Time	Date	Tail #	Adjustment	Amount	Blade				
13:47:44	04/25/08	84-24319	TP 105-117	-2.00	BLU				
		Previous Flight		New Coefficient Prediction		NN Prediction		Measured Results	
		Vib (IPS)	ϕ (deg)	Vib (IPS)	ϕ (deg)	Vib (IPS)	ϕ (deg)	Vib (IPS)	ϕ (deg)
Idle	Lat	0.14	146					0.15	135
	Vert	0.03	163					0.02	173
FPG100	Lat	0.21	313	0.25	324	0.63	247	0.27	321
	Vert	0.05	31					0.03	72
Hover	Lat	0.24	250	0.19	312	0.14	187	0.21	301
	Vert	0.12	328	0.06	71			0.07	31
60K	Lat	0.16	238	0.14	313			0.12	292
	Vert	0.25	268	0.04	325	0.32	180	0.03	321
80K	Lat	0.17	204	0.15	329			0.13	311
	Vert	0.37	248	0.03	241	0.58	170	0.05	303
100K	Lat	0.21	180	0.18	2			0.09	342
	Vert	0.45	243	0.03	196	0.62	162	0.03	163
120K	Lat	0.36	167	0.13	33			0.1	348
	Vert	0.6	230	0.08	159	0.84	130	0.1	179

Table 1. Vibration prediction performance comparison of new LRS coefficients against VMEP neural net

The LRS algorithm coupled with the new coefficients was validated by taking vibration and track data from a previous flight and applying a manual solution in the PC-GBS identical to the actual changes made to the aircraft. Predicted vibration and track were then compared with the data from the next flight. The majority of predictions made the LRS coefficients were under 0.1 IPS in magnitude different from the actual test results. The VMEP NN predictions were also compared in the same manner, but they were rarely within 0.25 IPS from actual measurements for adjustments involving large tab bends. An example of the procedure’s results is given in Table 1. Note that predictions that were over 0.1 IPS in magnitude different from the actual measured results are highlighted in green, those over 0.25 IPS are highlighted in yellow, and those over 0.5 IPS are highlighted in red. Not all of the prediction comparisons yielded results with such an extreme contrast, but the LRS algorithm applied in conjunction with the newly derived coefficients did outperform the neural net every time.

The most important part of the development process is checking the ability of the LRS coefficients to provide accurate recommendations for tab bends in order to reduce vibration levels. Aircraft with purposefully induced high vibration levels were corrected to acceptable levels of vibration by restoring a large tab bend which had been applied before the flight. The high vibration data was fed to the PC-GBS, and the LRS algorithm was used to recommend an adjustment. In all cases examined, the LRS coefficients provided a solution nearly identical to the actual restoring tab bend. The VMEP NN did not have the same success. An example of the recommendations made by the two different algorithms is given in the following tables:

		Previous Flight	
		Vib (IPS)	ϕ (deg)
Idle	Lat	0.14	146
	Vert	0.03	163
FPG100	Lat	0.21	313
	Vert	0.05	31
Hover	Lat	0.24	250
	Vert	0.12	328
60K	Lat	0.16	238
	Vert	0.25	268
80K	Lat	0.17	204
	Vert	0.37	248
100K	Lat	0.21	180
	Vert	0.45	243
120K	Lat	0.36	167
	Vert	0.6	230

Table 2. Measured High-Level Vibrations

Blade:	BLU	YEL	GRN	BLK	RED	WHT
PL						
TP 93-105						
TP 105-117	-1		-1			
TP 124-142						

Table 3. VMEP NN Recommended Adjustments

Blade:	BLU	YEL	GRN	BLK	RED	WHT
PL						
TP 93-105						
TP 105-117	-2					
TP 124-142						

Table 4. New LRS Coefficient Recommendations

All cells highlighted in Table 2 contain a vibration level above goal. An actual move of -2° applied to TP 105-117 on the BLU blade resolved all vibrations within goal except for FPG100 Lateral. Note that the recommended adjustment given by the new LRS coefficients corresponds to the actual adjustment applied, while the VMEP recommendation does not even share the same phase.

