Design for Vibration Monitoring:
A Methodology for Reliable and Cost-Effective Vibration Monitoring

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- **Health monitoring systems:**
  - Purpose: failure/defect detection for increased safety and performance; on-condition maintenance with reduced cost
  - Problems: high rates of false alarms and missed failures make monitoring an unreliable and costly task!
  - Reason: unaccounted variations invalidate signal modeling assumptions
- **Our approach:**
  - Focus: vibration monitoring of rotating components
  - Analyze baseline signals to determine statistical variations
  - Identify/model factors that influence vibrations: pre-production vs. post-production variations
  - Determine hit and false alarm rates with baseline flight data
  - Model and predict effect of defects and variations on vibrations
  - Develop algorithms/metrics for failure and anomaly detection in the presence of variations
- **Current application: Helicopter transmission vibrations**

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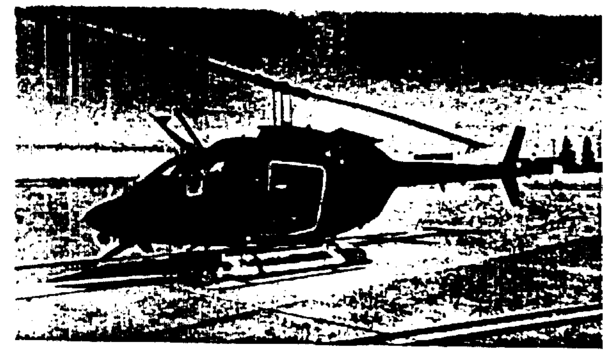
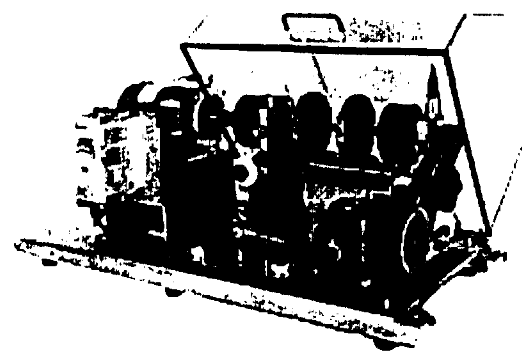
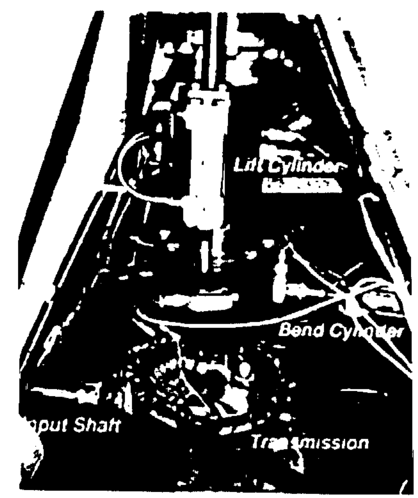
- **Flight tests for rotorcraft transmissions:**
  - AH1 Cobra
  - OH58 Kiowa
- **Controlled tests using OH58 test rig at NASA Glenn**
- **Defect tests using rotating machinery rig at Ames**
- **Data collection:**
  - HealthWatch I: controlled maneuvers
  - HealthWatch II: free flight state
- **Develop rich empirical database for analysis, modeling & evaluation**



