# Remote Synthesis of Loads on Helicopter Rotating Components using Linear Regression, Load Path and Statistical Analyses

**Xiaobo Yu, Callum Wright and Manfred Heller**

Defence Science and Technology Organisation
506 Lorimer Street, Fishermans Bend, Victoria 3207 Australia

**Key words:** rotating components, load history, remote synthesis, linear regression, load path analysis, reactionless components

**Abstract:** Maintenance costs of helicopters can be reduced by applying individual tracking of rotating component usage. This study investigated the possibility of synthesizing a load-time history of the main rotor pitch links from strain measurements on stationary components. Four approaches were tried, namely linear regression in the frequency domain, linear regression in the azimuth domain, load path analysis of the swashplate assembly, and supplementary statistical analysis. Cross-validation and an advanced linear regression method called Elastic Net were employed. All the approaches of load syntheses were tested against a data set containing 42 runs of level flights selected from the Joint USAF-ADF S-70A-9 Black Hawk flight strain survey conducted in 2000. The main finding of the study was that an accurate or complete load synthesis was not always possible due to the existence of reactionless force components. This remained true no matter what synthesis approach was applied. The load path analysis was recommended as an essential step in remote synthesis of loads on helicopter rotating components. This recommendation applies to activities including evaluating reported case studies, utilizing existing data set, and developing new strategies of load synthesis.

## Nomenclature

| | |
|---|---|
| $a_k$ | coefficient of cosine terms |
| $b_k$ | coefficient of sine terms |
| $f_{MR}$ | nominal main rotor revolving frequency |
| $k$ | multiplier of $f_{MR}$ |
| $m$ | number of events in linear regression |
| $n$ | number of predictors selected by a linear regression |
| $p$ | number of equations in linear regression |
| $q$ | number of all possible predictors in linear regression |
| $r$ | distance from a servo link connection to the centre of swashplate assembly |
| $u$ | re-sampled measurements at selected azimuth points |
| $\mathbf{y}$ | vector of dependent variables in linear regression |
| $F(t)$ | load history of main rotor pitch link |
| $N_R$ | ratio of actual and nominal main rotor revolving frequencies |
| $P_{idx}$ | forces on four pitch links, $idx$ = 1, 2, 3, 4 |
| $R$ | distance from a pitch link connection to the centre of swashplate assembly |
| $S_{idx}$ | forces on three servo links, $idx$ = 1, 2, 3 |
| $\mathbf{X}$ | matrix of independent variables in linear regression |
| $\hat{\boldsymbol{\beta}}$ | vector of deduced parameters used to predict $\mathbf{y}$ |
| $\varphi_0$ | angle between MRPR1 and lateral servo link at the start of a data logging |
| $\varphi_a$ | angle swept by MRPR1 from the start of data logging |
| $\lambda_1, \lambda_2$ | a pair of tuning parameters in Elastic Net regression |
| $\lambda, t_{EN}$ | a pair of tuning parameters in Elastic Net regression |

## 1. Introduction

One of the important maintenance cost drivers for helicopters is Component Retirement Times (CRTs). Currently, CRTs are determined based on a defined design usage spectra and most fleets do not employ individual aircraft tracking to enable correlation to the design spectra. Added to this is the simplistic way usage spectra are developed. Typically, the design usage spectrum and the corresponding fatigue loads are chosen so that they have a high probability of being conservative for all the envisaged roles of a helicopter type. Inevitably, this means that almost all of the airframes within the fleet have overly-conservative replacement times applied to the dynamic components, regardless of the operator [1].

Monitoring the usage of dynamic helicopter components can be performed in many ways and to varying degrees of accuracy. Currently, the norm is to assume each fleet aircraft flies the design spectra and usage is based on the hours of operation. An improvement to this is becoming more widely used where the types of flying are recorded for each aircraft and damage is attributed based on the type of flight. This is the simplest form of individual aircraft tracking. This approach can be extended to identify the duration of segments of the flight and attribute damage based on these segments. Another improvement is to identify manoeuvres and attribute damage for each one performed. The manoeuvre would be attributed damage based on the duration and original design assumptions. The manoeuvres can be identified from flight parameters, such as velocity, mass, altitude, angle of attack, and control inputs. A more robust approach would be to find the load history for critical components, either by direct measurement or from load synthesis, and calculate the damage directly on a location by location basis.

Detailed literature reviews of the topic have been previously conducted by several authors [2, 3]. In these reviews the authors summarise that extending beyond individual aircraft tracking to individual component tracking would provide a significant dividend to fleet lifing and therefore costing. This would be especially true if implemented at the design stage of the aircraft. Therefore, in an effort to reduce the cost of ownership many researchers are attempting to develop techniques for monitoring the usage of dynamic helicopter components. Direct loads monitoring would provide the most accurate reflection of loads experienced by individual components. However, direct usage monitoring of rotating components is currently considered impractical for use in an operational squadron environment, although developments of this technology continue [4-7].

