Australian Government
Department of Defence
Defence Science and
Technology Organisation

Integration of Load Path Analysis and Harmonic Regression for Usage Monitoring of Helicopter Dynamic Components

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15th Australian International Aerospace Congress,
25-28 Feb 2013, Melbourne

Introduction & Motivation

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Motivation of Individual Load Monitoring

- **Existing approach: Fleet wide design usage spectrum**
  - -- Does not accurately reflect individual usage
  - -- Operational requirements / usage are constantly changing
- **Alternative approach: Flight regime recognition**
  - -- Loads within a nominally identical flight regime: can vary by “10+ times”
  - -- Small changes in loads can cause large changes in fatigue damage
- **This study: Individual aircraft load monitoring:**
  - -- To reduce costs and increase life; or
  - -- To identify risk and improve safety

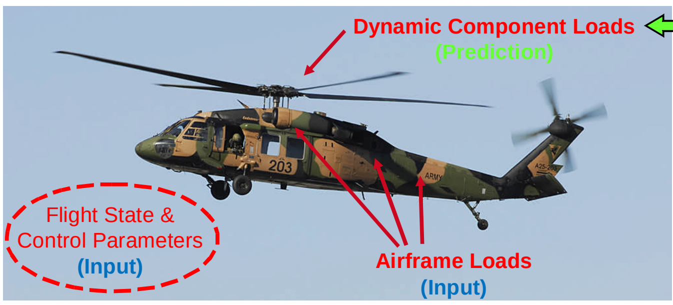
Increasing accuracy on damage estimation

Fleet-wide Usage Spectrum	Individual Regime Recognition	Individual Load Monitoring
Current Approach	*Alternative Approach*	*This Study*

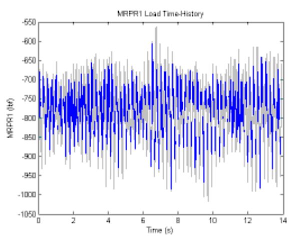
DSTO 3

Justification for Load Synthesis

- **Direct monitoring of dynamic component usage:**
  - -- Requires physical connections with rotating sensors
  - -- Mechanical assemblies (slip-rings) are expensive and lack reliability
  - -- On-site or wireless data logging / storage technology is still maturing
- **Load synthesis:**
  - -- Prediction of loads based on indirect measurements.



Loads mean time-history



DSTO 4

Previous Study by DSTO

- **Using: Joint USAF-ADF S-70A-9 Blackhawk flight strain survey data.**
- **A number of approaches have been investigated:**

Inverse problem / Regression

- Neural Network
- Generic Program
- Linear Regression (azimuth domain)
  - Latest development: concurrent regression: Allows selecting predicting parameters concurrently at all azimuth locations
- Linear Regression (harmonic domain)
  - Coefficient regression: $Load(t)=\sum_k [a_k \cos(2\pi k f_0 t)+b_k \sin(2\pi k f_0 t)]$
  - Amplitude-phase regression: $Load(t)=\sum_k [c_k \cos(2\pi k f_0 t+\theta_k)]$

Forward problem / Deterministic

- Load Path Analysis
  - Across swashplate assembly:
  - Force balance & moment balance.

☑ **Load path analysis & Harmonic (amplitude-phase) regression are most promising → Approach of this study.**

DSTO 5

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Primary Objective of Load Synthesis

<u>Synthesise</u>
Time-history of loads on main rotor pitch link

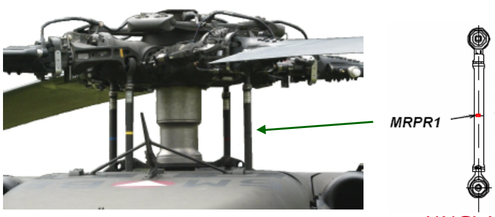
<u>From</u>
Time-history of strain measurements on stationary components

<u>Test Cases</u>

42 forward level-flight runs, with variations of:

- Velocity: $0.3v_h$ to v_h
- N_R : 95% to 101%
- Gross weight
- Centre of gravity
- Day of flight
- Pilot

