Experimental Investigation of a Fullspan Tiltrotor Model with Higher-Harmonic Vibration Control

David J. Piatak
Aerospace Engineer
NASA Langley Research Center
Hampton, VA

Donald L. Kunz
Associate Professor
Department of Aerospace Engineering
Old Dominion University
Norfolk, VA

Presented at the Eighth ARO Workshop on Aeroelasticity of Rotorcraft Systems, October 17-20, 1999, State College, Pennsylvania

Experimental Investigation of a Fullspan Tiltrotor Model with Higher-Harmonic Vibration Control

David J. Piatak
Aerospace Engineer
NASA Langley Research Center
Hampton, VA

Donald L. Kunz
Associate Professor
Department of Aerospace Engineering
Old Dominion University
Norfolk, VA

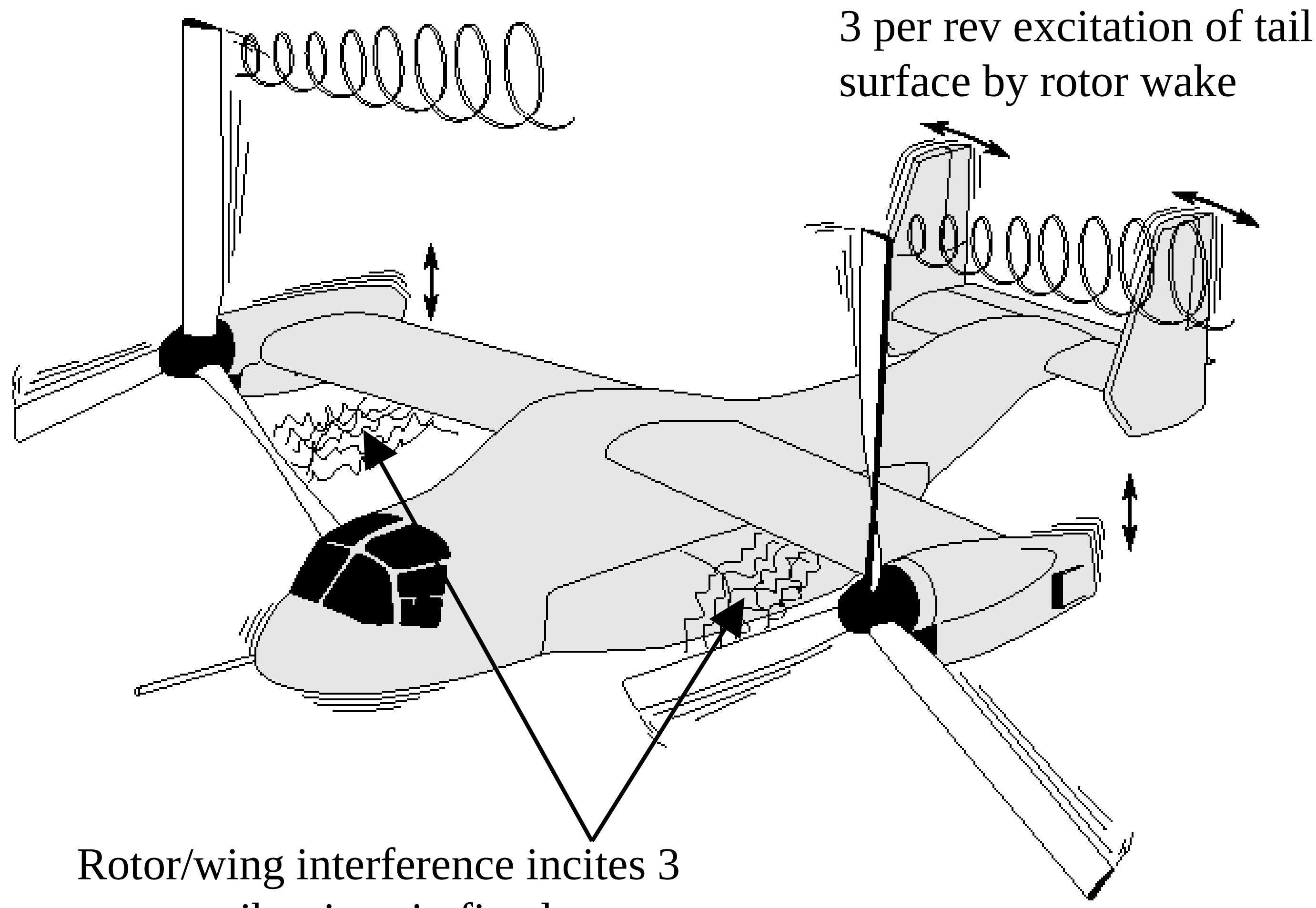
Abstract

The performance of a higher harmonic control system called the Multipoint Adaptive Vibration Suppression System (MAVSS) at reducing 3/rev wing vibratory loads and fuselage vibrations on a dynamically-scaled, fullspan, tiltrotor model is presented. Previous wind tunnel tests on a semispan aeroelastic tiltrotor model have demonstrated the effectiveness of MAVSS for reducing wing vibratory loads using both an active flaperon and swashplate. The primary goal, however, of such a vibration suppression system is to reduce tiltrotor fuselage vibrations in order to improve passenger comfort. The present study addresses the reduction of both wing and fuselage vibrations using simulated MAVSS active flaperons on a 1/10-scale dynamic tiltrotor model designed to be representative of a tiltrotor configuration. Also, this study attempts to identify possible problems that may impede the application of MAVSS flaperon control forces for the purpose of tiltrotor vibration reduction in the presence of fullspan symmetric and antisymmetric wing modes of vibration. Electromagnetic shakers applied simulated 3/rev vibratory hub loads and higher harmonic control forces, simulating active flaperons, to the tiltrotor model. MAVSS flaperon control forces are shown to be effective at reducing wing vibratory loads or fuselage vertical accelerations, but not as effective at reducing wing loads and fuselage vibrations simultaneously. Vibration reduction trends are shown to be a function of the simulated rotor speed for the fullspan configuration. These results suggest that the application of MAVSS-controlled flaperons to a tiltrotor configuration may prove to be difficult due to elevated wing vibratory loads during reduction of fuselage vibrations and because wing vibratory loads and fuselage vibrations cannot be reduced simultaneously.

Presentation Outline

- Background and motivation
- Higher harmonic control system
- Tiltrotor dynamic model
- Results
- Conclusions

Tiltrotor Vibratory Environment



Vibration Reduction Solutions

- Passive Vibration Reduction
  - Tuned vibration absorber
  - Pendulum absorber
  - Passive systems account for nearly 410lbs on V-22
- Higher Harmonic Control
  - Relies on superposition of vibratory loads
  - Vibratory control loads from control surfaces
  - Frequency domain based system
  - Has been successfully demonstrated on several model and full scale rotorcraft applications
  - Hammond, Wood, et. al.; Straub and Byrns (OH-6A); Westland Helicopters and Moog (ACSR); Nixon, Settle, Kvaternik (MAVSS/V-22)