Indirect approaches, such as remote load synthesis from strain measurements on stationary components [8-10], or load range predictions from flight and control parameters [11-14], would provide individual aircraft tracking and estimate components loads. These have been investigated in the past few decades with varying degrees of success. Current onboard electronics provide enough parametric data to mine for manoeuvre identification for damage prediction [15]. This is a cost effective, minimum intervention solution that could be deployed in most fleets. However, this is still highly conservative because it relies on the original design assumptions. Synthesizing component loads would allow for component tracking, if the methodology could be shown to be robust, accurate and cost effective. This would require the addition of a complete tracking system to the aircraft and consequently is likely to be less cost-effective than the parametric approach. Therefore, such a system would require a high degree of accuracy to warrant development.

The purpose of this study was to further investigate the possibility of synthesizing load-time histories on helicopter rotating components, with a high degree of accuracy, from remote strain measurements on stationary components.

## 2. Description of Study

The study makes use of the data from the Joint USAF-ADF S-70A-9 Black Hawk flight strain survey conducted in 2000 [16]. As a first step, loads on the main rotor pitch links (abbreviated as MRPR in the flight loads data), see Fig. 1, were selected as the target variables for prediction. Forty-two level-flight runs were selected as test cases, where horizontal velocities varied from 0.3Vh to 1.0Vh (Vh is maximum level flight speed). Also varied were $N_R$, gross weight, centre of gravity and pilot. Each run of the flight data used in the study is approximately 10 seconds long, logged at 416.7Hz, and contains up to 195 strain parameters, of which 11 parameters are related to the main rotor.

The main challenges of the study were: 1) to select a minimum number of predictor variables from more than a hundred channels of strain measurements on the stationary components across the whole helicopter structure; and 2) to establish transfer functions between the predictor and target variables.

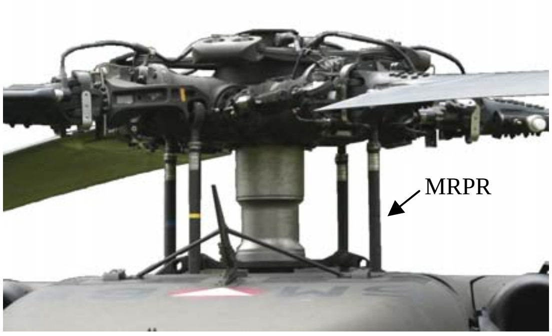



*Figure 1. Rotor head of a Black Hawk helicopter.*

Initial trials were based on cross-validation (CV) and linear regression analyses, using a regression algorithm called Elastic Net. The linear regressions were performed in both the frequency and azimuth domains.

The results of the linear regression analyses motivated the analysis of load path from the MRPR to the fuselage. This was done by considering the force and moment equilibriums on the main rotor swashplate assembly. The load path analysis was then supplemented by statistical analysis.

During the earlier stages of development, it became apparent that it was important to know the position, or 'azimuth' of the rotating components, such that data sets could be aligned. Unfortunately, azimuth angles were not recorded in the flight test data. Therefore the results presented in this paper were all based on alignments using $\varphi_0$, which is the angle between MRPR1 and lateral servo link at the start of a data logging for a particular manoeuvre. $\varphi_0$ was back-calculated in the load path analysis.

## 3. Linear Regression in Frequency Domain

Discrete Fourier Transforms (DFTs) were performed on load-time histories of a MRPR. As shown in Fig. 2, the resulting spectrum is dominated by harmonic terms, of which the base frequency equals the main rotor rotating frequency, $f_{MR}$.

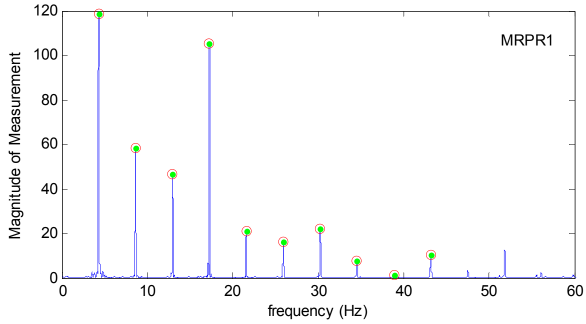



*Figure 2. Typical spectrum of a load-time history at a main rotor pitch link, deduced using DFT (units removed).*

As a result, the MRPR load-time history, $F(t)$, was approximated as,

$$F(t) = a_0 + \sum_{k=1}^{K} (a_k \cos\phi_k + b_k \sin\phi_k) \qquad (1)$$

where, $k$ is multiplier of $f_{MR}$ and,

$$\phi_k = k\int_0^t 2\pi f_{MR} N_R dt \qquad (2)$$

The coefficients in Eq.(1)—$a_k$, $b_k$, and $a_0$—were deduced using an Ordinary Least Square (OLS) regression, instead of invoking DFT. The OLS regression required less than one second of flight data as input, therefore the drift of main rotor frequency within a run could be handled properly.