Hovering / Auto-descending: also investigated



MRPR: main rotor pitch link

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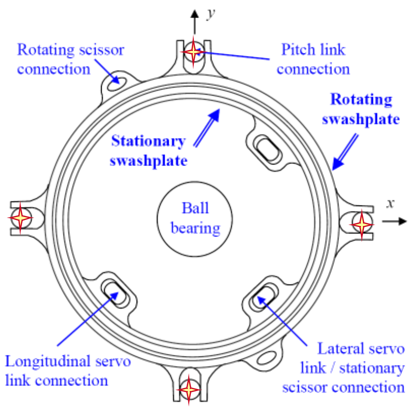
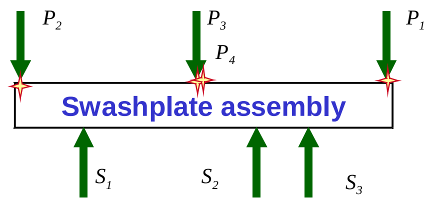
Load Path Analysis of Swashplate

Loads on Swashplate



Loads along z-direction are of interests

Loads from pitch links



Loads from server links

- 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)

Rules of Rigid-body Mechanics
Loads below & above swashplate assembly are in equilibrium

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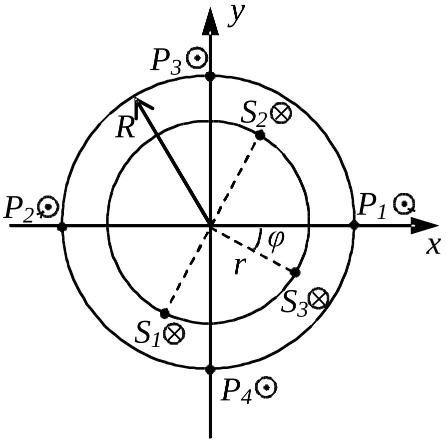
Assumption of Loads on Pitch Links



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

The four MRPR forces were nearly identical except for phase shifts

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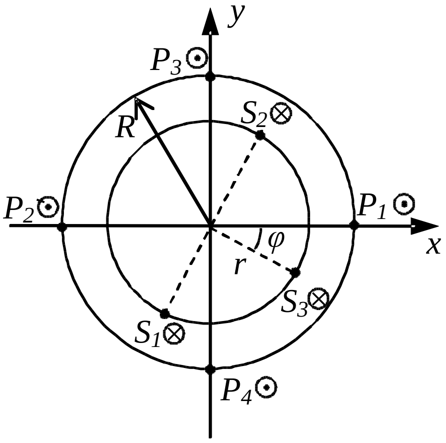
Force Equilibrium Along z-Direction



$$P_1 + P_2 + P_3 + P_4 = S_1 + S_2 + S_3$$

$$a_0 + \sum_{k=4,8,12,\ldots}[a_k \cos(k\varphi) + b_k \sin(k\varphi)]$$

$$= \frac{1}{4}[S_1 + S_2 + S_3] - \frac{1}{4}(\varepsilon_2 + \varepsilon_3 + \varepsilon_4)$$

The zero-Hertz, $4f_{MR}$, $8f_{MR}$, $12f_{MR}$, …
components of MRPR force can be deduced

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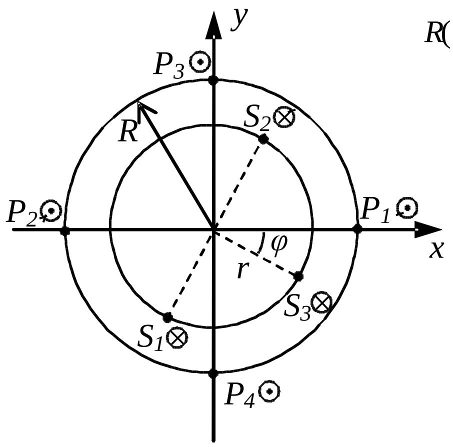
Moment Equilibrium About y-Axis



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

$$S_a = (S_2 - S_1)\sin\varphi_a + S_3\cos\varphi_a$$
$$S_b = (S_2 - S_1)\cos\varphi_a - S_3\sin\varphi_a$$
$$a = \frac{r}{R}\cos\varphi_0$$
$$b = \frac{r}{R}\sin\varphi_0$$

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

The f_{MR}, $3f_{MR}$, $5f_{MR}$, $7f_{MR}$ …
components of MRPR force can be deduced