MAVSS/WRATS

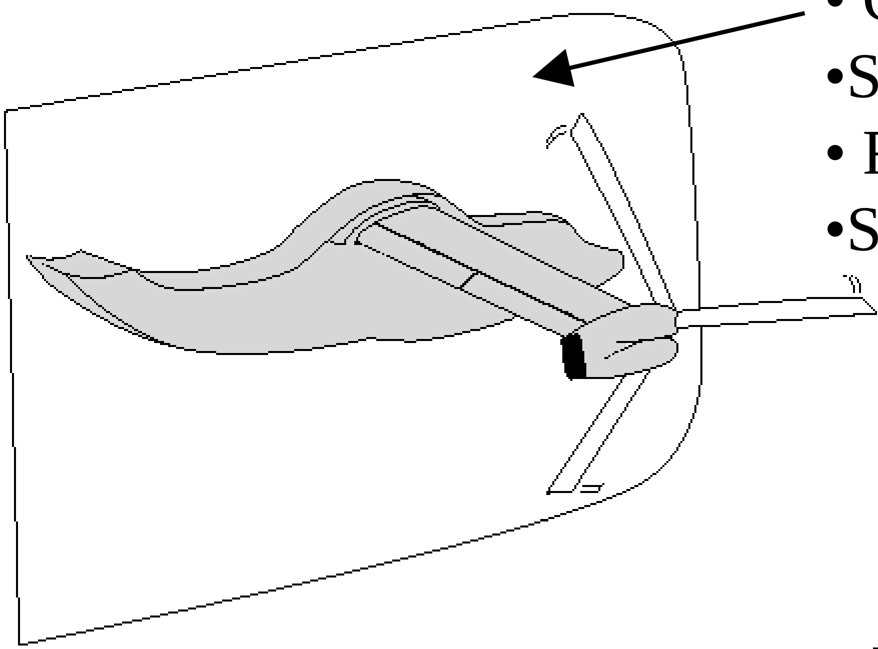
- The Multipoint Adaptive Vibration Suppression System (MAVSS) successfully demonstrated on semispan Wing and Rotor Aeroelastic Test System (WRATS) at Transonic Dynamics Tunnel (TDT)

• Successful wing vibratory loads reduction using active flaperon and active swashplate

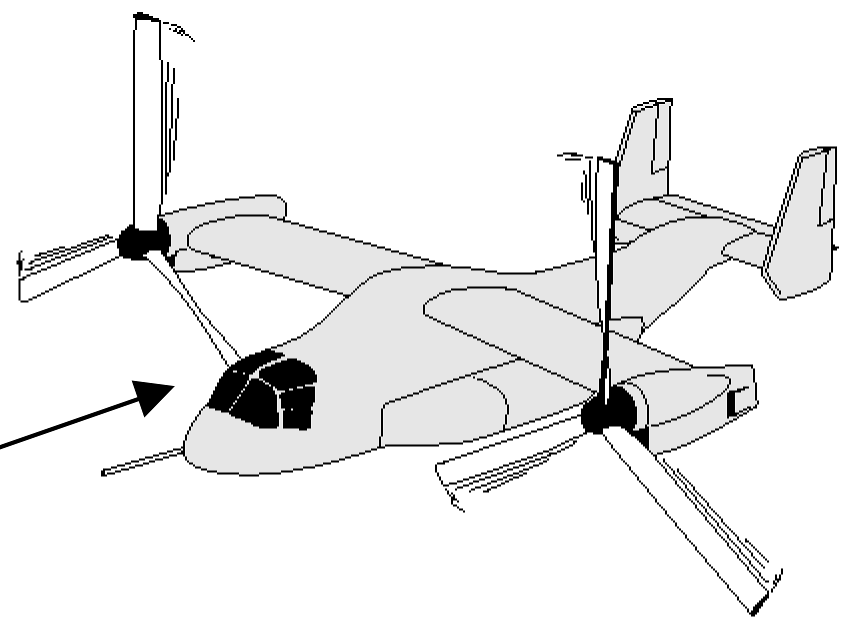
• Assumed wing vibratory loads reduction corresponds to reduced fuselage vibrations

(Nixon, Kvaternik, Settle et. al.)

Semi-span WRATS vs. Full-span V-22



- Cantilevered boundary condition
- Simple modes of vibration
- Rigid fuselage fairing
- Single MAVSS flaperon



- Fuselage boundary condition
- Fullspan modes of vibration
- Flexible fuselage
- Two MAVSS flaperons

Objectives

- Demonstrate effectiveness of MAVSS on a fullspan 1/10 scale dynamic tiltrotor model using active flaperon control forces
- Address fullspan effects of MAVSS controllability
- Address MAVSS effectiveness for reduction of fuselage vibrations

Presentation Outline

- Background and motivation
- Higher harmonic control system
- Tiltrotor dynamic model
- Results
- Conclusions

The Multipoint Adaptive Vibration Suppression System (MAVSS)

- Developed by Bell Helicopter and successfully tested on V-22 aeroelastic model using active flaperon and swashplate
- HHC system which relies on the superposition of vibratory loads to minimize unwanted vibrations
- MAVSS assumes a linear relationship between vibratory response and control inputs
- MAVSS responses and control inputs in the form of harmonic amplitudes determined at multiples of rotor speed

MAVSS Response Vector

- MAVSS responses are periodic in nature (Fourier series)
- The MAVSS response vector is comprised of harmonic analysis amplitudes
- There are *M* number of response points

$$\{z\} = \begin{Bmatrix} Z_{ic} \\ Z_{is} \end{Bmatrix} \quad 2M \text{ x } 1$$

where

$$\{Z_{ic}\}_n = \left\{ \frac{2}{K} \sum_{k=1}^{K_s} z_i(k\Delta\psi)\cos(nk\Delta\psi) \right\}$$
$$\{Z_{is}\}_n = \left\{ \frac{2}{K} \sum_{k=1}^{K_s} z_i(k\Delta\psi)\sin(nk\Delta\psi) \right\} \qquad i=1, M$$

MAVSS Control Vector

- The MAVSS control vector is comprised of harmonic amplitudes of the periodic control forces
- There are *N* control points

$$\{\theta\} = \begin{Bmatrix} \Theta_{jc} \\ \Theta_{js} \end{Bmatrix} \quad 2N \text{ x } 1$$

- jth periodic control force is written as

$$\Theta_j(\psi) = \{\Theta_{jc}\}_n \cos(n\psi) + \{\Theta_{js}\}_n \sin(n\psi)$$

- Superposition of several harmonic amplitudes can be used to control several response harmonics

MAVSS System Identification

- Changes in response harmonic amplitudes are linearly proportional to control inputs

$$\{\Delta z\} = [T]\{\Delta\theta\}$$

- Small test signal applied to each control point
- Changes in control and response vectors are

$$\begin{Bmatrix} \Delta\theta_{jc} \\ \Delta\theta_{js} \end{Bmatrix} = \begin{Bmatrix} \theta_{jc} \\ \theta_{js} \end{Bmatrix}_{test} - \begin{Bmatrix} \theta_{jc} \\ \theta_{js} \end{Bmatrix}_{base} \qquad \begin{Bmatrix} \Delta Z_{ic} \\ \Delta Z_{is} \end{Bmatrix} = \begin{Bmatrix} Z_{ic} \\ Z_{is} \end{Bmatrix}_{test} - \begin{Bmatrix} Z_{ic} \\ Z_{is} \end{Bmatrix}_{base}$$

MAVSS System Identification

- Once changes in each response point due to each control point are known, sensitivities are determined (numerical derivatives)

$$\begin{Bmatrix} \dfrac{\Delta Z_{ic}}{\Delta \Theta_{jc}} \\ \dfrac{\Delta Z_{is}}{\Delta \Theta_{jc}} \end{Bmatrix} \quad \text{and} \quad \begin{Bmatrix} \dfrac{\Delta Z_{ic}}{\Delta \Theta_{js}} \\ \dfrac{\Delta Z_{is}}{\Delta \Theta_{js}} \end{Bmatrix} \quad i=1, M$$