It was assumed that each harmonic component of a MRPR load could be expressed as a linear combination of modulated strain measurements on stationary components. The modulations were applied on amplitude, phase and frequency. In the case of one set of flight test data, this assumption led to:

$$\sum_{i=1}^{N} \begin{bmatrix} \mathbf{A} & -\mathbf{B} \\ \mathbf{B} & \mathbf{A} \end{bmatrix}_i \boldsymbol{\beta}_i = \begin{bmatrix} a_k \\ b_k \end{bmatrix}_{MRPR} \qquad (3)$$

where, $k$ is the multiplier of $f_{MR}$ as used in Eq. (1). Here, $i$ = 1, 2, …, $N$, corresponds to selected measurements on the fixed components. A strain gauge measurement was selected if its time history was dominated by harmonic terms. For each $i$, **A** and **B** are row vectors of coefficients of harmonic terms,

$$\left.\begin{aligned}\mathbf{A} &= [a_0 \quad a_1 \quad a_2 \quad \ldots \quad a_J] \\ \mathbf{B} &= [0 \quad b_1 \quad b_2 \quad \ldots \quad b_J]\end{aligned}\right\} \tag{4}$$

where, $j$ = 0, 1, 2, …, $J$, represents the order of harmonic terms; $\boldsymbol{\beta}_i$ is a column vector, containing 2($J$+1) parameters that are to be determined.

In the case of $m$ sets of flight test data, Eq.(3) is assembled by row and transformed into:

$$\mathbf{X}_{p\times q}\boldsymbol{\beta}_{q\times 1} = \mathbf{y}_{p\times 1} \tag{5}$$

where, $\boldsymbol{\beta}^T = [\boldsymbol{\beta}_1^T, \quad \boldsymbol{\beta}_2^T, \quad \ldots, \quad \boldsymbol{\beta}_N^T]$, $p = 2m$, $q = 2(J+1)N$, $\mathbf{X}$ is assembled from the matrix before $\boldsymbol{\beta}_i$ in Eq.(3), and $\mathbf{y}$ is assembled from the right-hand-side of Eq.(3).

The load synthesis was then transformed into a linear regression problem, that is, to determine the best fit $\boldsymbol{\beta}$ to satisfy Eq. (5).

In the current application, Eq. (5) featured far more variables than equations. Also, linear correlations probably exist among variables and equations. The main challenges in solving such a problem were: 1) how to avoid over-fitting so that the predictive capability was not compromised; and 2) how to select the least number of variables, thus producing the most robust load synthesis model from the linear regression.

An advanced regression method, named Elastic Net [17] was selected to solve Eq. (5). As suggested in Ref. [17] and adapted based on arguments in Ref. [18], this method was considered more suitable than the alternatives, including forward stepwise selection, backward stepwise selection, subset selection, principal component, ridge regression and lasso. The mathematical expression of the Elastic Net method is given in Eq. (6):

$$\hat{\boldsymbol{\beta}} = (1+\lambda_2)\arg\min_{\boldsymbol{\beta}}\{|\mathbf{y}-\mathbf{X}\boldsymbol{\beta}|^2 + \lambda_1|\boldsymbol{\beta}|_1 + \lambda_2|\boldsymbol{\beta}|^2\} \tag{6}$$

The solution of Eq. (6) depends on a pair of tuning parameters: $\lambda_1$ and $\lambda_2$; or equivalently $\lambda$ and $t_{EN}$ when it is transformed for implementation, (see [17] for details). A CV approach, as illustrated in Fig. 3, was used to choose the tuning parameters, such that the resulting $\hat{\boldsymbol{\beta}}$ produced the best prediction.

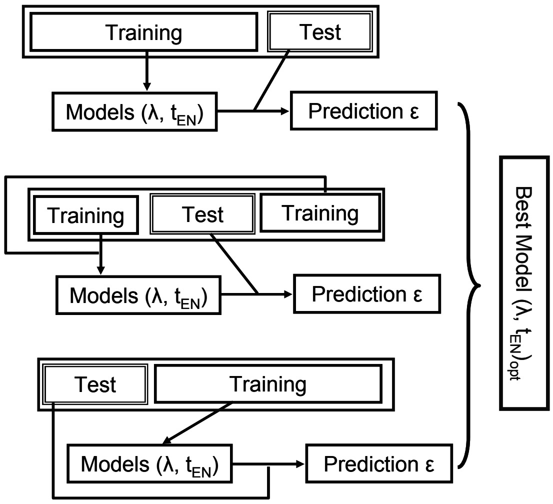
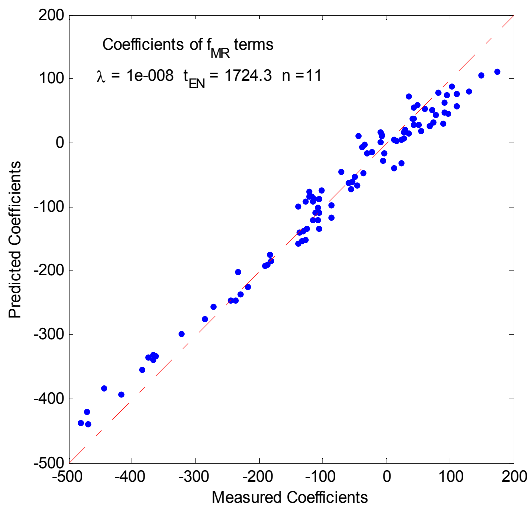