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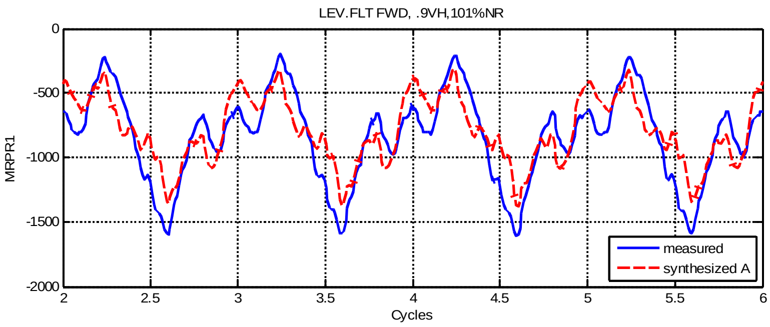
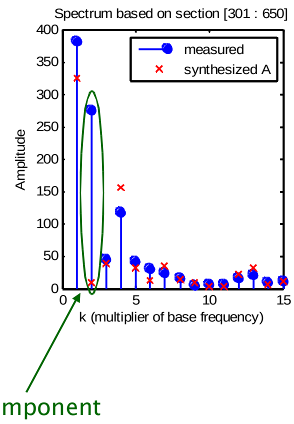
Load Path Analysis Results: Missing of $2f_{MR}$ component





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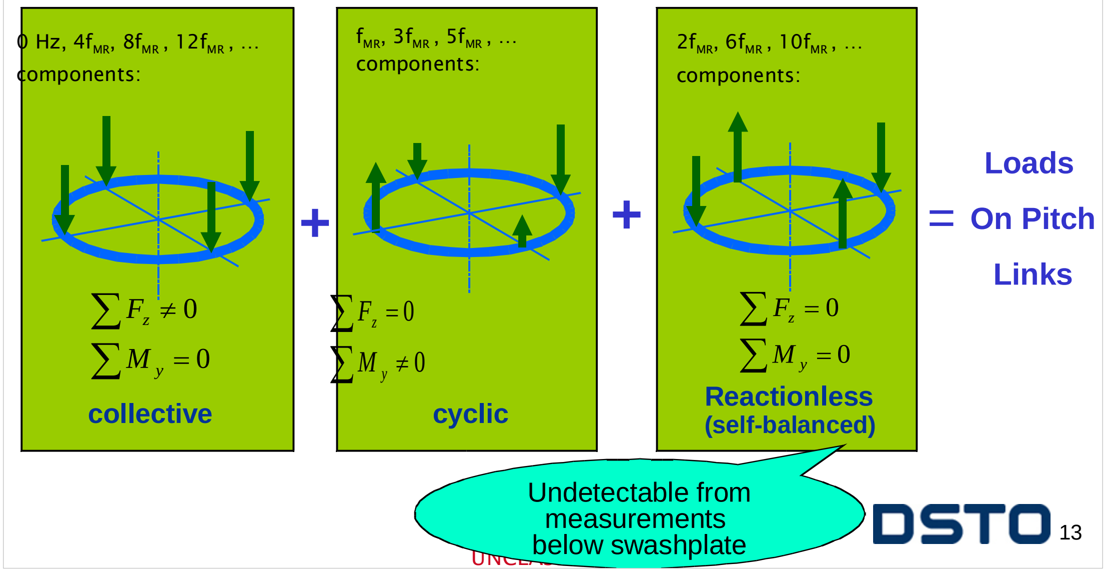
Load Conditions on Swashplate

- Consider four pink links as a group;
- Assume 90° phase shift between neighbouring pitch links;
- Express load on each pitch link in Fourier series;