- Linear relationship between response and control

$$\begin{Bmatrix} \Delta Z_{ic} \\ \Delta Z_{is} \end{Bmatrix} = \begin{bmatrix} \dfrac{\Delta Z_{ic}}{\Delta \Theta_{jc}} & \dfrac{\Delta Z_{ic}}{\Delta \Theta_{js}} \\ \dfrac{\Delta Z_{is}}{\Delta \Theta_{jc}} & \dfrac{\Delta Z_{is}}{\Delta \Theta_{js}} \end{bmatrix} \begin{Bmatrix} \Delta \Theta_{jc} \\ \Delta \Theta_{js} \end{Bmatrix} \quad i=1, M \text{ and } j=1, N$$

Scalar Objective Function

- Optimum arrangement, $M=N$
- Practical application calls for $M>N$
- Scalar objective function or performance index

$$J = z_k^T R_{kk} z_k + \theta_l^T Q_{ll} \theta_l \qquad \begin{array}{l} k = 1 \text{ to } 2M \\ l = 1 \text{ to } 2N \end{array}$$

- Diagonal weighing matrices

$$R_{kk} = \frac{1}{\left[(z_{\max})_k \right]^2} \qquad Q_{ll} = \frac{1}{\left[(\theta_{\max})_l \right]^2}$$

Control Law Calculation

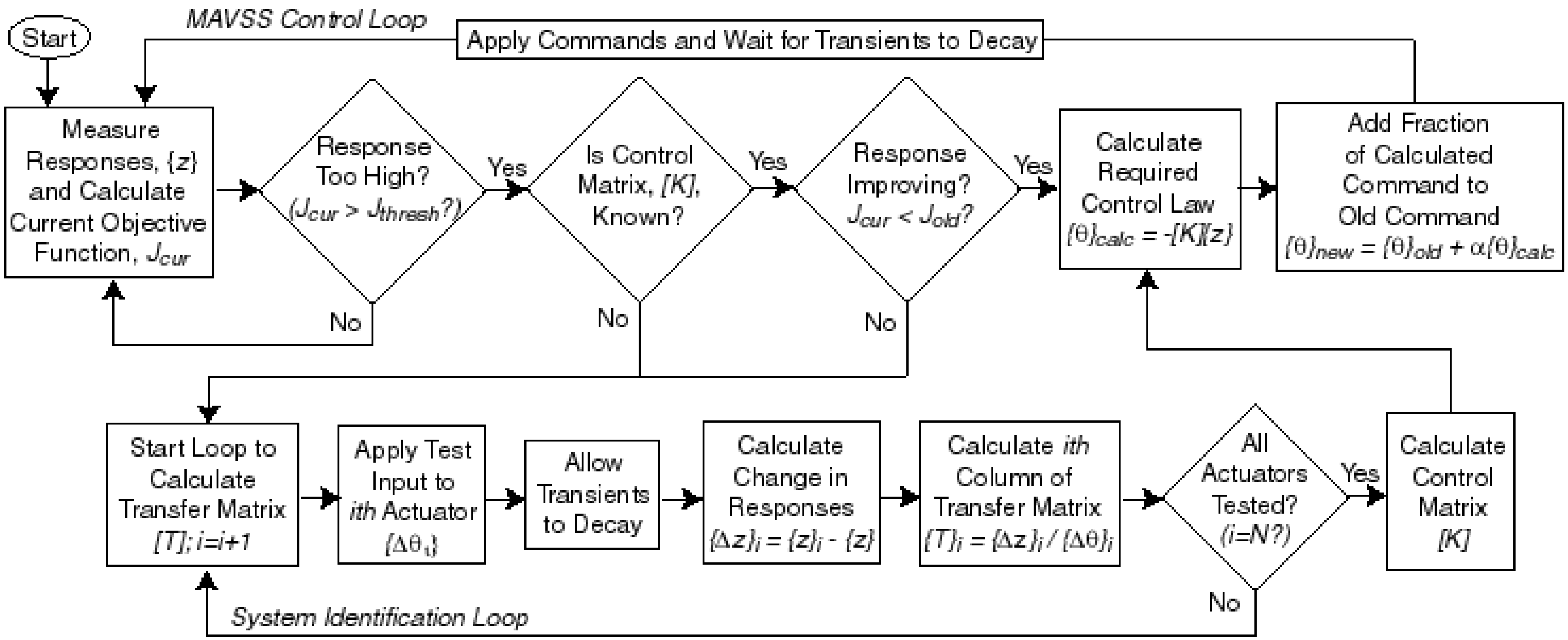
- Change in response due to control: $\Delta z = z_{con} - z_{base}$
- Linear change in response: $\Delta z_k = T_{kl}\theta_l$
- Quantity to be reduced: $z_{con} = \Delta z + z_{base} = T_{kl}\theta_l + (z_{base})_k$
- Scalar objective function: $J = (z_{con})_k^T R_{kk} (z_{con})_k + \theta_l^T Q_{ll}\theta_l$
- We wish to minimize the objective function

$$J = \left[T_{kl}\theta_l + (z_{base})_k\right]^T R_{kk}\left[T_{kl}\theta_l + (z_{base})_k\right] + \theta_l^T Q_{ll}\theta_l$$

$$\left(\frac{\partial J}{\partial \theta}\right)_l = T_{kl}^T R_{kk} T_{kl}\theta_l + T_{kl}^T R_{kk}(z_{base})_k + Q_{ll}\theta_l = 0$$

$$\theta_l = -\left[T_{kl}^T R_{kk} T_{kl} + Q_{ll}\right]^{-1}\left[T_{kl}^T R_{kk}(z_{base})_k\right]$$