While not the purpose of the study, it was also determined that there is no exclusive adjustment tab for high speed or low speed solutions. All trim tab bends affect vibration levels in every flight regime. The coefficients did show a pattern of increasing magnitude as airspeed increases. Also, the farther out the location of the tab on the blade station, the higher the magnitude of the adjustment coefficient.

Conclusions

The magnitude of the recommendations made by the PC-GBS to reduce vibration needs to be updated. The VMEP neural network needs much improvement if it is to be considered for use in main rotor smoothing for the MH-6 in the future. The best solution currently is the implementation of the newly derived LRS coefficients in conjunction with the LRS algorithm. By studying the recommendations made by the neural network, it is obvious that the adjustments applied to the aircraft are not affecting vibrations to the extent the VMEP NN algorithm predicts. Implementing the LRS algorithm with less sensitive coefficients will result in less test flights required to bring an aircraft within acceptable vibration levels. Reducing the magnitude of a coefficient will cause the PC-GBS to recommend larger adjustments to the tab pockets.

The VMEP NN was also incorrect concerning the phase angle of vibration change caused by adjustments applied to TP 105-117. This could possibly cause vibration levels to increase during the rotor smoothing process, which is highly detrimental to time required for fleet maintenance.

Recommendations

The newly developed coefficients need to be tested on aircraft outside of the set used to determine the coefficients. To improve accuracy, a larger sample set of aircraft can be included in the development of the coefficients. This will be more representative of the "average" aircraft.

Due to the large number of adjustment options available for vibration management and the programming of the LRS algorithm, the PC-GBS requires nearly a full minute to calculate optimum solutions for recommended trim tab bends. This is somewhat frustrating for a user accustomed to the faster calculation time required by the neural network algorithm. However, it should still be more efficient to take more time on calculations than on actual test flights. Improvements should be made to the LRS algorithm to minimize the calculation time.

From Figures 3 and 4 it is apparent that the track heights of all the blades are affected by a tab adjustment to a single blade. The LRS algorithm does not account for this, making the assumption that any cross-effects are negligible. However, the blade immediately lagging the master blade consistently had a track coefficient magnitude up to 25% of the master blue blade coefficient. The LRS algorithm needs to be updated to include the unique effects on the track height of each blade corresponding to an adjustment on the master blade.

References

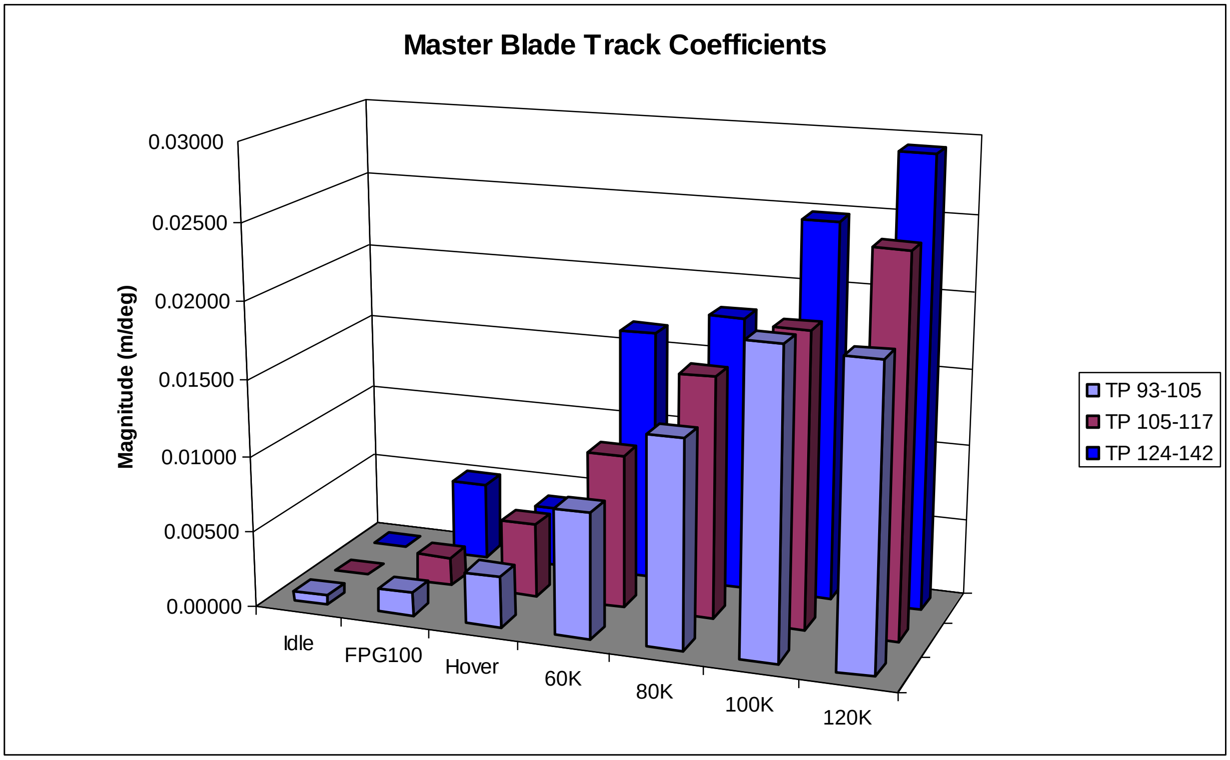
1. Miller, Nathan A. A Comparison of Main Rotor Smoothing Adjustments Using Linear and Neural Network Algorithms. Thesis. Air Force Institute of Technology, 2006.
2. Keller, Jonathan A., Steven M. Krick, and Joshua C. Hasty. "Improved Rotor Smoothing for the U.S. Army CH-47." American Helicopter Society.

