

Alexander A. Nikolsky Honorary Lectureship



William A. "Bill" Welsh

Sikorsky, a Lockheed Martin Company

*"Helicopter Vibration Technology for
Jet Smooth Ride"*

2026 Alexander Nikolsky Honorary Lecture Helicopter Vibration Technology for a Jet Smooth Ride

Bill Welsh
LM Senior Fellow (Emeritus)
Sikorsky A Lockheed Martin Company

May 2026

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Get to “Jet Smooth”

In 1982, the then AHS Northeastern Region, sponsored a national meeting entitled “Helicopter Technology for the Jet Smooth Ride”

Since then, innovation has yielded inventions/ tools to achieve that goal i.e.

Globally low vibration:

- Higher Harmonic Control

- Fuselage/On-rotor Active Vibration Control

- Isolation

Why Global ?

- Less fatigue for both crew *and passengers* over long missions

- Eliminate equipment failures due to vibration

 - Cockpit equipment gets the benefit of low pilot vibes

 - Equipment elsewhere (tail cone) often experiences high vibes

- Lighter avionics might be possible with lower vibration

The 1981 the AHS Northeast Region National Specialists meeting: “Technology for a Jet Smooth Ride”

THE HELICOPTER RIDE REVOLUTION

R. W. Balke
Chief of Dynamics
Bell Helicopter Textron
Fort Worth, Texas

PRESENTED AT THE AMERICAN HELICOPTER
SOCIETY NORTHEAST REGION NATIONAL
SPECIALISTS' MEETING ON HELICOPTER VIBRATION
'TECHNOLOGY FOR THE JET SMOOTH RIDE'
HARTFORD, CONNECTICUT
NOV 1981