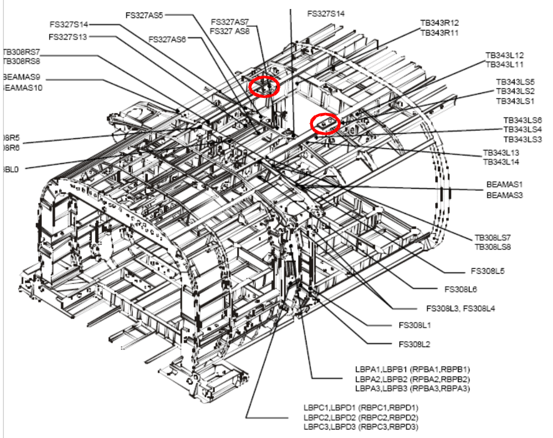
DSTO 13

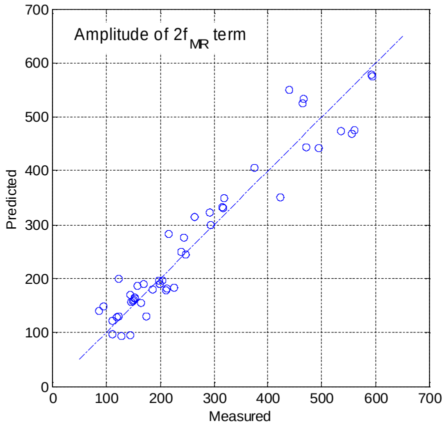
Harmonic Regression

$2f_{MR}$ term

DSTO 14

Amplitudes of $2f_{MR}$ Components: 42 Level Flights



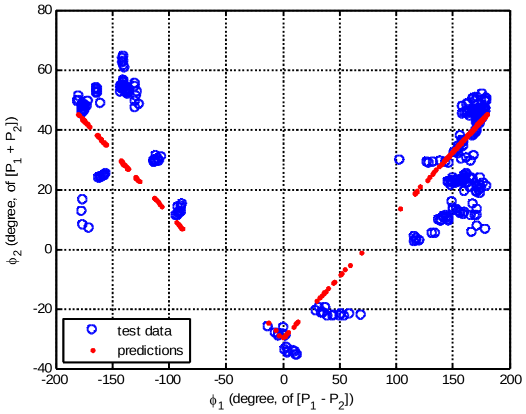


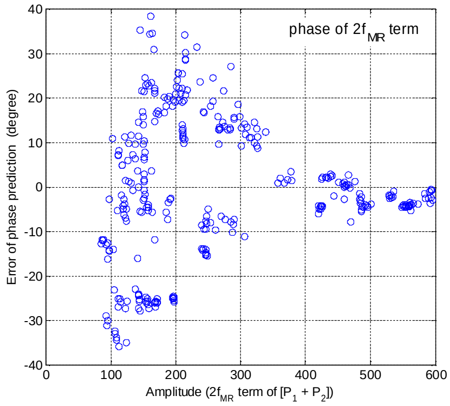
Can be predicted, with some errors, from zero-Hertz components of *two* strain measurements at transmission support beams

☑ **Using prediction parameters for all 42 runs**

DSTO 15

Phases of $2f_{MR}$ Components: 42 Level Flights



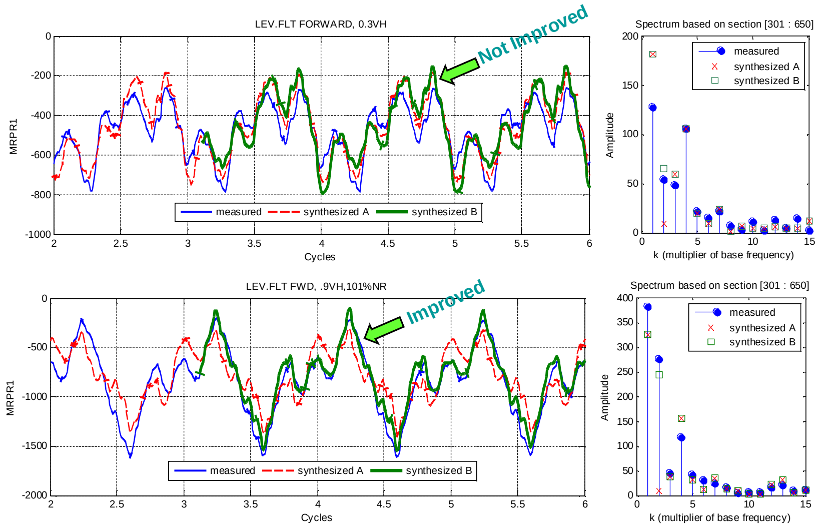


☑ Best fitting : $\Phi_2 = -30 + 0.4169 \times abs(\Phi_1)$

☑ Reasonable prediction when the amplitude of $2f_{MR}$ component > 300

DSTO 16

Effects of adding $2f_{MR}$ Components: Visual Assessment



Synthesized A:
Load Path Analysis

Synthesized B:
Load Path Analysis + Harmonic Regression ($2f_{MR}$)

- ☑ Visual Assessment is not ideal:
  it cannot assess relative importance to damage estimation.
- ☑ Need a better approach to assess the effects