MAVSS Iterative Control Loop



Implemented on a PC using Labview and National Instruments A/D and D/A boards

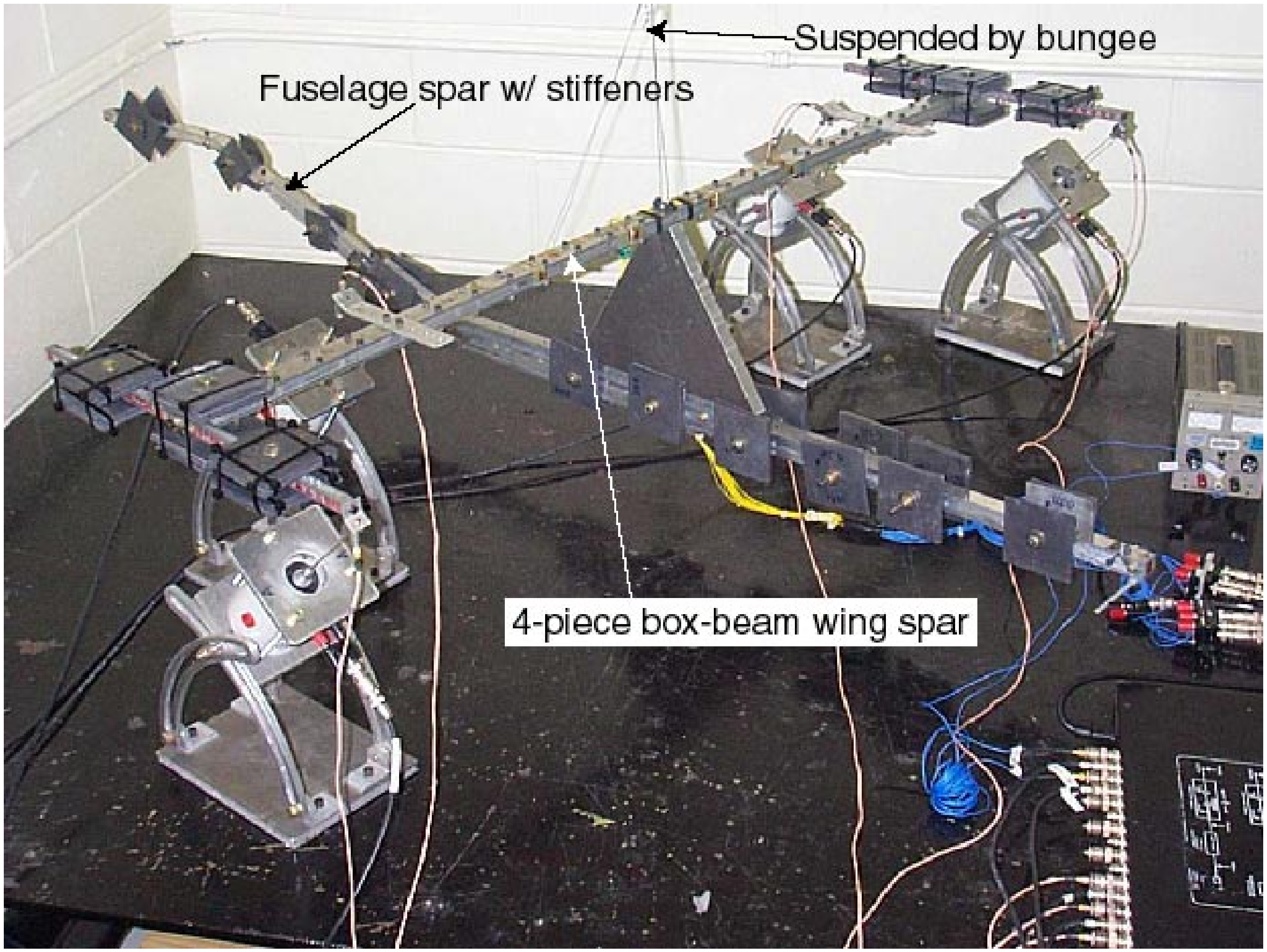
Presentation Outline

- Background and motivation
- Higher harmonic control system
- Tiltrotor dynamic model (AViRTTS)
- Results
- Conclusions

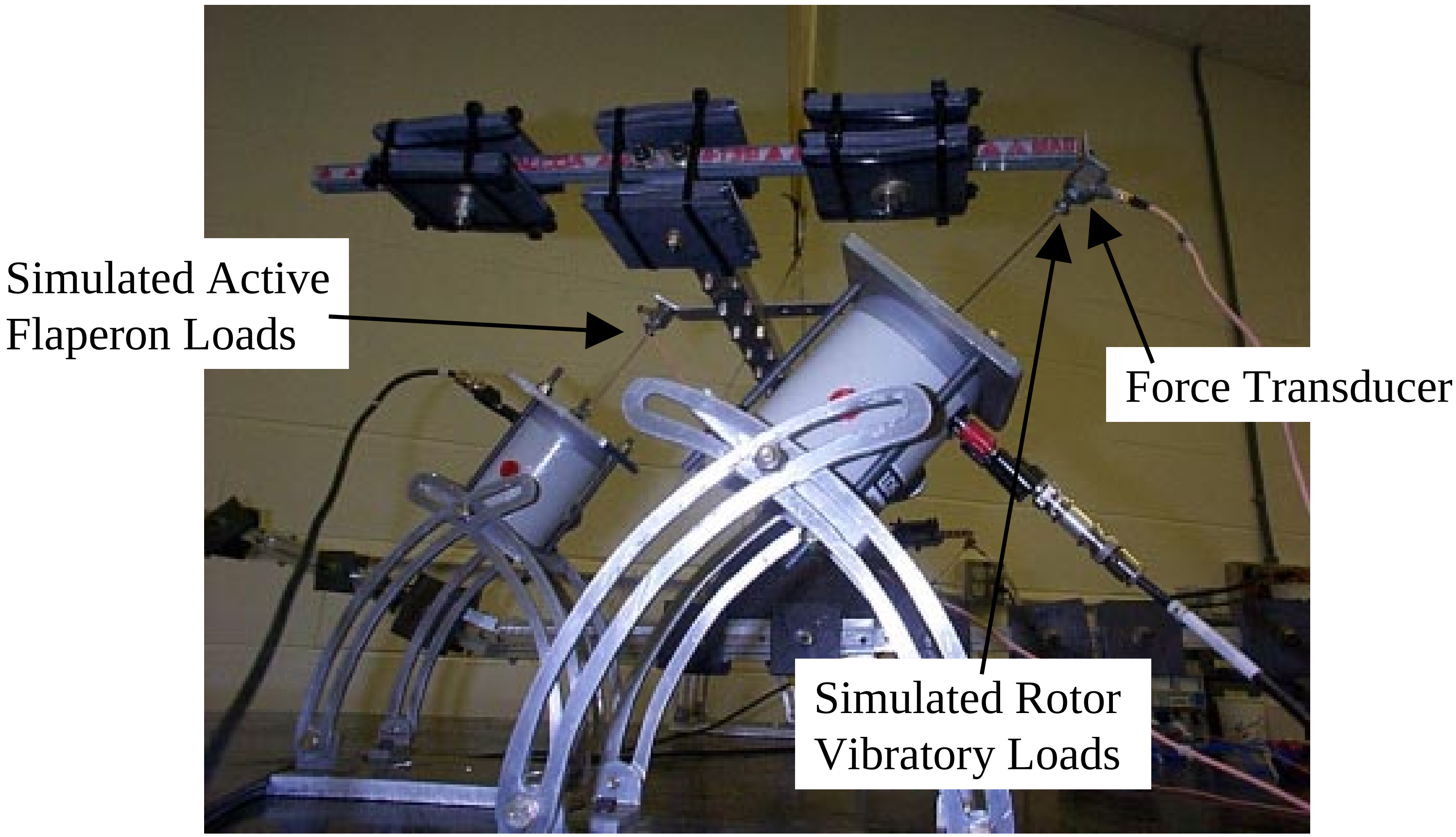
AViRTTS Model

- **A**ctive **Vi**bration **R**eduction for **T**iltrotors **T**est **S**ystem
- 1/10 Froude-scaled dynamic model
- Scaled fuselage and wing spar properties based on V-22 fullspan aeroelastic model (this later became the WRATS model)
- Simple construction using NASA stock materials
- Instrumented with wing spar strain gages for wing vibratory load responses and accelerometers for fuselage vibration
- Simulated rotor loads and control forces supplied by electromagnetic shakers

Fullspan AViRTTS Model



Electromagnetic Shaker



AViRTTS Ground Vibration Test

- Ground Vibration Test (GVT) performed
- Used electromagnetic shakers to randomly excite the model
- IDEAS modal analysis