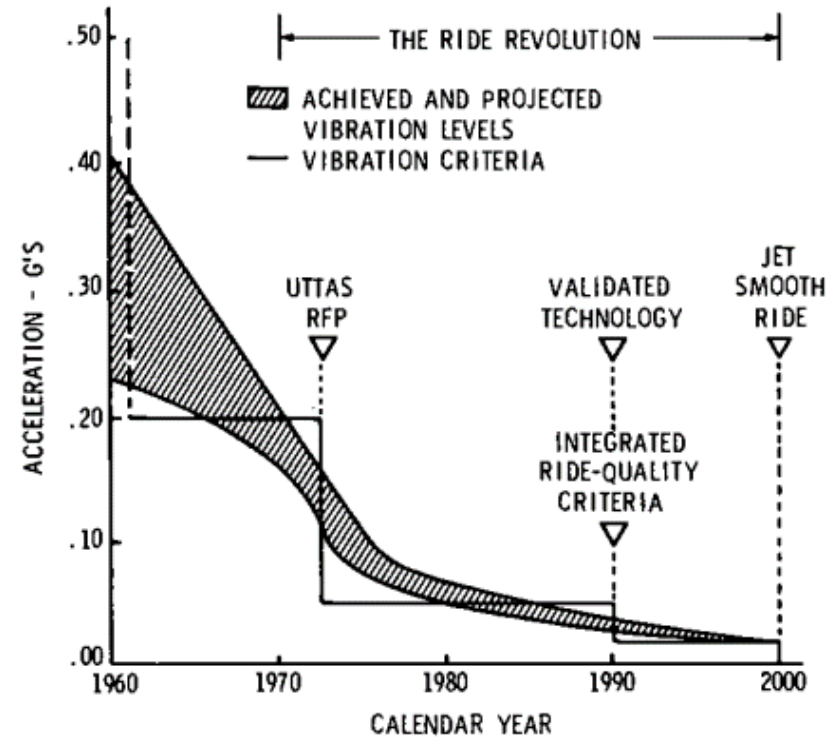


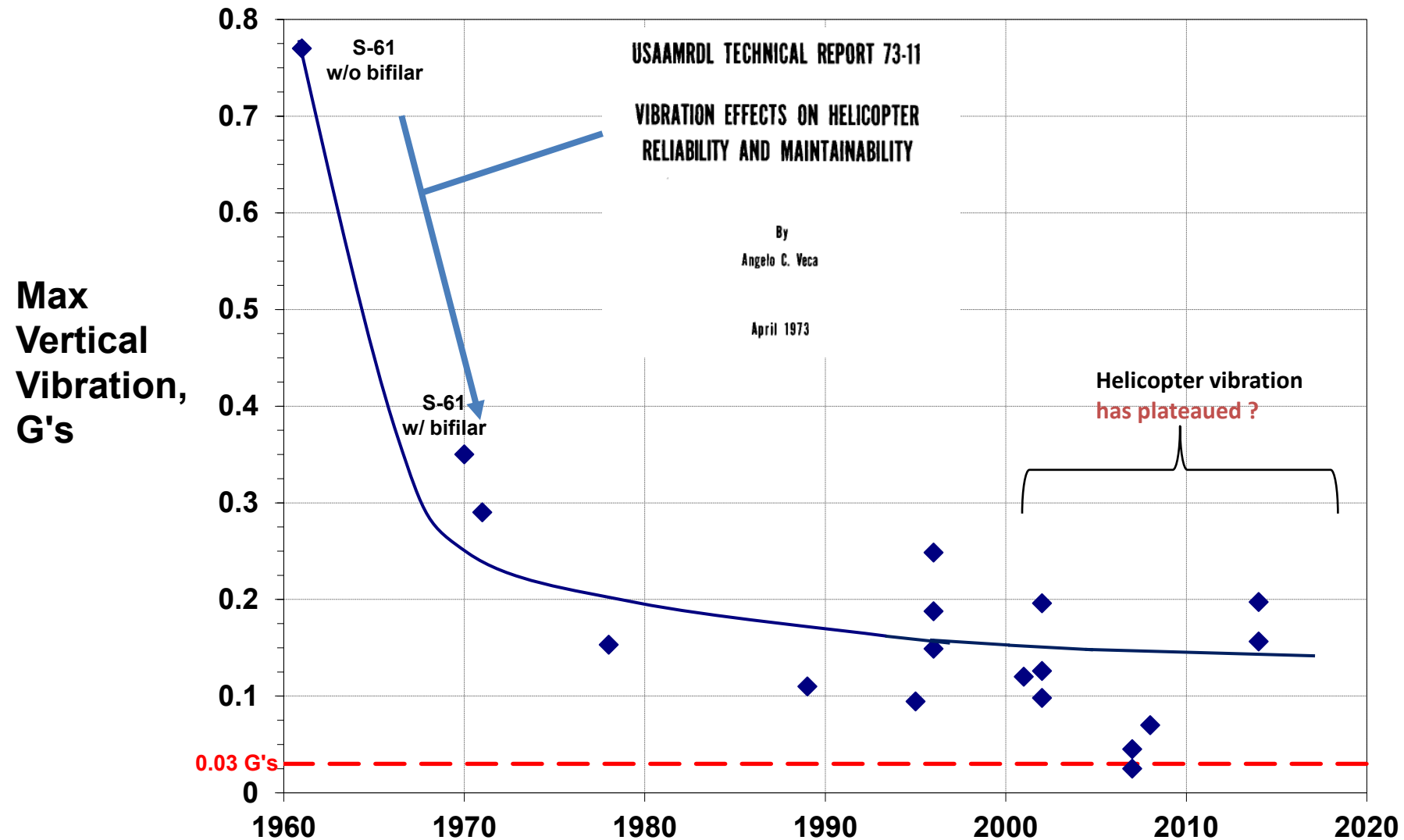
Figure 2. Achieved and projected vibration levels

Where are we now?