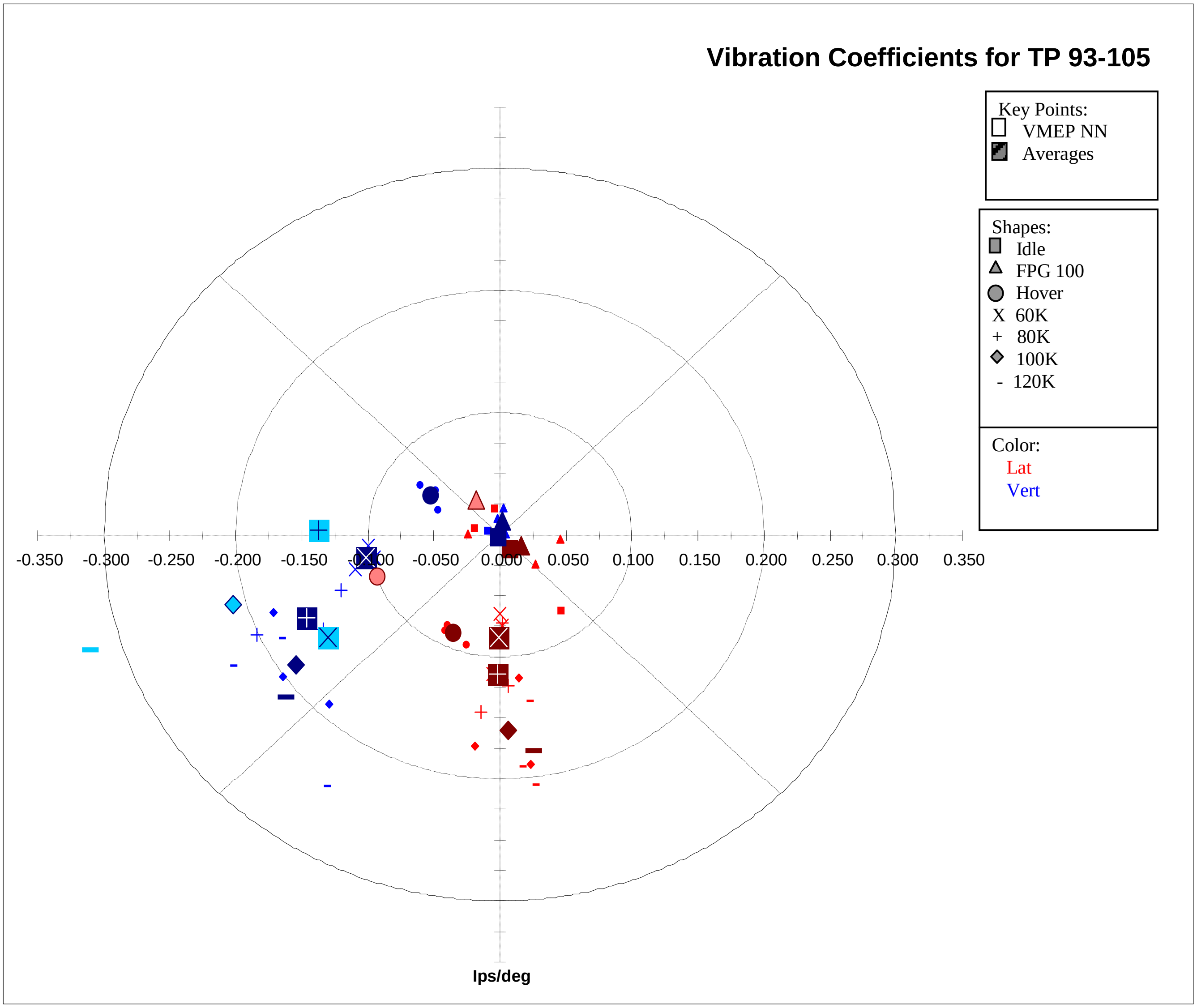
Appendix

		New Vibration Coefficients					
		TP 93-105		TP 105-117		TP124-142	
		Vib (IPS/deg)	ϕ (deg)	Vib (IPS/deg)	ϕ (deg)	Vib (IPS/deg)	ϕ (deg)
Idle	LAT						
	VERT						
FPG100	LAT	0.018	119	0.032	187	0.071	157
	VERT						
Hover	LAT	0.088	204	0.113	204	0.132	208
	VERT	0.061	302	0.075	304	0.100	308
60K	LAT	0.085	181	0.093	191	0.143	188
	VERT	0.103	260	0.114	260	0.159	262
80K	LAT	0.114	181	0.140	179	0.178	177
	VERT	0.161	245	0.173	249	0.223	252
100K	LAT	0.160	178	0.194	181	0.243	178
	VERT	0.188	236	0.217	246	0.289	244
120K	LAT	0.179	174	0.230	179	0.262	172
	VERT	0.214	232	0.289	238	0.326	233