Fullspan AViRTTS GVT Results

Mode Description	Frequency, Hz
Symmetric wing beam	9.22 (3.4%)
Symmetric wing chord	14.30 (2.5%)
Symmetric wing torsion	16.18 (1.8%)
Antisymmetric wing torsion	17.39
Antisymmetric wing beam	20.45
Fuselage vertical	24.23 (0.04%)
Fuselage lateral	28.03 (-11.7%)
2nd fuselage vertical	38.84
2nd fuselage lateral	42.39
2nd antisymmetric wing chord	49.88
2nd symmetric wing chord	55.37
Lateral pylon	62.87
Antisymmetric vertical pylon	81.81
Symmetric vertical pylon	86.70
3rd fuselage vertical	88.12

Presentation Outline

- Background and motivation
- Higher harmonic control system
- Tiltrotor dynamic model (AViRTTS)
- Results
  - Semispan AViRTTS vs WRATS loads
  - Fullspan results
- Conclusions

Hub Shear Loads

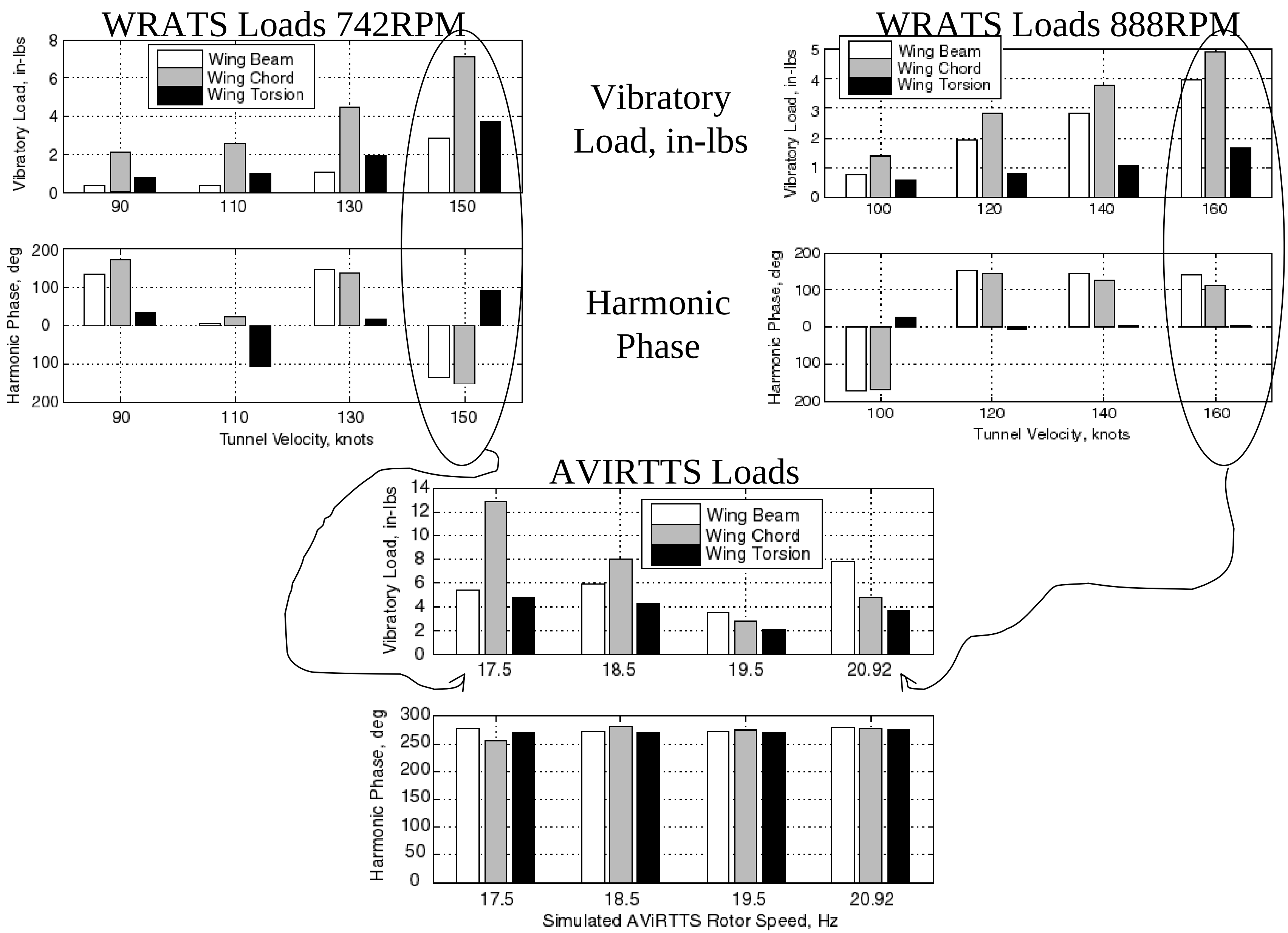
- Applied at 45 degree angle w/ respect to pylon tip
- Max shaker output force (4 lbf)
- Test results presented for four simulated rotor speeds

742 RPM

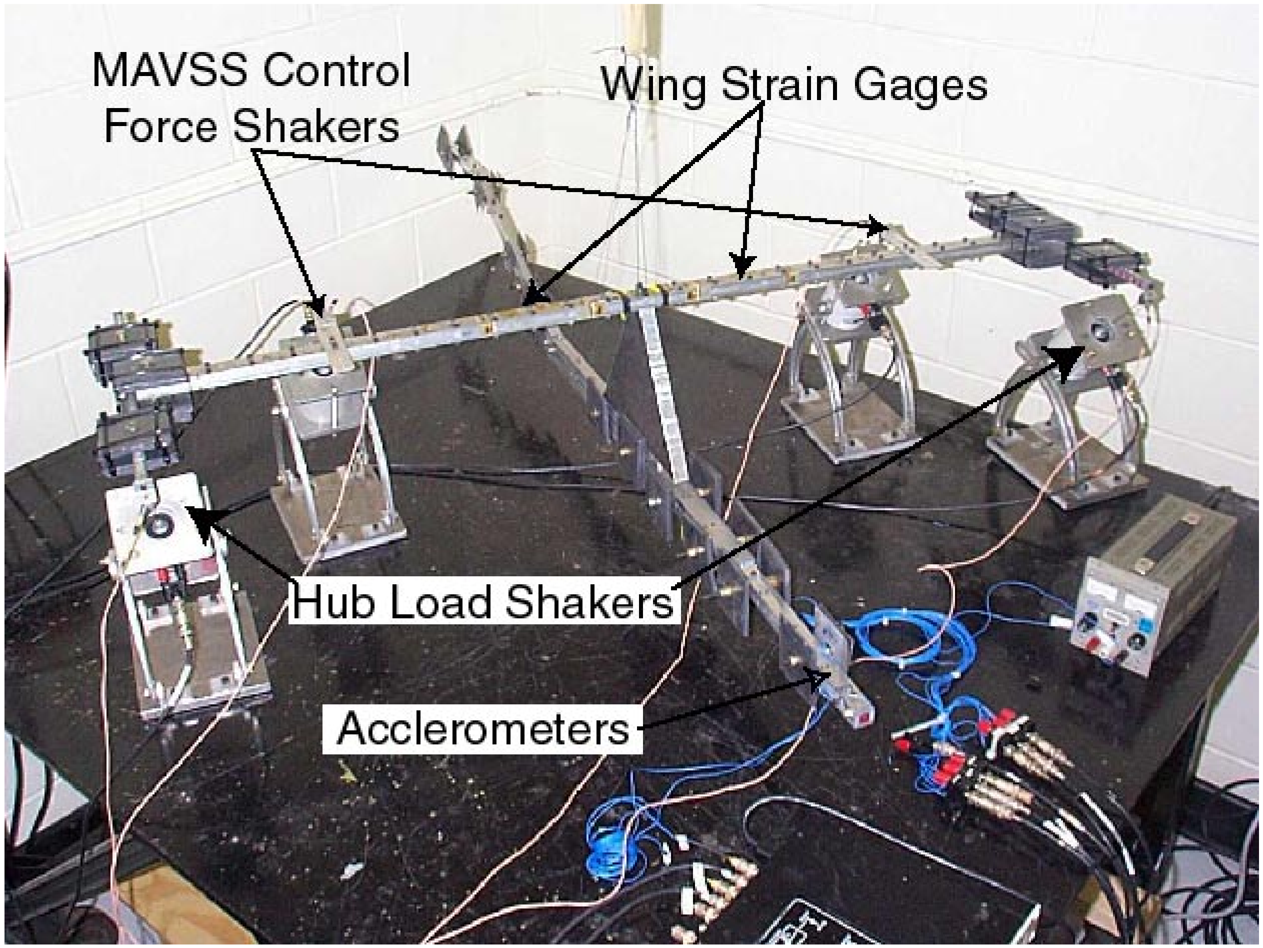
	1P Frequency	3P Frequency
Scaled cruise rotor speed	17.5 Hz	52.5 Hz
	18.5 Hz	55.5 Hz
	19.5 Hz	58.5 Hz
Scaled hover rotor speed	20.92 Hz	62.76 Hz