- Can meet $< .05$ g in the cockpit or cabin but often not both
- Even meeting $< .05$ g in the cockpit is a challenge with rigid rotors

(Welsh)

Helicopter vibration levels have plateaued



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Driven by Invention, we have the ingredients to
achieve virtually Zero Vibration ... *Globally...*

Frahms

Absorber, Pendulum, Bifilar
1911

Multicyclic Control
Higher Harmonic Control
Individual Blade Control
1963 (UH-1A) -1982 (OH-6A), 1986 (S-76A)

Isolation
DAVI, IRIS, LIVE, SARIB
1976 1978 1980 2008

**Fuselage Active
Vibration Control**
SIFG, FG, CFG
1995

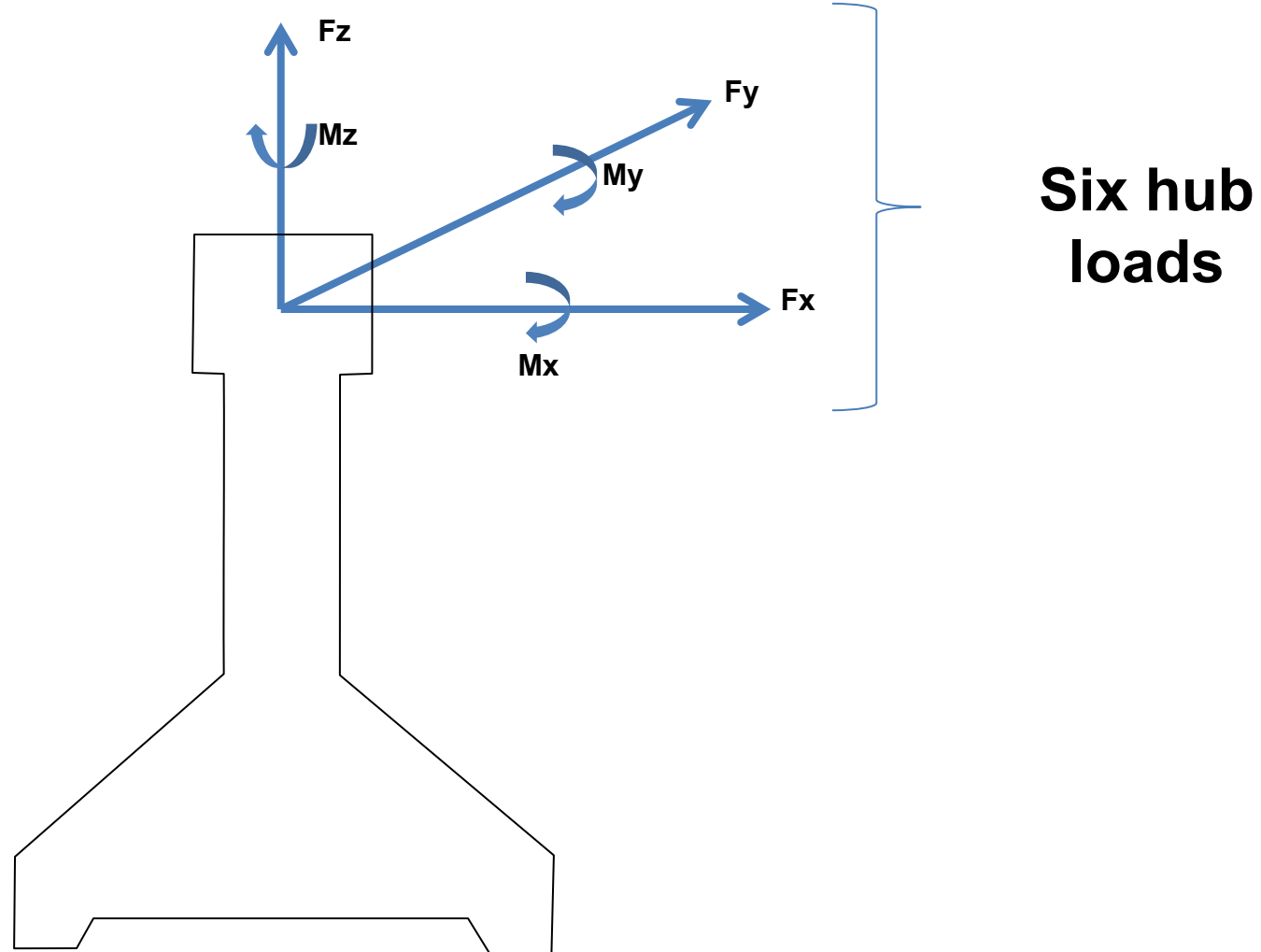
AVC Counter-Force
AVC, CFG at choke points
X2, HMVS
2008 2012