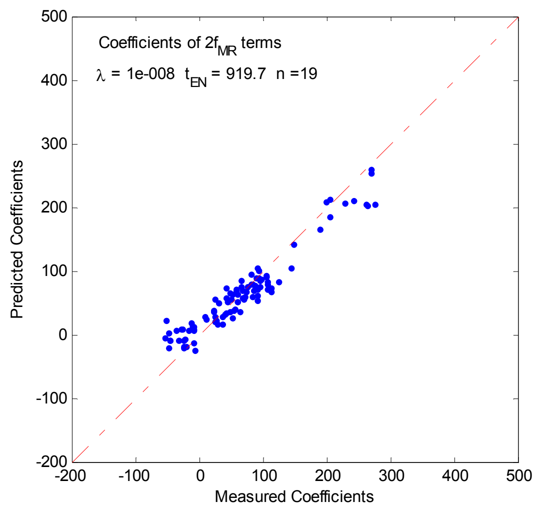

*Figure 3. A $K_{CV}$-fold cross validation was used to determined the optimized set of (λ, $t_{EN}$). $K_{CV}$ =3 is illustrated for simplicity.*

A Matlab® implementation of the Elastic Net and CV, which was modified from the source codes published in [19], was used in this study.

The results shown in Fig. 4 were obtained using 10-fold CV of 49 events ($m$=49). For the coefficients of the base frequency ($f_{MR}$) terms, 11 variables were selected from 1200 candidates. For the coefficients of the double frequency ($2f_{MR}$) terms, 19 variables were selected. The results raised two concerns that: 1) the number of selected variables was larger than ideal for a robust implementation; and 2) the prediction errors were larger than ideal. If the regression approaches were forced to select less than 10 predictor variables, more prediction errors would appear, especially for the case of $2f_{MR}$ terms where the plotted predictions were based on 19 predictor variables. This implied that the linear regression analyses in the frequency domain did not yield an acceptable solution for the current problem, even though an advanced regression method had been used.




(a)




(b)

*Figure 4. Load synthesis using linear regression in frequency domain. (a) $f_{MR}$ terms; (b) $2f_{MR}$ terms.*

## 4. Linear Regression in Azimuth Domain

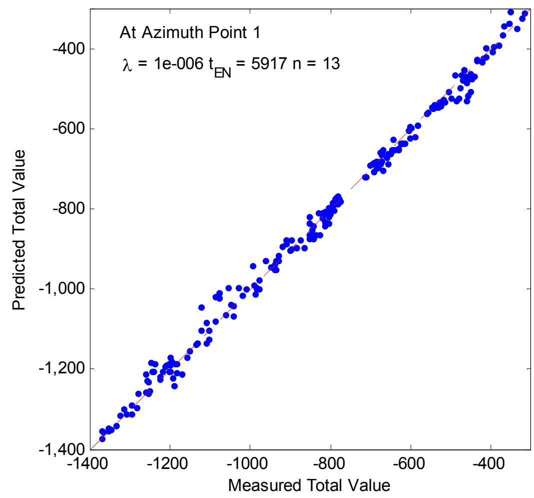
Prior work on a holometric flight demonstration [10] showed that linear regression within the azimuth domain may be useful for load estimation. This concept was considered in the second phase of this study.

Firstly, the load-time histories were re-sampled into data relating to selected azimuth points. For each azimuth point, it was assumed that the measurement on a rotating component was a linear combination of those on the stationary components. For a single set of data, this assumption led to the following expression:

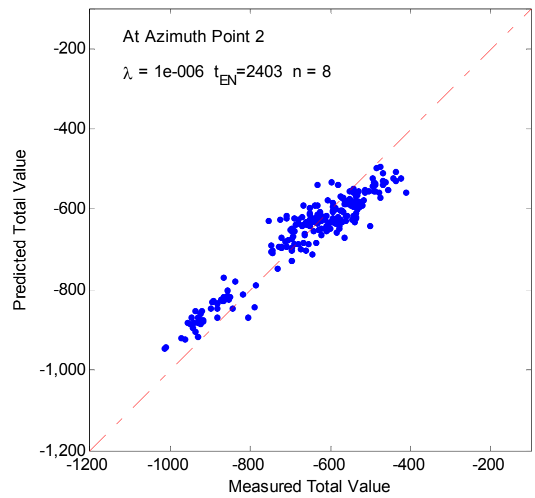
$$\sum_{i=1}^{N} u_i \beta_i = u_{MRPR} \tag{7}$$

In the case of $m$ events, Eq. (7) was assembled by row into a form the same as expressed in Eq. (5), except that $p = m$ and $q = N$. The linear regression problem was then solved using the Elastic Net in conjunction with CV.

Figure 5 plots typical results using 5-fold CV of 223 events of data sets. The two azimuth points are ¼-main-rotor-revolution apart. Good predictions are only seen in one of the azimuth points.




(a)




(b)

*Figure 5. Load synthesis using linear regression in azimuth domain. (a) at azimuth point 1; (b) at azimuth point 2.*

## 5. Load Path Analysis

Due to the errors produced by load synthesis via linear regression in both the frequency and azimuth domains, an improved understanding of the behaviour of the components was sought. Therefore, the load path from main rotor pitch links through the swashplate assembly, as shown in Fig. 6, to stationary components was analyzed.