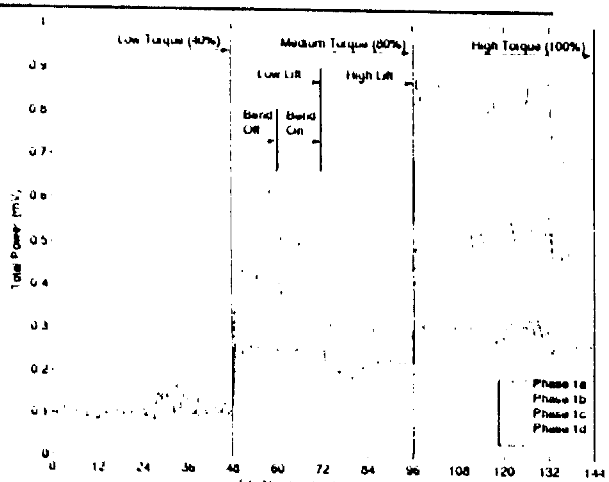




- **Lessons learned:**
  - Engineering knowledge and prior analysis required for proper signal models and defect prediction
  - Variation information and analysis required prior to implementation
  - Other platforms need to be explored to establish generality & robustness
- **Research question:**
  - Do Health Monitoring Systems need to be considered at the early stages of design? Potentially more reliable and cost-effective!
- **C-17 engines: a platform for *Design for Monitoring* methodology:**
  - Statistical effects & variation sources (NASA Ames)
  - Sensor directionality and location (NASA Ames)
  - Variation propagation models (NASA Ames)
  - Failure prediction and prevention (NASA Ames)
  - Disk crack detection (NASA Glenn)
  - Intelligent bearing damage detection (NASA Glenn)

- **Goal:**
  - Understand inherent variations that must be accounted for in engine vibrations
- **Preliminaries:**
  - Study of schematics and engineering specifications (from Pratt&Whitney)
  - Computation of frequencies for gears & bearings (Ames & Glenn)
  - Study of preliminary vibration data: triaxial accel being purchased
  - Development of HealthWatch-III for flight data collection
- **Analysis of baseline data:**
  - See current research (AHS papers and ASME/DETC papers)
- **Potential for simulated data:**
  - NASA Glenn
  - Pratt & Whitney

MANEUVER	PERCENT STATIONARY RECORDS OH-58 Kiowa	PERCENT STATIONARY RECORDS AH-1 Cobra
A. Forward Flight, Low Speed	70.8%	55.6%
B. Forward Flight, High Speed	65.3%	61.1%
C. Sideward Flight Left	12.5%	22.2%
D. Sideward Flight Fight	9.7%	31.9%
E. Forward Climb, Low Power	50.0%	97.0%
F. Forward Descent, Low Power	16.7%	68.1%
H. Hover	30.2%	80.2%
I. Hover Turn Left	11.1%	59.7%
J. Hover Turn Right	15.3%	36.1%
K. Coordinated Turn Left	79.2%	80.6%
L. Coordinated Turn Right	83.3%	80.6%
M. Forward Climb, High Power	65.3%	86.1%
N. Forward Descent, High Power	22.2%	72.2%
Average Stationarity	40.6%	64.2%



Combined Sources	OH-58 Kiowa Sum of Squares (SS)	OH-58 Kiowa Percent Total SS	OH-58 Kiowa Percent Corrected Total SS	AH-1 Cobra Sum of Squares (SS)	AH-1 Cobra Percent Total SS	AH-1 Cobra Percent Corrected Total SS
PC-1						
Covariates	83.355	61.66		555.872	90.94	
Main Effects	24.461	18.10	47.20	29.261	4.79	52.65
2-Way Interactions	10.212	7.55	19.71	9.787	1.60	17.68
3-Way Interactions	10.845	8.02	20.93	9.356	1.53	16.90
Model	128.873	95.34		604.276	98.86	
Residual Error	6.303	4.66	12.16	6.965	1.14	12.58
Total	135.176	100.00	100.00	611.241	100.00	100.00
PC-2						
Covariates	0.185	0.47		0.198	0.49	
Main Effects	31.873	80.72	81.10	37.398	92.03	92.48
2-Way Interactions	2.838	7.19	7.22	1.174	2.89	2.90
3-Way Interactions	2.550	6.46	6.49	1.095	2.69	2.71
Model	37.446	94.83		39.866	98.10	
Residual Error	2.041	5.17	5.19	0.773	1.90	1.91
Total	39.487	100.00	100.00	40.638	100.00	100.00
PC-3						
Covariates	0.291	6.16		0.285	16.12	
Main Effects	0.855	18.11	19.30	0.738	41.74	49.76
2-Way Interactions	1.530	32.41	34.54	0.340	19.23	22.93
3-Way Interactions	1.481	31.37	33.43	0.224	12.67	15.10
Model	4.158	88.07		1.587	89.76	
Residual Error	0.563	11.93	12.71	0.181	10.24	12.20
Total	4.721	100.00	99.98	1.768	100.00	100.00
Grand Total	179.384			653.647		