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Relative Damage Assessment

DSTO 18

Relative Damage Assessment

- **Not real damage**
  - **- Quantitative assessment of prediction accuracy.**

- **How we did it**
  - **- Rain-flow count signal according to the ASTM standard for cycle counting in fatigue analysis (code downloaded from MATLAB Central)**
  - **- Calculate Fatigue Life using Miner's Rule approach and MIL HDBK 5 Material Data.**
  - **- Modify pitch link load time history (treated as an indication load): a) load → stress; b) "+/-" sign reverse; & c) apply scale factor (S_factor)**

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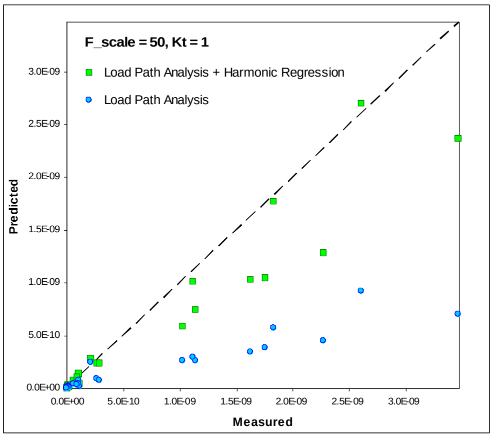
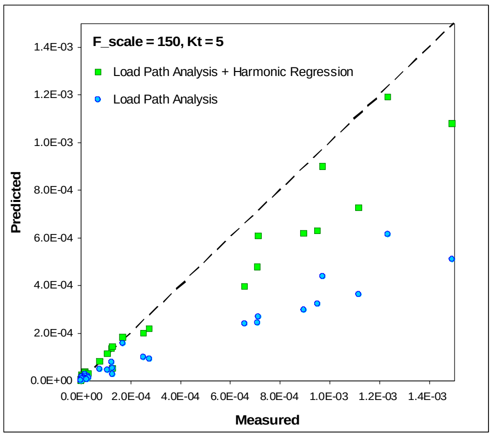
Relative Damage Assessment: Sumamry (I)

- **Linear-linear plot**

-- 42 Level Flight runs, relative damage per second (rDps)



Kt = 1 (max rDps = 3.46e-9)



Kt = 5 (max rDps = 1.49e-3)

☑ **Improvement (by adding Harmonic Regression): varied Kt & F_scale → max(rDps): from 3.46e-9 to 1.49e-3.**

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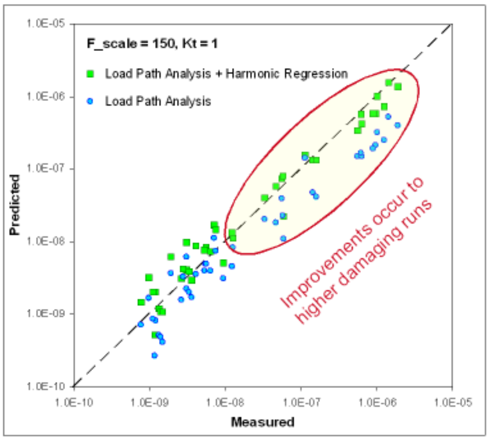
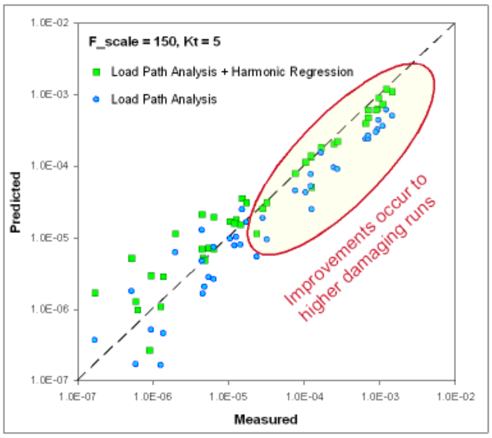
Relative Damage Assessment: Summary (II)

- **Log-log plot**

-- 42 Level Flight runs, relative damage per second (rDps)



Kt = 1 (max rDps = 1.94e-6)



Kt = 5 (max rDps = 1.49e-3)

☑ **For given F_Scale & Kt:**
Improvements occur to higher damaging runs

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Conclusion & Future Work

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Conclusion

- Integration of "Load Path Analysis" and "Harmonic (Amplitude-Phase) Regression" is promising,
  -- for all 42 level flight runs, only 5 prediction parameters are needed;
  -- for runs with higher damage, the predicted relative damages are within approximately -30% to +5% range.