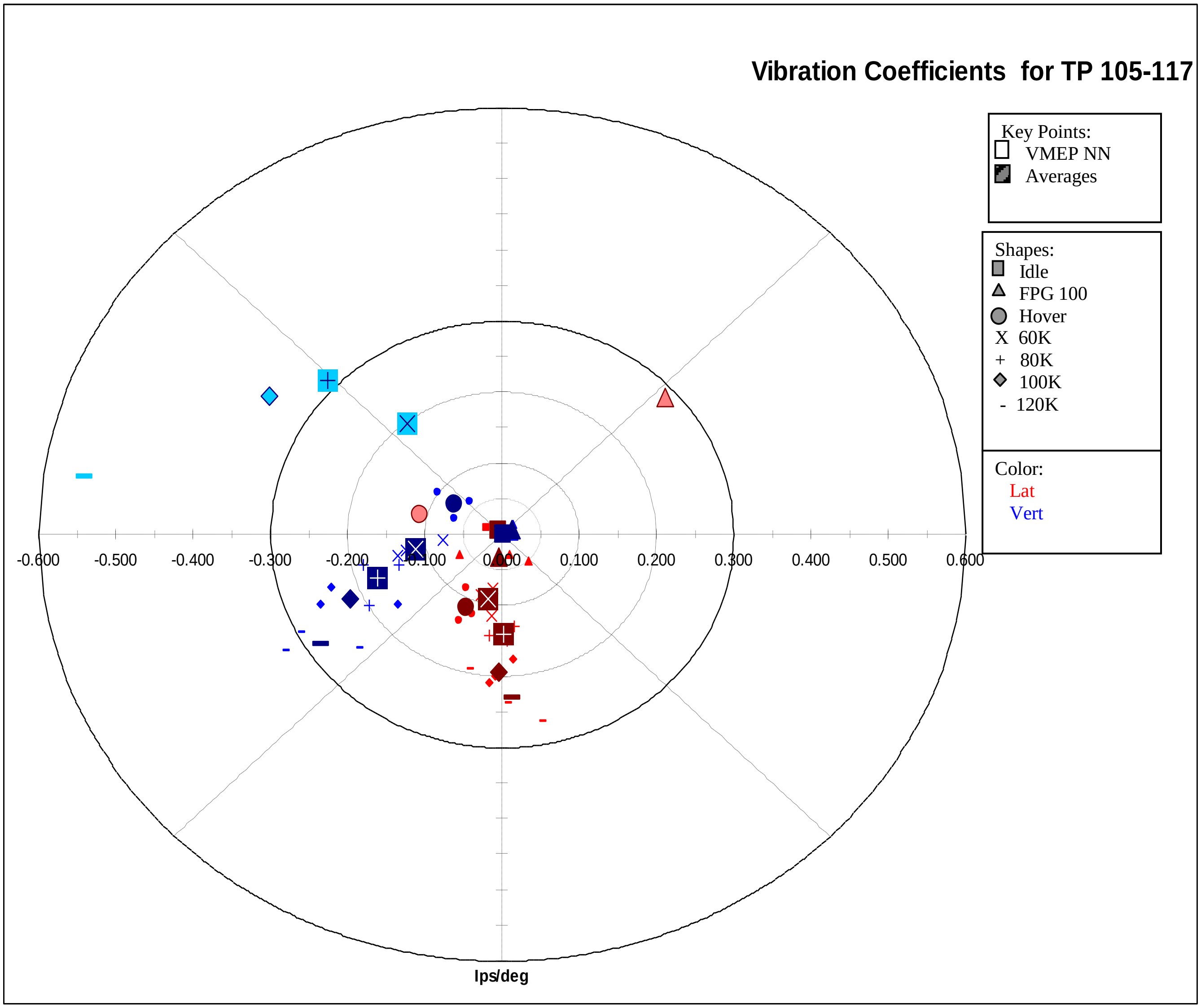
		Equivalent VMEP NN Vibration "Coefficients"					
		TP 93-105		TP 105-117		TP124-142	
		Vib (IPS/deg)	ϕ (deg)	Vib (IPS/deg)	ϕ (deg)	Vib (IPS/deg)	ϕ (deg)
Idle	LAT						
	VERT						
FPG100	LAT	0.034	328	0.285	48	0.167	212
	VERT						
Hover	LAT	0.099	249	0.110	285	0.279	171
	VERT						
60K	LAT						
	VERT	0.155	237	0.199	322	0.408	252
80K	LAT						
	VERT	0.138	272	0.314	314	0.444	233
100K	LAT						
	VERT	0.210	254	0.359	303	0.583	234
120K	LAT						
	VERT	0.330	253	0.557	278	1.023	226