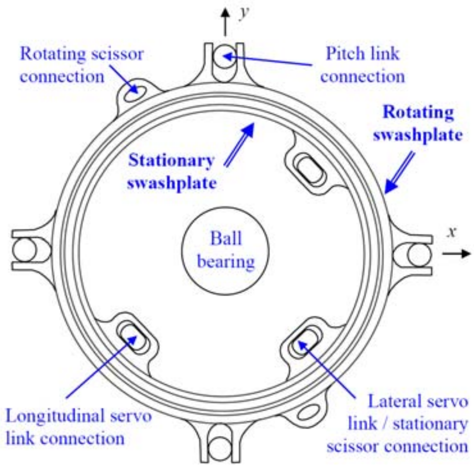



*Figure 6. Schematic illustration of the swashplate assembly of S-70A-9 Black Hawk helicopter. (z-axis, not shown, is normal to the xy-plane) .*

In conducting this analysis, the effects of swashplate tilting, inertia, friction and self-weight were ignored. Further, it was assumed that forces on the pitch links and servo links acted in the *z*-direction. Consequently, the forces on the swashplate assembly were limited to those from:

- 4 pitch links (along *z*-direction)
- 3 servo links (along *z*-direction)
- 2 rotating scissors (in *xy*-plane)
- 1 stationary scissor (in *xy*-plane)
- 1 ball joint to main shaft (in *xy*-plane)

The forces in the *z*-direction are plotted in Fig. 7, where the coordinates are fixed on the rotating swashplate, such that *P1* and *P2* are always on the *x*-axis, and *P3* and *P4* always on the *y*-axis.

As internal stresses were not considered, the swashplate was approximated as a rigid body. Out of six degrees of freedom of the rigid body, three equations were established to deduce pitch link forces: one related to force equilibrium along *z*-direction, and the remaining two related to moment equilibriums about *x*- and *y*-directions. Obviously, three equations could not uniquely determine four unknown MRPR forces.

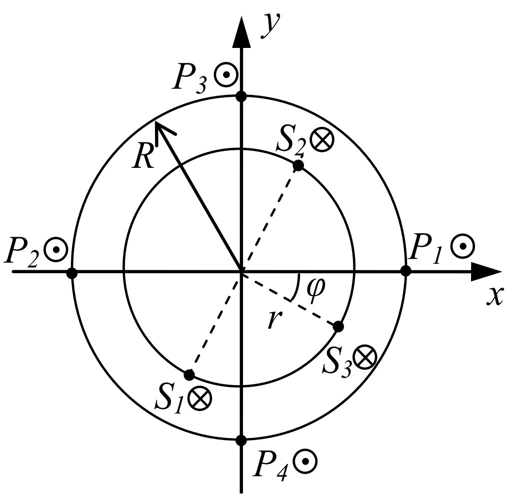



*Figure 7. Schematic illustration showing z-directional forces on the swashplate assembly. $P_1$ to $P_4$: pitch link forces; $S_1$ to $S_3$: servo link forces.*

Nevertheless, as an approximation of reality, we assumed that the four MRPR forces were nearly identical except for phase shifts as follows:

$$\left.\begin{aligned}
&P_1(\varphi) = a_0 + \sum_{k=1}^{K}[a_k \cos(k\varphi) + b_k \sin(k\varphi)] \\
&P_3(\varphi) = P_1(\varphi + 0.5\pi) + \varepsilon_3 \\
&P_2(\varphi) = P_1(\varphi + \pi) + \varepsilon_2 \\
&P_4(\varphi) = P_1(\varphi + 1.5\pi) + \varepsilon_4 \\
&\varphi = \varphi_0 + \varphi_a \\
&\varphi_a = \int_0^t 2\pi f_{MR} N_R dt
\end{aligned}\right\} \quad (8)$$

where, $\varepsilon_2$, $\varepsilon_3$ and $\varepsilon_4$ are error terms. Based on Eq. (8), the force equilibrium along the *z*-direction is shown in Eq. (9):

$$P_1 + P_2 + P_3 + P_4 = S_1 + S_2 + S_3 \quad (9)$$

and this was transformed into Eq. (10):

$$\begin{aligned}
&a_0 + \sum_{k=4,8,12,\ldots}[a_k \cos(k\varphi) + b_k \sin(k\varphi)] \\
&= \frac{1}{4}[S_1 + S_2 + S_3] - \frac{1}{4}(\varepsilon_2 + \varepsilon_3 + \varepsilon_4)
\end{aligned} \quad (10)$$

Because of the approximate rotational symmetry, only one of the two moment equilibrium equations needed to be considered, of which the moment balance about the $y$-axis is shown in Eq. (11):

$$R(P_1 - P_2) = r[(S_2 - S_1)\sin\varphi + S_3\cos\varphi] \quad (11)$$

and this was transformed into Eq. (12):

$$\sum_{k=1,3,5,..}[a_k\cos(k\varphi) + b_k\sin(k\varphi)] = \frac{1}{2}[aS_a + bS_b] + \frac{1}{2}\varepsilon_2 \quad (12)$$

where,

$$\left.\begin{aligned} S_a &= (S_2 - S_1)\sin\varphi_a + S_3\cos\varphi_a \\ S_b &= (S_2 - S_1)\cos\varphi_a - S_3\sin\varphi_a \\ a &= \frac{r}{R}\cos\varphi_0 \\ b &= \frac{r}{R}\sin\varphi_0 \end{aligned}\right\} \quad (13)$$