- The "Relative Damage Assessment" provides a reasonable assessment of the accuracy of predicted load-time history:
  -- allows to relate accuracy to damage level;
  -- provides consistent indication for a range of scaling and Kt factor (covers 5 orders of pseudo damage range)

☑ Future work
1: Extend to more flight conditions & improve the regression approach;
2: Apply usage-based weight factors to relative or real damages.

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Questions ?

Backup Slides

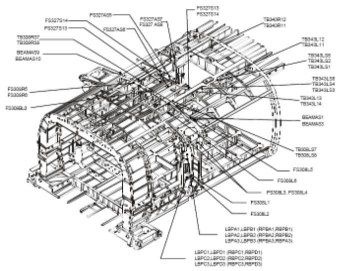
Data & Objective

Flight Data

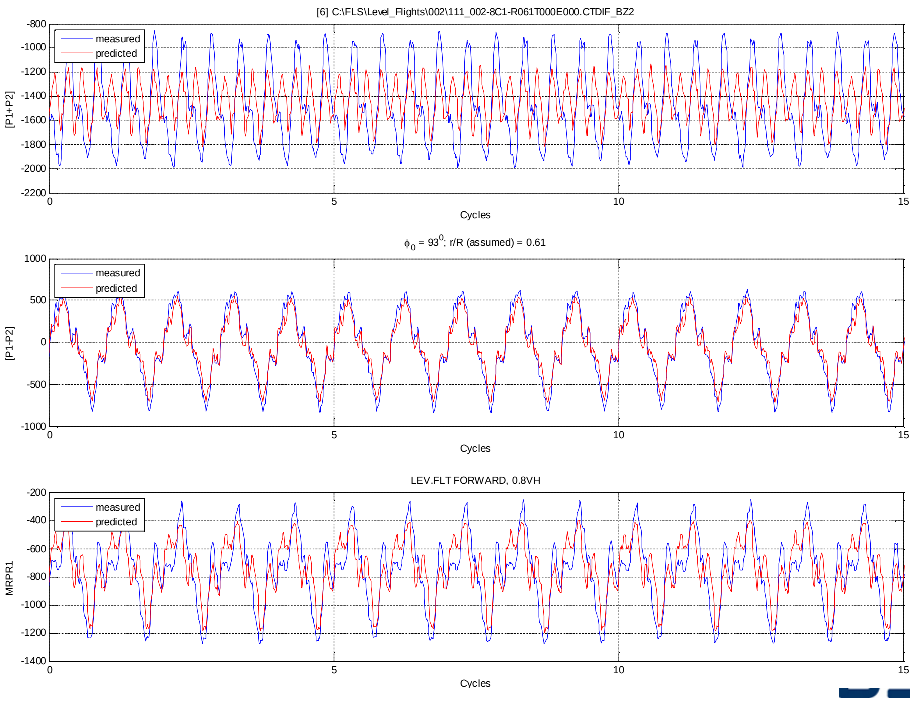
- **Joint USAF-ADF S-70A-9 Flight Strain Survey**
  - Conducted in 2000 by ARDU, DSTO & the Georgia Tech Research Institute
  - 65 hours useable flight test data, divided into runs
  - For each run (10 to 30 seconds):
    - 52Hz : 31 parameters, mainly control & flight parameters;
    - 416 Hz: 195 parameters, mainly strain gauge measurements;