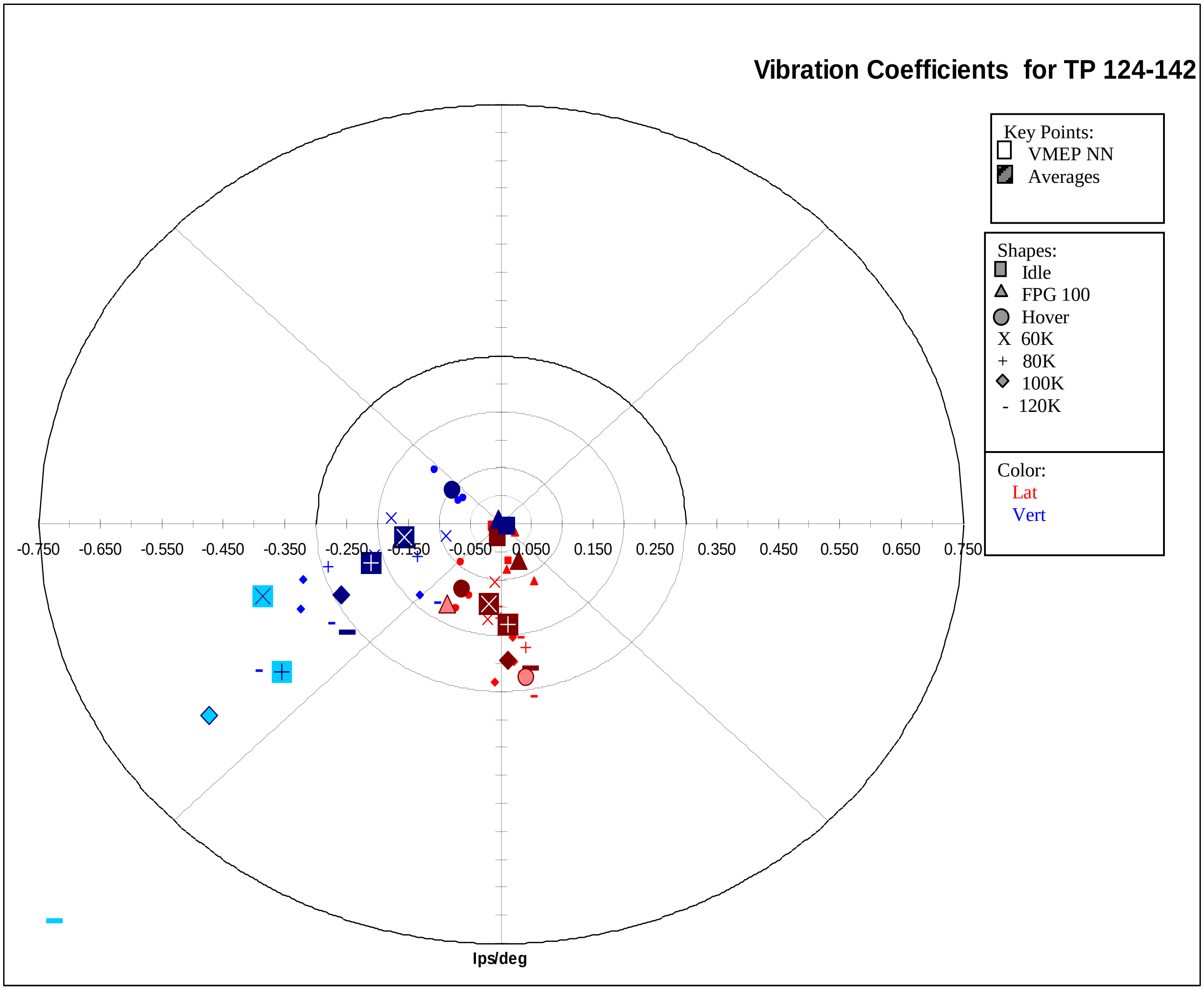
	New Track Coefficients for Master Blade (m/deg)			Equivalent VMEP NN Track "Coefficients" (m/deg)		
	TP 93-105	TP 105-117	TP 124-142	TP 93-105	TP 105-117	TP 124-142
Idle	0.00061	-0.00187	-0.00200	0.00348	0.00261	0.00076
FPG100	0.00152	0.00188	0.00509	0.00642	0.00347	0.00508
Hover	0.00334	0.00485	0.00401	0.01198	0.01228	0.00530
60K	0.00819	0.01004	0.01659	0.02726	0.02132	0.00947
80K	0.01353	0.01578	0.01807	0.03741	0.02643	0.01736
100K	0.01984	0.01921	0.02473	0.04912	0.04032	0.01922
120K	0.01944	0.02459	0.02933	0.06777	0.06756	0.02530





Vibration Coefficients for TP 93-105


Vibration Coefficients for TP 105-117
Key Points:
☐ VMEP NN
▨ Averages
Shapes:
■ Idle
▲ FPG 100
● Hover
X 60K
+ 80K
◆ 100K
- 120K
Color:
Lat
Vert
-0.600
-0.500
-0.400
-0.300
-0.200
-0.100
0.000
0.100
0.200
0.300
0.400
0.500
0.600
Ips/deg


Vibration Coefficients for TP 124-142
Key Points:
VMEP NN
Averages
Shapes:
Idle
FPG 100
Hover
X 60K
+ 80K
100K
- 120K
Color:
Lat
Vert
-0.750
-0.650
-0.550
-0.450
-0.350
-0.250
-0.150
-0.050
0.050
0.150
0.250
0.350
0.450
0.550
0.650
0.750
Ips/deg