MR
Pylon ✓
Tail ✓

A path to a Jet-Smooth ride

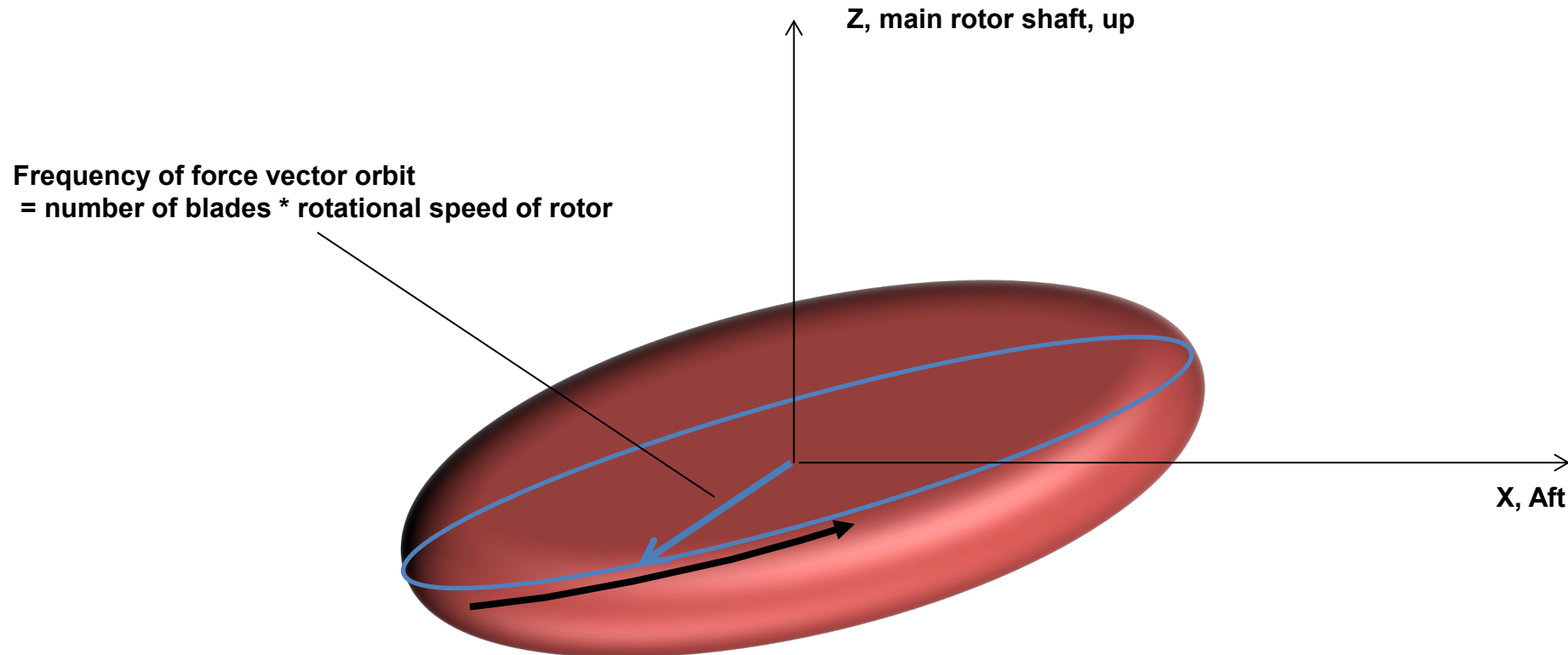
-“Team” systems at the *two major load paths* i.e main rotor pylon and tail planes