888 RPM

Semispan AViRTTS/WRATS Loads



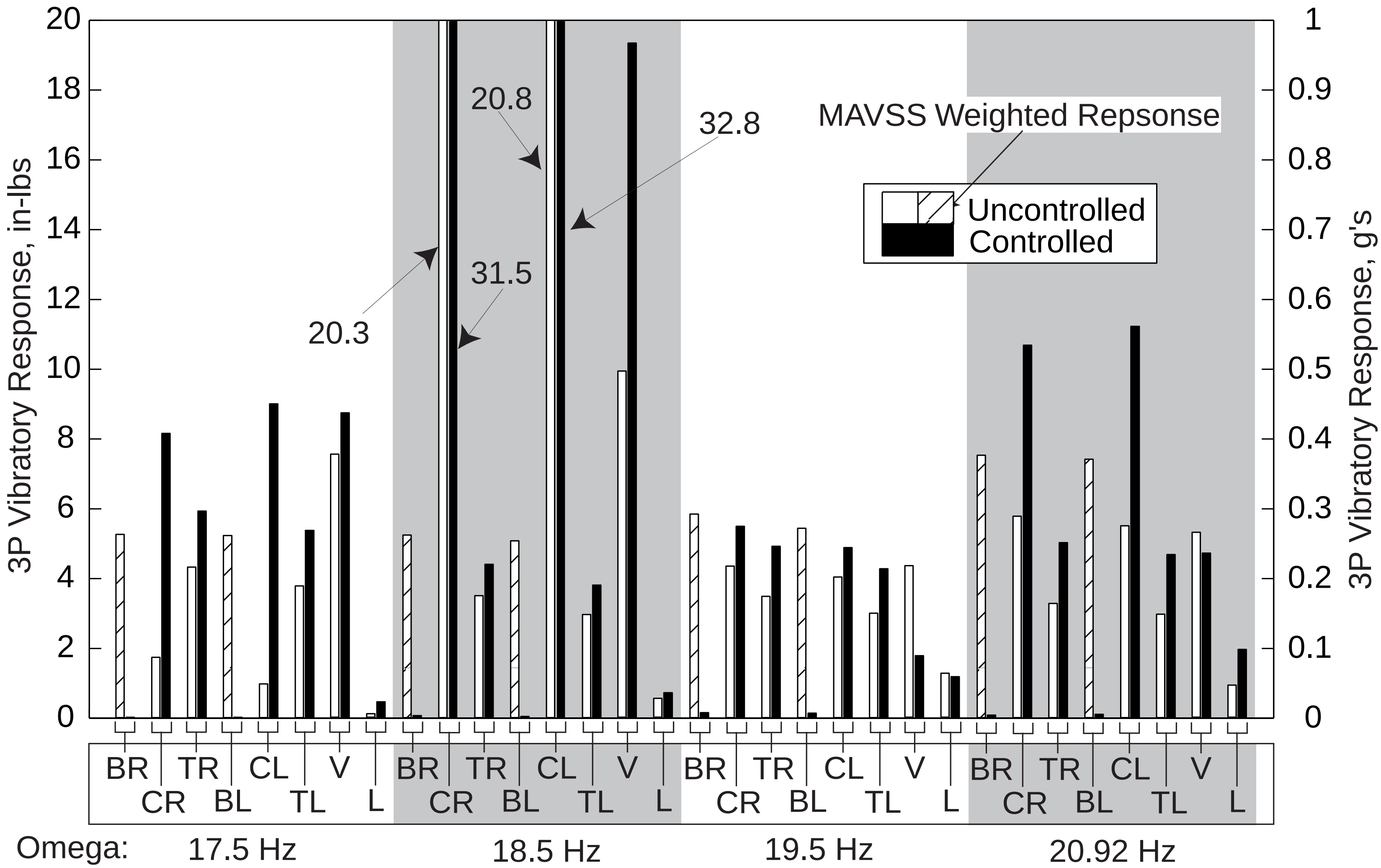
Fullspan AViRTTS Test Setup



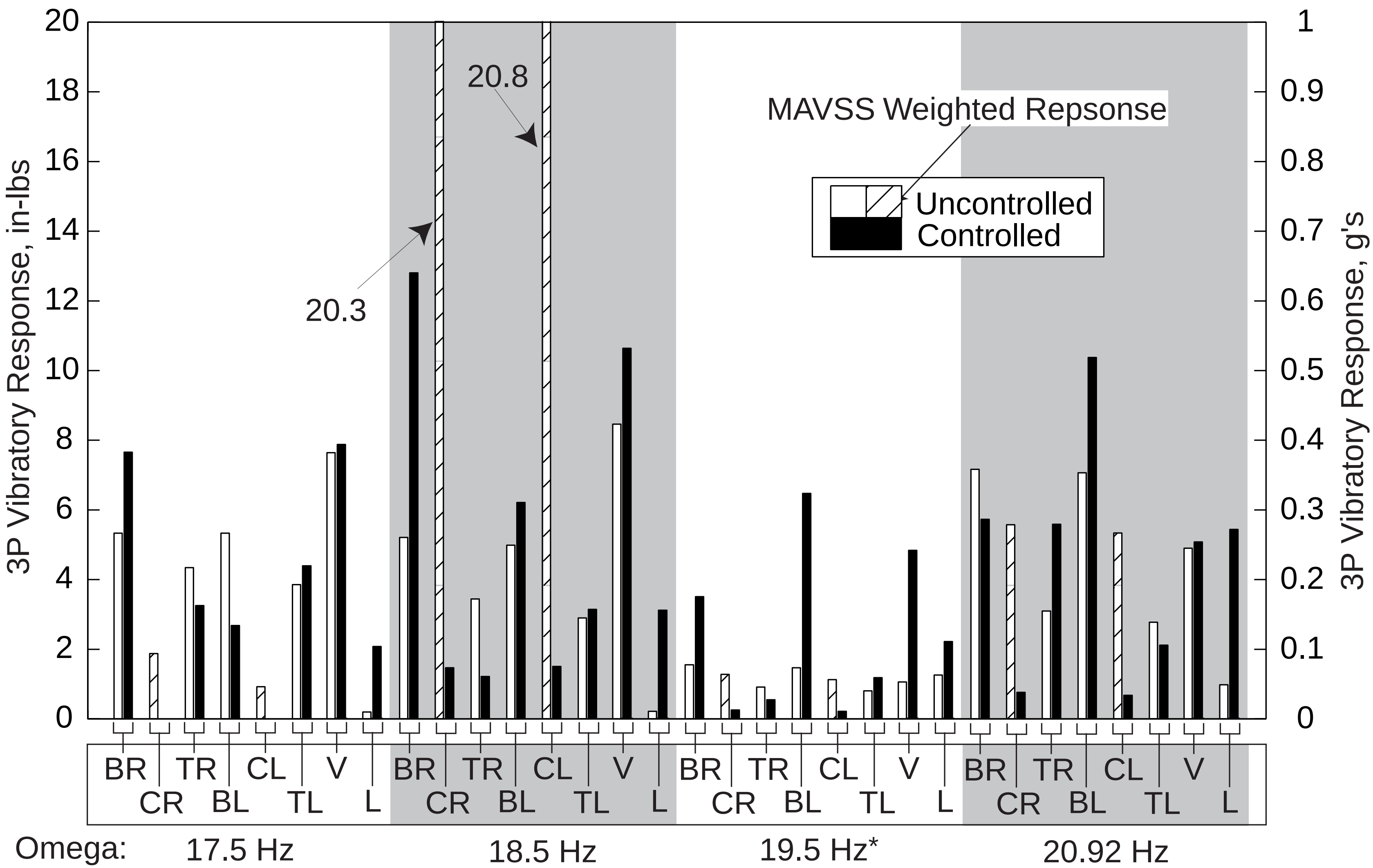
Presentation Outline

- Background and motivation
- Higher harmonic control system
- Tiltrotor dynamic model (AViRTTS)
- Results
  - Semispan AViRTTS vs WRATS loads
  - Fullspan results
- Conclusions