Equations (10) and (12) indicated that:

a) The zero-Hertz, $4f_{MR}$, $8f_{MR}$, $12f_{MR}$, … components of MRPR force could be deduced from the force equilibrium. In a simplified form, they could be expressed as a quarter of the sum of servo link forces;

b) The $f_{MR}$, $3f_{MR}$, $5f_{MR}$ , … components of MRPR force could be deduced from the moment equilibrium equation. The transfer function involves frequency modulation by $f_{MR}$ ;

c) The $2f_{MR}$, $6f_{MR}$, $10f_{MR}$ , … components of MRPR force could ***not*** be deduced from any of the equilibrium equations.

As illustrated in Fig. 8, the aforementioned force components resulted in distinct load conditions on the swashplate assembly. These load conditions were previously catalogued as collective, cyclic and reactionless load conditions [20]. Here, the same terminologies were used to refer corresponding MRPR force components. A reactionless component is self-balanced within the swashplate assembly. Therefore it is impossible to synthesize a reactionless component from forces on the servo links, or any measurements on the stationary components further down-stream.

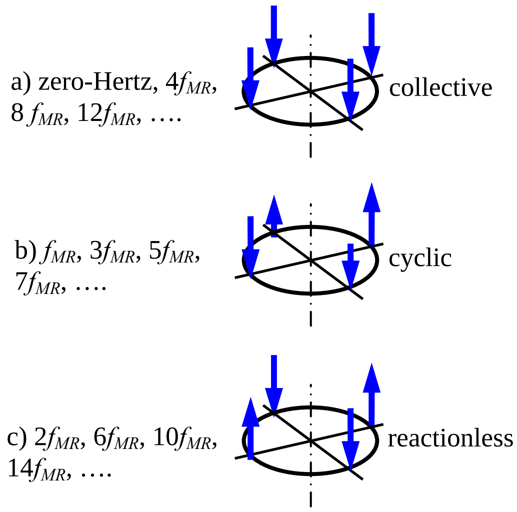
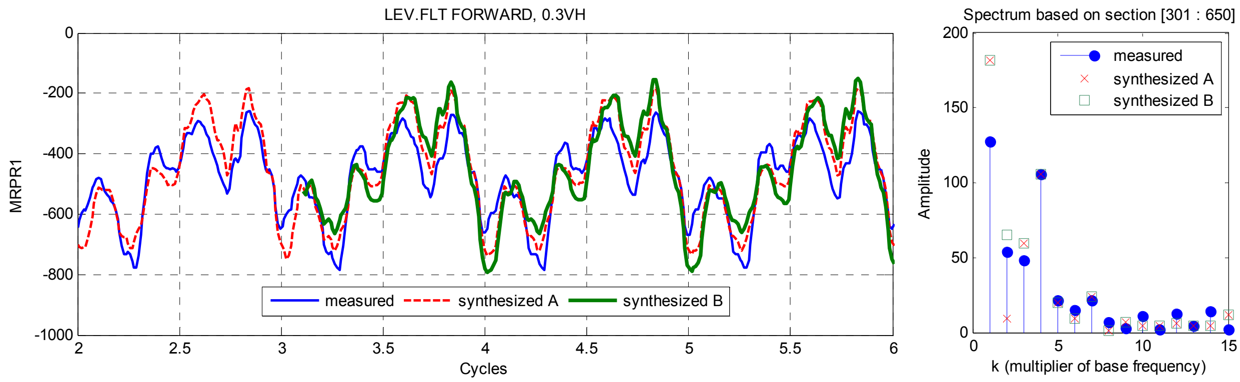


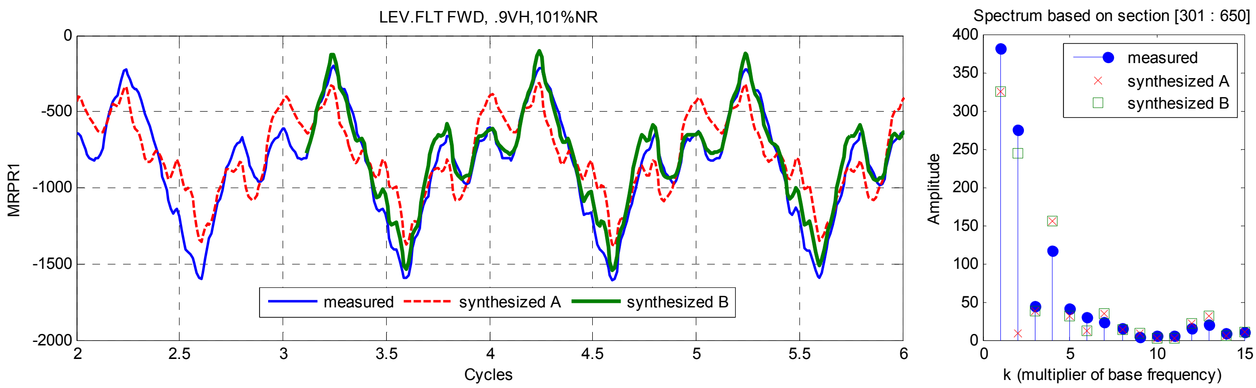

*Figure 8. Schematic illustration of three types of load conditions on a swashplate induced by varied MRPR force components.*