Source	OH-58c Aircraft Average 4 Radial Channels Variance (MS)	df	Percent Total MS	OH-58c Test Rig Sensor #3 Radial Variance (MS)	df	Percent Total MS
Planetary	17.98	70	17.48	23.38	70	13.79
Pinion - Gear	15.86	18	15.42	30.14	18	17.77
Engine	22.29	6	21.68			
Residual Variance	46.70	8098	45.42	116.07	8104	68.44
Total Mean Square (MS)	102.83	8192	100.00	169.59	8192	100.00

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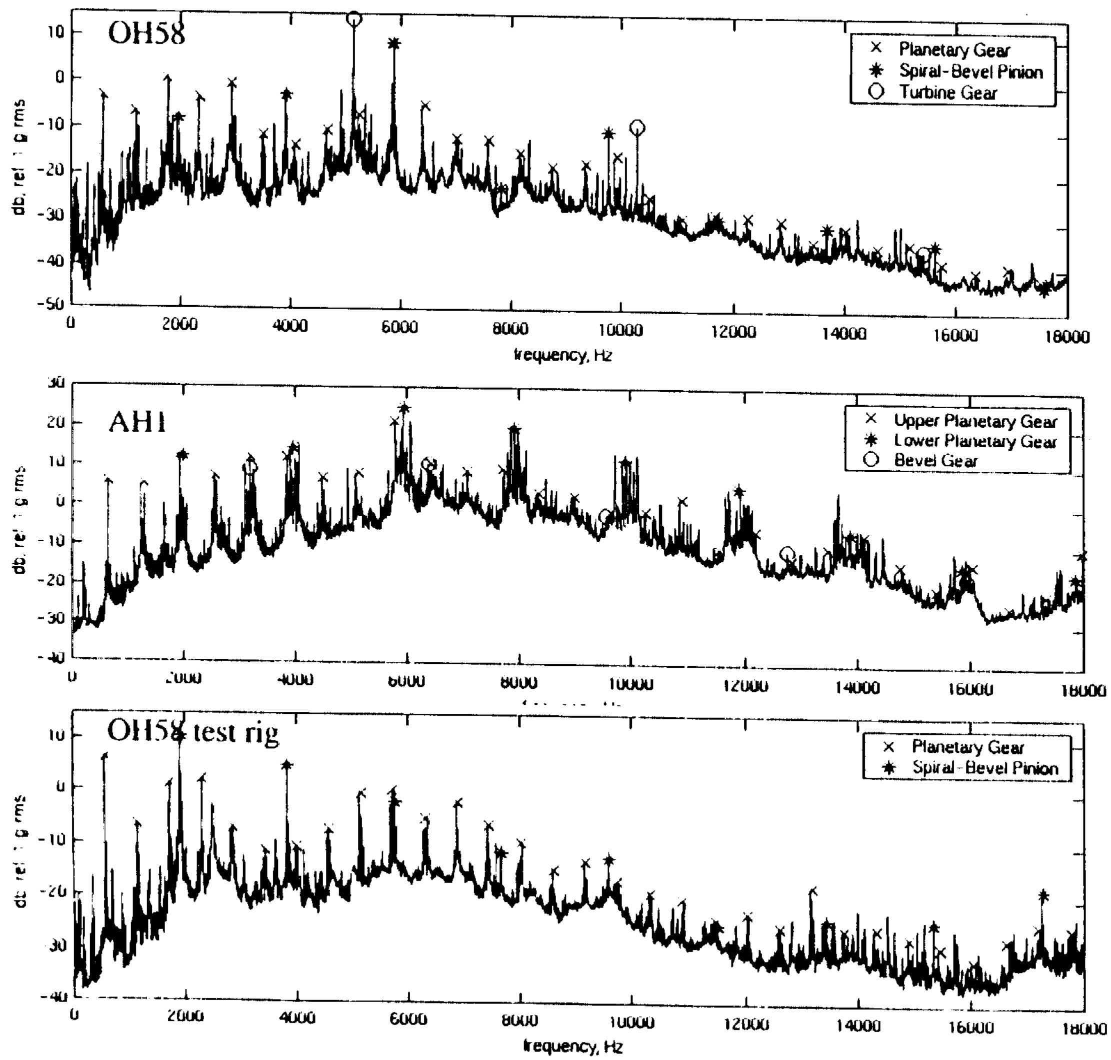