Strain gauges on fixed components

Strain gauges on rotating components



Load Path Analysis Results: Level Flight



measured

predicted

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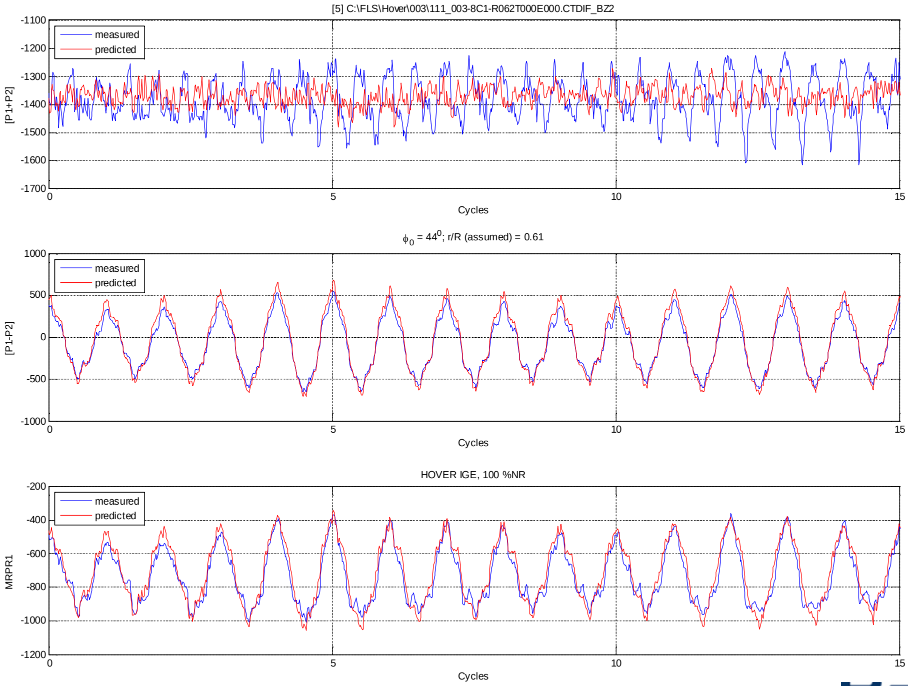
Load Path Analysis Results: Hovering



measured

predicted

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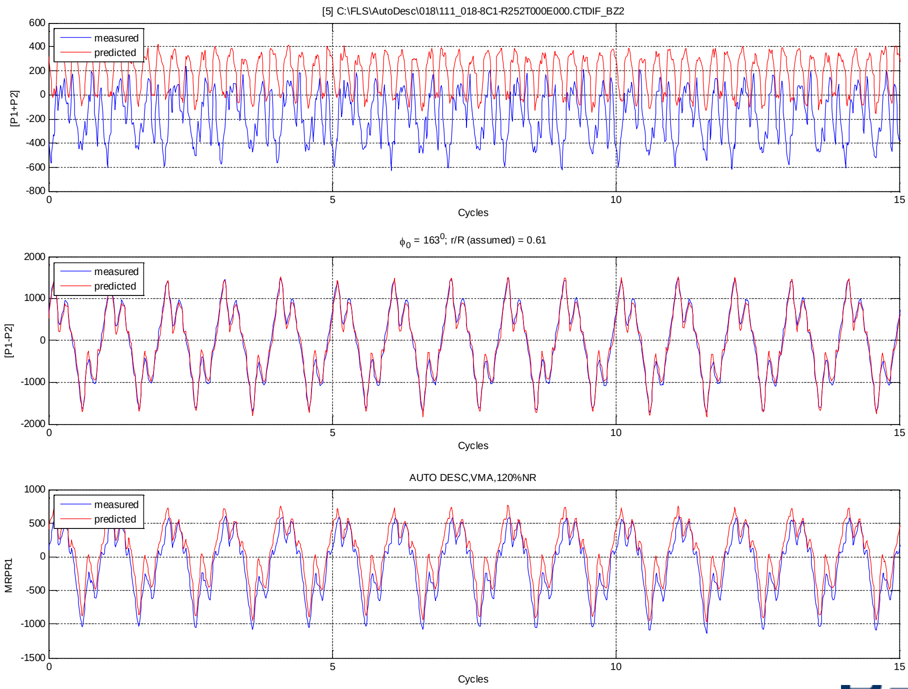
Load Path Analysis Results: Auto-Desc



measured

predicted

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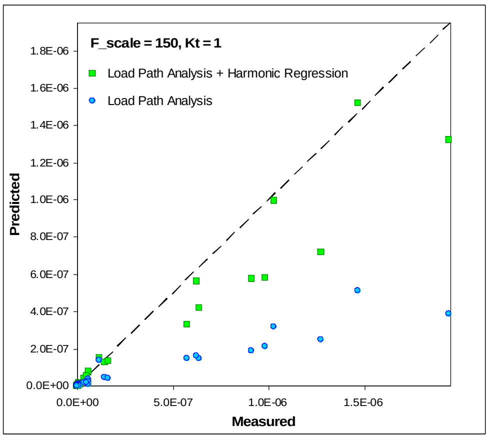
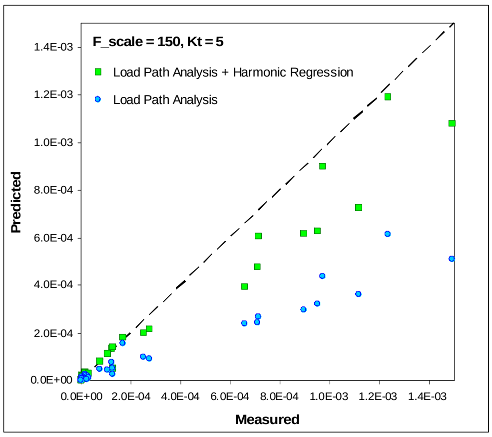
Relative Damage Assessment: F_Scale = 150