Wing Beam Weighted Objective Function

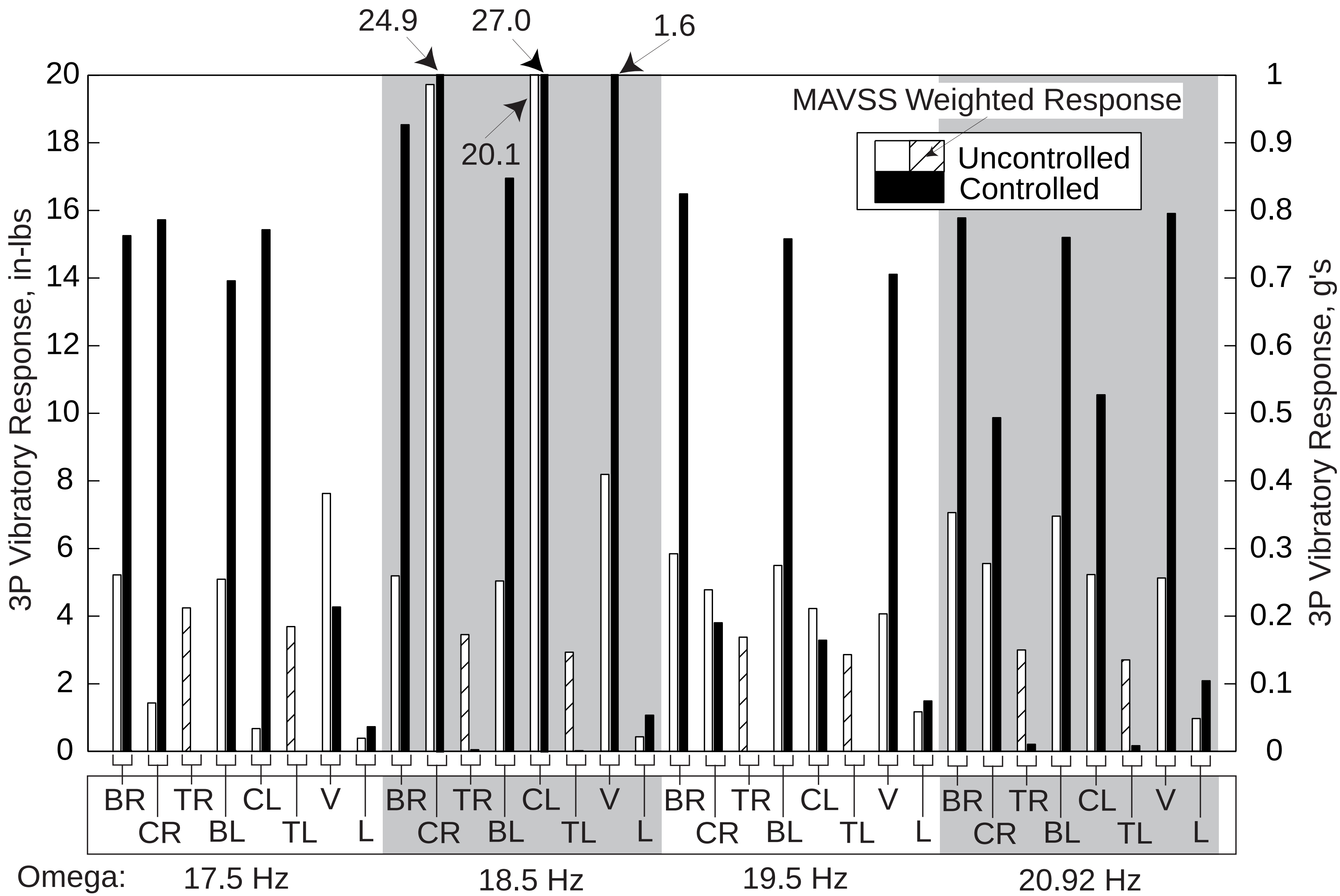


Wing Chord Weighted Objective Function

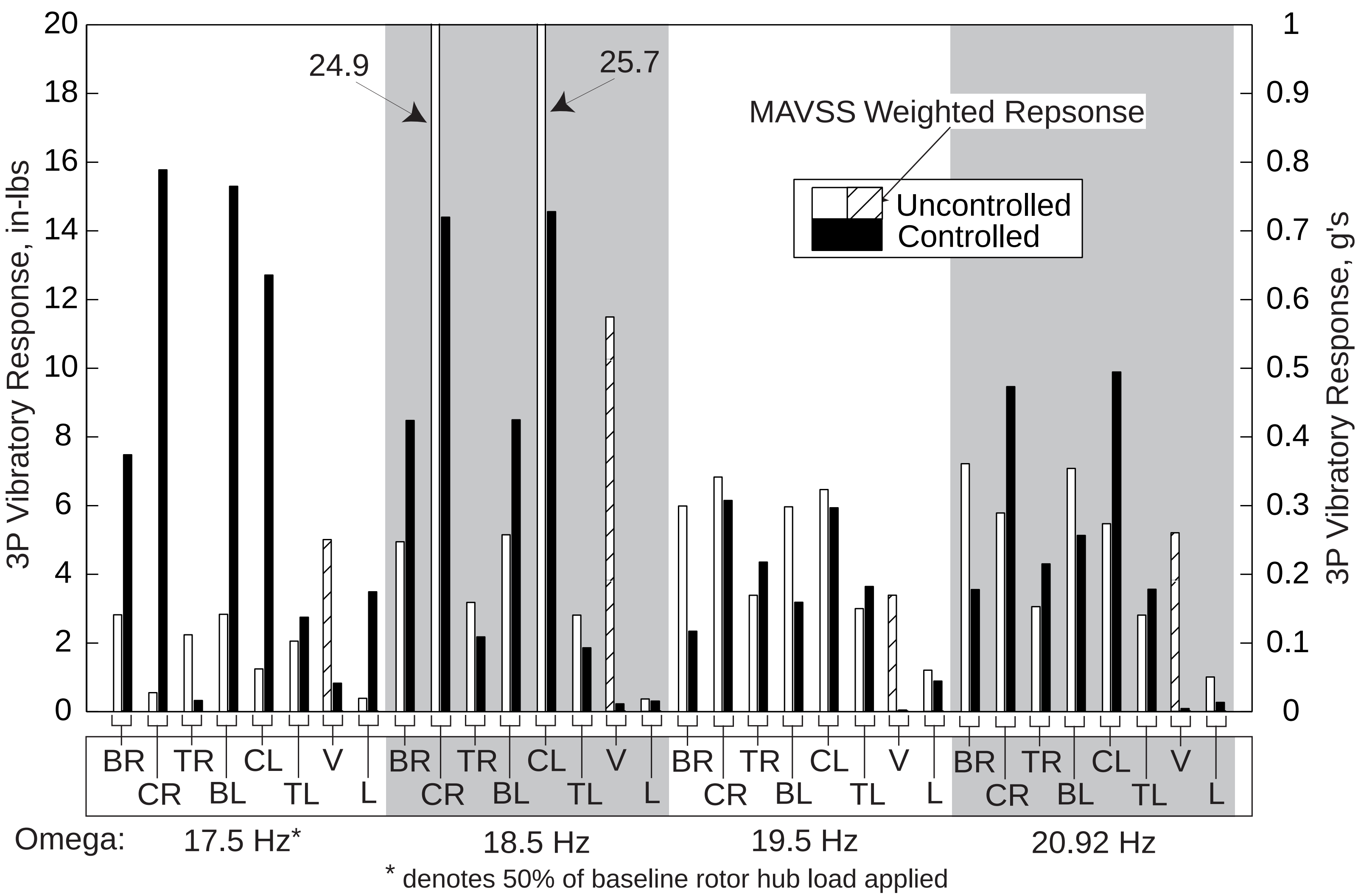


* denotes 25% of baseline rotor hub load applied

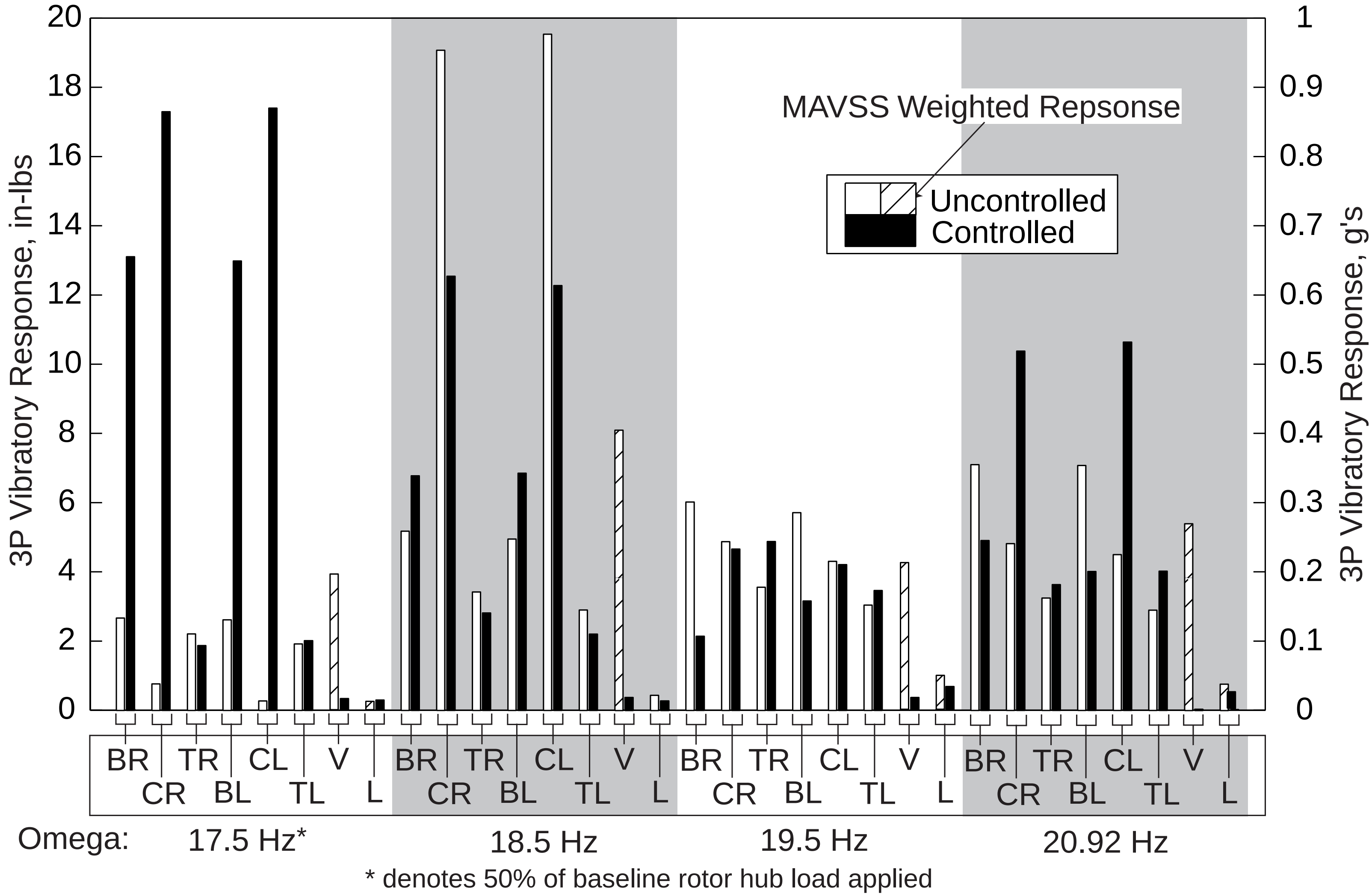
Wing Torsion Weighted Objective Function



Fuselage Vertical Weighted Objective Function



Fuselage Vertical and Lateral Weighted Objective Function



Presentation Outline

- Background and motivation
- Higher harmonic control system
- Tiltrotor dynamic model (AViRTTS)
- Results
- Conclusions

Fullspan Conclusions

- MAVSS is effective at suppressing fuselage vibrations
- MAVSS response weights must be applied to both vertical and lateral response (unsymmetrical loads)
- Individual component pairs of wing vibratory load suppressed
- Suppression of wing vibratory loads does not always results in reduced fuselage vibrations
- Reduction of wing chord loads may result in adverse unsymmetrical wing beam and torsion loads