- Compare two aircraft
- Compare aircraft and test rig
- Extract expected frequencies
- Determine extraneous frequencies
- Analyze residual for unpredicted changes
- Develop signal learning algorithms for different maneuvering and regime states

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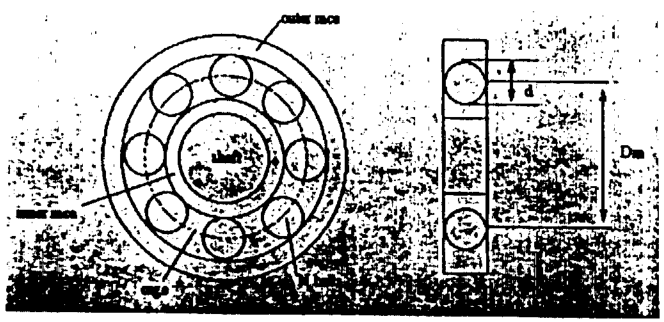
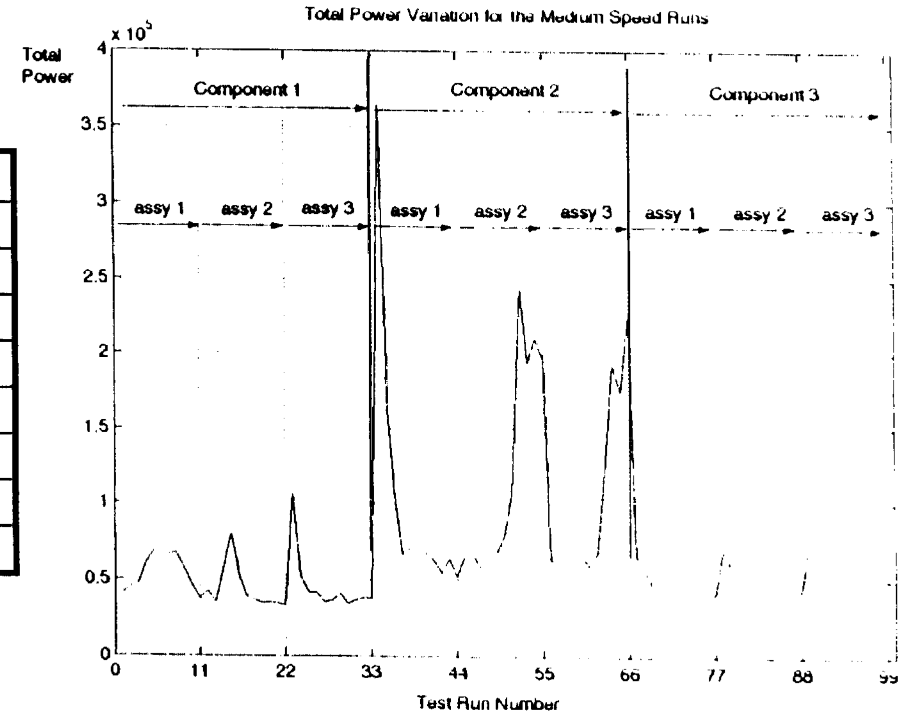