None of the parameters in Eq. (10) or (12) is able to be tuned. For example, $r/R$ is a fixed value for any given swashplate, $\varphi_0$ is an angle that defines the initial position of a pitch link connection in relative to servo link connection, $\varphi_a$ is an angle swept by the rotating swashplate. For this study, $\varphi_a$ can be readily integrated from rotor speed and elapsed time, $\varphi_0$ was back-calculated because it was not recorded in the flight data. The back-calculation of $\varphi_0$ did not hinder the load path analysis to be applied individually onto each of the 42 runs of level flights.

Figure 9 compares the measured and synthesized MRPR forces (labeled as “synthesized A”) under two typical level flight conditions: one at 0.3Vh, the other at 0.9Vh. The relationships described in Eqs. (10) and (12) are generally observed. As expected, the reactionless components could not be synthesized. Also it was shown that the reactionless MRPR force components were dominated by the $2f_{MR}$ term. This led to an attempt to supplement the load path analysis with statistical analysis to estimate the $2f_{MR}$ term.




(a)




(b)

*Figure 9. A comparison of measured and synthesized loads on MRPR1 under two level flight conditions. (a) 0.3Vh; (b) 0.9 Vh. ("synthesized A" was obtained using load path analysis. "synthesized B" was obtained using load path analysis then supplemented by statistical analysis.)*

## 6. Supplemented Statistical Analysis

A statistical analysis was performed to seek the coincidence between the $2f_{MR}$ component of the MRPR force and strain measurements on stationary components. In this analysis, the amplitude and phase of the $2f_{MR}$ component were regressed separately. Based on the data set of 42 runs of level fights, it was found that:

• The amplitude of a $2f_{MR}$ component could be predicted, with some errors, from zero-Hertz components of two strain measurements at transmission support beams, see Fig. 10. The predictor variables were manually selected from those suggested by an Elastic Net regression.

• The phase of $2f_{MR}$ component could not be reasonably predicted, unless its amplitude was sufficiently large, see Fig. 11. The predictor variables were selected mainly by relying on trial-and-error.

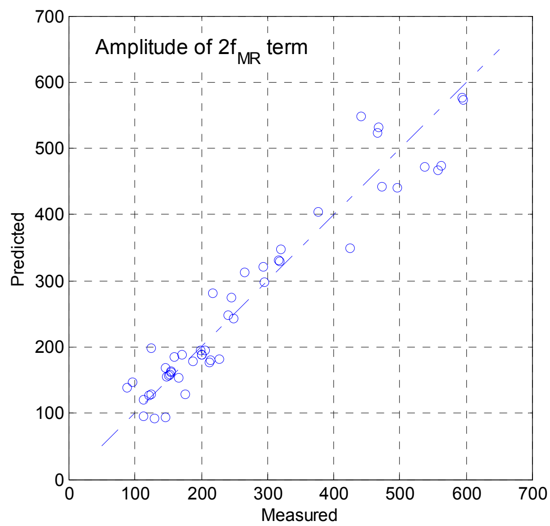



*Figure 10. A comparison of measured and predicted amplitudes of $2f_{MR}$ component.*

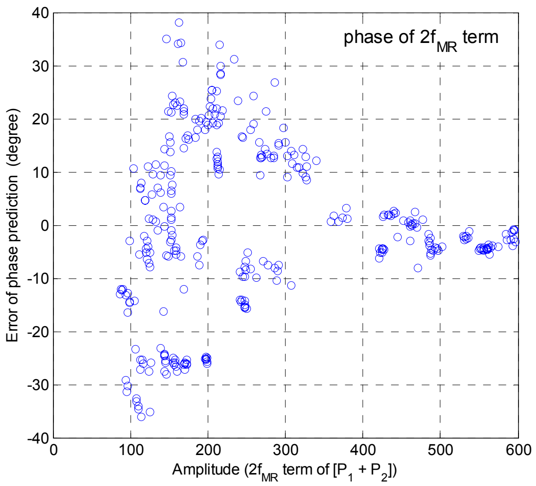



*Figure 11. The error of phase prediction at varied amplitude of $2f_{MR}$ component.*

The results of the supplementary statistical analysis were then added to those obtained using the load path analysis. The summed results were plotted as "synthesized B" in Fig. 9. It can be seen that the MRPR force syntheses were improved in one case but not in the other. This supports the finding of the load path analysis that a reactionless component could not be synthesized with sufficient accuracy and repeatability from the measurements below the swashplate.

## 7. Conclusions

In this study, four approaches were considered for synthesizing load-time histories of helicopter MRPR forces from strain measurements on stationary components. The trials were based on 42 runs of level flights, selected from existing data set of the Joint USAF-ADF S-70A-9 Black Hawk flight strain survey. A strict criterion was set up in assessing the accuracy of load synthesis. It is concluded that:

• The linear regression approach, either in frequency domain or azimuth domain, was shown to have excessive errors for this structural layout and data set.