- **Linear-linear plot**

-- 42 Level Flight runs, relative damage per second (rDps)



Kt = 1 (max rDps = 1.94e-6)



Kt = 5 (max rDps = 1.49e-3)

☑ **Kt – selection: not sensitive.**

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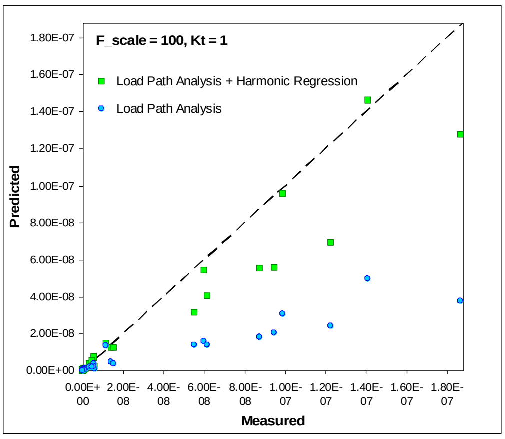
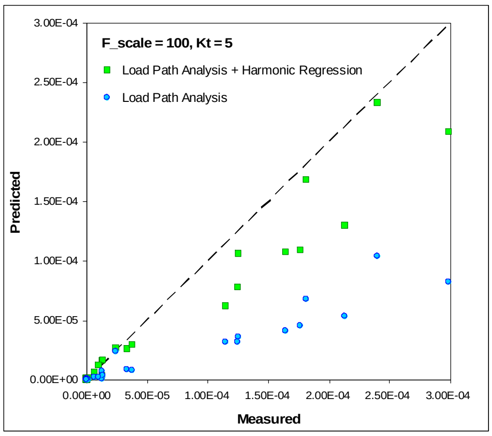
Relative Damage Assessment: F_Scale = 100

- **Linear-linear plot**

-- 42 Level Flight runs, relative damage per second (rDps)



Kt = 1 (max rDps = 1.87e-7)



Kt = 5 (max rDps = 2.99e-4)

☑ **Kt – selection: not sensitive.**

DSTO 32

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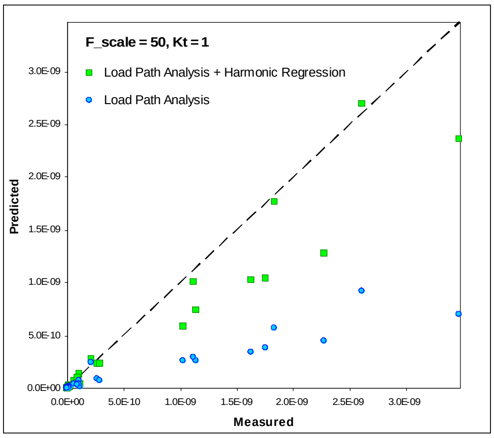
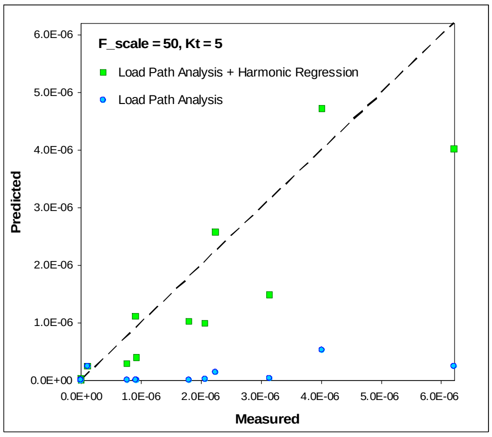
Relative Damage Assessment: F_Scale = 50

- **Linear-linear plot**

-- 42 Level Flight runs, relative damage per second (rDps)



Kt = 1 (max rDps = 3.46e-9)



Kt = 5 (max rDps = 6.21e-6)

☑ **Kt – selection: not sensitive.**

DSTO 33