Fshaft	Fouter	Finner	Fball Fcage
30	89.93 x K	150.1 x K, 30	112.2 x K, 11.24
45	134.9 x K	225.1 x K, 45	168.3 x K, 16.86
80	239.8 x K	400.2 x K, 80	299.3 x K, 29.98

Source	SS	F	Sig.
Intercept	37221.74	4047.49	.000
Speed	454.17	101.34	.001
Assy	.807	1.43	.510
Component	18.22	4.15	.117
Sp*Assy	1.46	.90	.505
Sp*Comp	9.12	5.62	.019
Assy*Comp	1.27	.78	.565
Sp*Assy*Comp	3.24	3.19	.002



Information Technology

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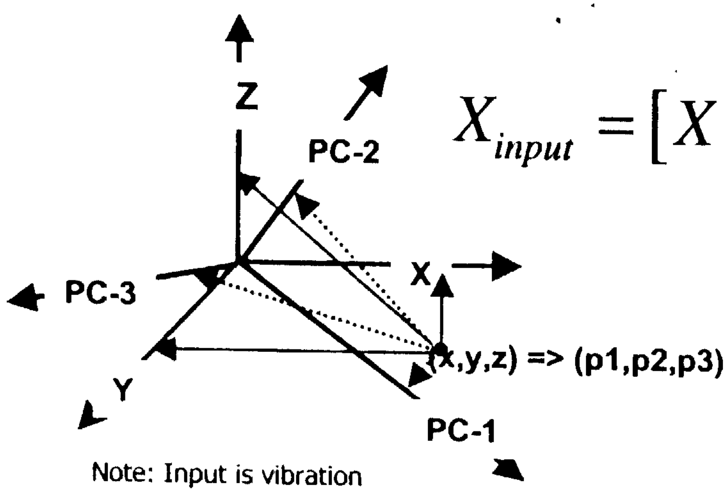
- **Typical vibration monitoring via single-axis accelerometers, mounted radially**
- **Machinery vibrate in all three directions:**
  - Are some directions more appropriate for certain types of faults?
  - Are there "less-favorable" directions for monitoring & detection?
- **Explore sensor locations and directionality:**
  - Triaxial accelerometers
  - Multiple locations
- **Develop metrics using triaxial data:**
  - PCA decomposition and angles
  - Time-domain monitoring metrics
- **Develop requirements for "optimal monitoring"**



Note: Input is vibration data in three directions, OH58 flight tests, TSP data, n=512, flight 1, file 4, maneuver FFLS

$$X_{input} = \begin{bmatrix} X & Y & Z \end{bmatrix}$$

$$LAT = \begin{bmatrix} 365.16 \\ 40.96 \\ 14.83 \end{bmatrix} \longleftarrow \text{86.8\% of variance}$$

$$PC = \begin{bmatrix} \boxed{\begin{matrix} 0.1324 \\ 0.9680 \\ -0.2133 \end{matrix}} & \begin{matrix} -0.9142 \\ 0.2024 \\ 0.3510 \end{matrix} & \begin{matrix} -0.3830 \\ -0.1486 \\ -0.9117 \end{matrix} \end{bmatrix}$$

$$SC_1 = 0.1324 \cdot X + 0.9680 \cdot Y - 0.2133 \cdot Z$$

$$\begin{cases} \theta = \arctan(pc(2,1) / pc(1,1)) \cdot 180 / \pi \\ \alpha = \arctan(pc(3,1) / pc(1,1)) \cdot 180 / \pi \end{cases}$$

- Find max variance axis
- Map vibration onto PC
- Compute angles of PC
- Directionality analysis
- Monitoring metric
- See ASME/DETC paper for case study

KL Decomposition:

Characteristic eigenvector equation: $\Sigma_X \times V = V \times D$

Orthonormality condition: $V^T \times V = I$

Eigenvalues and eigenvectors:

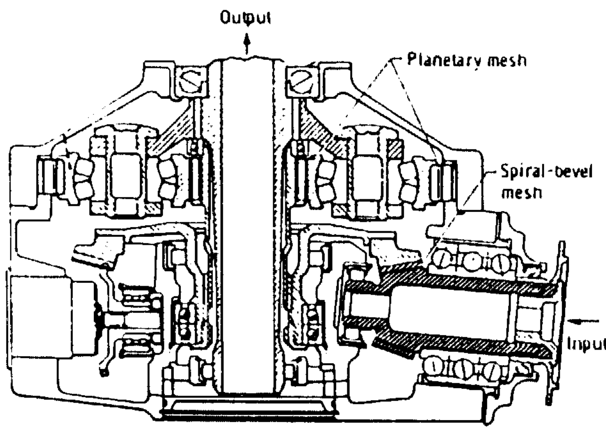
$$D = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \qquad V = \begin{bmatrix} V_1 & V_2 & \cdots & V_n \end{bmatrix}$$

Variance Decomposition:

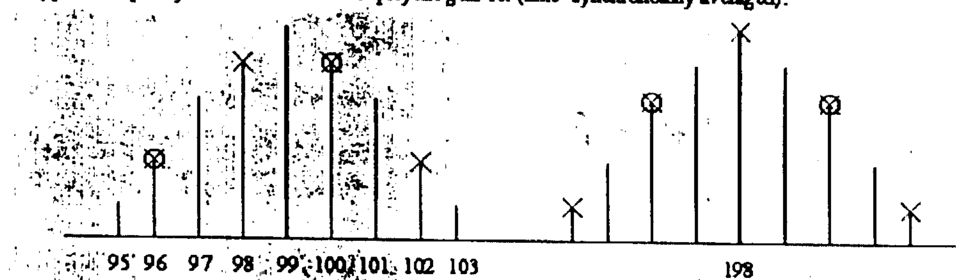
$$MS = (RMS)^2 = \sigma^2 = \sum_{i=1}^{N/2} P_i = \sum_{i=1}^{N/2} \sigma_i^2$$

$$\sigma_{Source}^2 = \sum_{i \ni Source} P_i = \sum_{i \ni Source} \sigma_i^2 \qquad df_{Source} = 2 \sum_{i \ni Source} df_i$$

- **Pre-production variations:**
  - Can be traced back to design and production stages
  - Can be propagated and modeled to determine effect of product quality
  - Potential effect on performance of monitoring systems ignored at the design stage
- **Research question:**
  - Is there a correlation between design variations and performance parameters?
- **Proposed work:**
  - Determine and model variation sources in machinery during design
  - Propagate effect to vibrations and health in machinery's operating state
  - Provide designers with predictive models as a design-aid tool
  - Pre-knowledge will enable the monitoring algorithms to have the correct modeling assumptions
  - Develop analytical tool for Design for Monitoring
  - See example: planetary gear tolerances



Typical Frequency Distribution from an epicyclic gear set (time-synchronously averaged):



Black: a single planet gear (ideal) —> planet gear with 99 teeth, sidebands, and harmonics

Red: 2 sets of equally spaced planets ... multiples of 2

Blue: 4 equally spaced planets ...

The variation in the spacing of planetary gears in an epicyclic gear system for the OH58 transmission results in the incorrect identification of the frequency components, hence causing potential false alarms during health and safety monitoring. A pre-knowledge of this effect will help eliminate this potential source of false alarm.