• The load path analysis revealed that reactionless components (here $2f_{MR}$, $6f_{MR}$, $10f_{MR}$, …) of the MRPR force were filtered by the swashplate assembly and therefore could not be synthesized from measurements below the swashplate.

• The supplementary statistical analysis confirmed that $2f_{MR}$, the dominant term of the reactionless components, could not always be predicted with sufficient accuracy.

## 8. Recommendations

The above findings lead to the suggestion that a load path analysis should be regarded as an essential step in developing remote synthesis of loads on helicopter rotating components. This leads to the following recommendations:

• In the case of evaluating reported studies of load synthesis, a close investigation should be performed to reveal whether the reported success is limited to a certain type of structural layout and/or a situation where the target load-time history is dominated by certain frequency terms.

• When a study is based on an existing data set of strain measurements, a load path analysis should be performed to reveal whether a complete load synthesis may be prohibited by reactionless components. This should be done before any other analysis.

• When a new strategy of load synthesis is to be developed, a load path analysis should be performed to determine appropriate locations of measurements, which can be used as prediction variables such that target force components are not filtered by the structural layout.

## Acknowledgements

The authors would like to thank for invaluable discussions with, and help provided by, their colleagues Domenico Lombardo, Luther Krake and Aaron James.

## References

1. Lombardo, D.C., *Helicopter Structures—A Review of Loads, Fatigue Design Techniques and Usage Monitoring* in

*Aeronautical Research Laboratories Technical Report 15*. 1993.
2. Polanco, F.G., *Estimation of Structural Component Loads in Helicopters: A Review of Current Methodologies*. 1999, DSTO.
3. Wallace, M., H. Azzam, and S. Newman, *Indirect approaches to individual aircraft structural monitoring.* Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2004. **218**(5): p. 329-346.
4. Seibt, R., *US Navy Awards MicroStrain, Inc. 3/4 Million for Wireless Sensors*, in *Machine Design*. 2006.
5. Arms, S.W., et al. *Energy harvesting, wireless, strain sensor for damage tracking of helicopter components*. in *Third European Workshop on Structural Health Monitoring*. 2006. Granada, Spain.
6. Bai, H., M. Atiquzzaman, and D. Lilja. *Wireless Sensor Network for Aircraft Health Monitoring*. in *First International Conference on Broadband Networks (BROADNETS'04)*. 2004.
7. Stashenko, J., *Accumetrics puts wireless sensors to work on Black Hawk helicopter*, in *The Business Review (Albany)*. 2006.
8. Gunsallus, C.T., W.L. Pellum, and W.G. Flannelly, *Holometrics: An information transformation methodology*, in *The American Helicopter Society 44th Annual Forum*. 1988: Washington DC.
9. Gunsallus, C.T. and E. Robeson, *AH-64A rotating load usage monitoring from fixed system information*, in *The American Helicopter Society National Technical Specialists Meeting on Rotor Craft Structures*. 1991: Williamsburg, Virginia.
10. Gustavson, B., W.L. Pellum, and E. Robeson, *Systematic application of holometric synthesis for cost-effective flight load monitoring*, in *The American Helicopter Society 49th Annual Forum*. 1993: St Louis, Missouri.
11. Haas, D.J., J. Milano, and L. Flitter, *Prediction of helicopter component loads using neural networks.* Journal of the American Helicopter Society, 1995. **40**(1): p. 72-82.
12. Cabell, R.H., C.R. Fuller, and W.F. O'Brien, *Neural network modelling of oscillatory loads and fatigue damage estimation of helicopter components.* Journal of Sound and Vibration, 1998. **209**(2): p. 329-342.
13. McCool, K.M., L.A. Flitter, and D.J. Haas, *Development and flight test evaluation of a rotor system load monitoring technology.* Journal of the American Helicopter Society, 2000. **45**(1): p. 19-27.
14. Uhl, T., *Identification of loads in mechanical structures - Helicopter case study.* Computer Assisted Mechanics and Engineering Sciences, 2002. **9**(1): p. 151-160.
15. Dore, C.A. and C.G. Knight. *Flight data recorder information retrieval trial*. in *11th Australian International Aerospace Congress*. 2005. Melbourne, Australia.
16. Georgia Tech Research Institute, *Joint USAF-ADF S-70A-9 Flight Test Program, Summary Report*. 2001.
17. Zou, H. and T. Hastie, *Regularization and variable selection via the elastic net.* Journal of the Royal Statistical Society Series B, 2005. **67**(2): p. 301-320.
18. Tibshirani, R., *Regression shrinkage and selection via the lasso* Journal of the Royal Statistical Society Series B, 2005. **58**(1): p. 267-288.
19. Sjöstrand, K., *Matlab implementation of LASSO, LARS, the elastic net and SPCA*. 2005, Informatics and Mathematical Modelling, Technical University of Denmark, DTU.
20. Kufeld, R.M. and W. Johnson, *Effects of control system stiffness models on the dynamic stall behavior of a helicopter.* Journal of the American Helicopter Society, 2000. **45**(4): p. 263-269.