- **Common failure modes:**
  - Most are manifestations of physical changes, component design attributes, material, and production process
  - Can be avoided at the early stages of design if accounted for
- **Failure prevention:**
  - No methods for accurate and reliable information to designers
- **Research question:**
  - Is there a correlation between functionality of components and the elemental failure modes?
- **Proposed work:**
  - Gather accident and failure reports to extract elemental failure modes
  - Study design specifications to determine elemental functionality
  - Develop analytical method to determine tradeoffs
  - Develop analytical method to determine commonalities for design/redesign
  - Provide as a tool for Design for Monitoring
  - See example: rotating machinery test rig components

$$CF = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 \end{bmatrix} \qquad EC = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

C1=gear
C2=bearing
C3=shaft

F1=wear
F2=fatigue
F3=corrosion
F4=fretting
F5=impact

E1=change ME
E2=guide ME
E3=transfer ME
E4=position ME
E5=stabilize ME

$$PC = \begin{bmatrix} \boxed{\begin{matrix} .39 \\ -.47 \\ .47 \\ .39 \\ -.47 \end{matrix}} & \begin{matrix} -.58 \\ -.32 \\ .32 \\ -.58 \\ -.32 \end{matrix} & \begin{matrix} .04 \\ -.57 \\ -.78 \\ -.04 \\ -.21 \end{matrix} & \begin{matrix} .70 \\ .03 \\ .04 \\ -.70 \\ .01 \end{matrix} & \begin{matrix} .00 \\ -.57 \\ .20 \\ .00 \\ .78 \end{matrix} \end{bmatrix} \qquad SC = \begin{bmatrix} \boxed{\begin{matrix} -0.21 \\ 1.22 \\ -1.00 \end{matrix}} & \begin{matrix} -0.71 \\ 0.25 \\ 0.46 \end{matrix} & \begin{matrix} 0.00 \\ 0.00 \\ 0.00 \end{matrix} & \begin{matrix} 0.00 \\ 0.00 \\ 0.00 \end{matrix} & \begin{matrix} 0.00 \\ 0.00 \\ 0.00 \end{matrix} \end{bmatrix}$$

$$LAT = \begin{bmatrix} 1.27 \\ 0.39 \\ 0.00 \end{bmatrix}$$

76.46% of variance in 1st PC

Pc1= .39 F1 - .47 F2 +.47 F3 + .39 F4 - .47 F5

Shows significance of
effect of each failure mode on the 1st PC

Sc1= -.21 C1 + 1.22 C2 - 1.00 C3

1st PC has the most effect on component 3

Function-Failure Matrix:

$$\begin{array}{c} \text{Fi} \longrightarrow \qquad \text{Ei} \downarrow \\ EF = EC \times CF = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 2 & 0 & 1 & 2 \\ 1 & 2 & 0 & 1 & 2 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 \end{bmatrix} \end{array}$$

Failures F2 & F5 occur more frequently for functions E2 & E3

Functions E2 & E3 experience same failure modes

Functions E4 & E5 experience same failure modes

Component-Failure Similarity Matrix:

$$\Lambda_{CF} = CF \times CF^T = \begin{bmatrix} 4 & 2 & 2 \\ 2 & 3 & 0 \\ 2 & 0 & 2 \end{bmatrix}$$

C1 shares 2 common failures modes with C2 & C3

C2 & C3 share no common failure modes

Diagonal gives the count of failure modes per component

$$\Lambda_{FC} = CF^T \times CF = \begin{bmatrix} 2 & 1 & 1 & 2 & 1 \\ 1 & 2 & 0 & 1 & 2 \\ 1 & 0 & 1 & 1 & 0 \\ 2 & 1 & 1 & 2 & 1 \\ 1 & 2 & 0 & 1 & 2 \end{bmatrix}$$

Etc...similar uses with EC and FC...

- **Develop a more complete understanding of issues related to health monitoring of C-17 engines**
- **Use research results and insight to propose a Design for Monitoring methodology for more reliable and cost effective health monitoring**
- **Immediate tasks:**
  - Study of engineering details
  - Installation of triaxial accelerometer for first flight tests
  - Analysis of preliminary data for gear and bearing component frequencies
  - Development and installation of data collection system
- **Long-term tasks:**
  - Analysis, modeling, false alarm evaluation, etc. (see previous slides)
  - Development of Design for Monitoring method