Primary vibration path; 6 vibratory hub loads

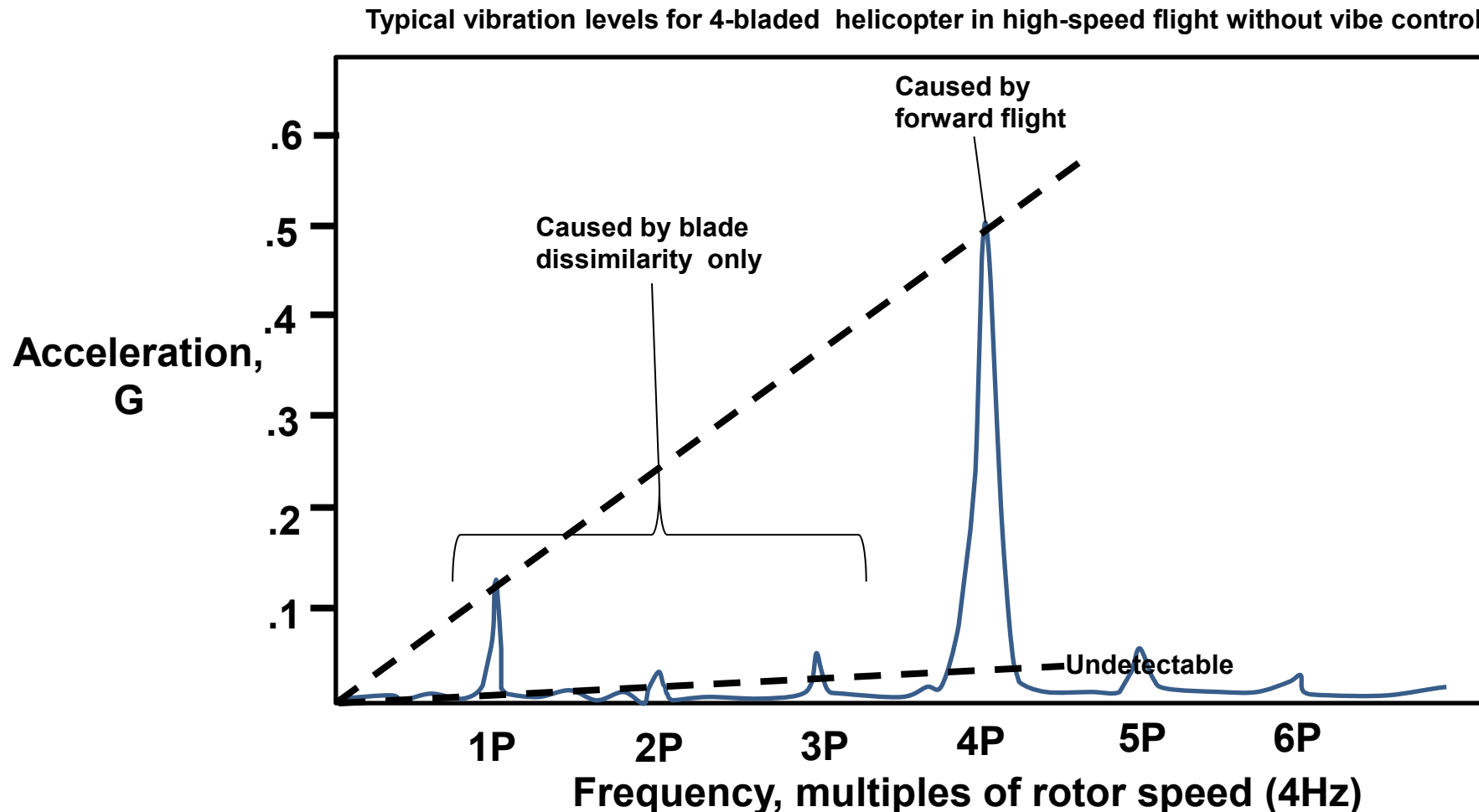


Vibratory loads produced by the rotor follow an ellipsoid

Forces produced by the rotor follows a “tilted” ellipsoid in three dimensions
Moment does the same but follows a differently shaped tilted ellipsoid



Two vibration frequencies dominate helicopter fuselage vibration: 1P and NP



Lower vibration enables longer, safer missions

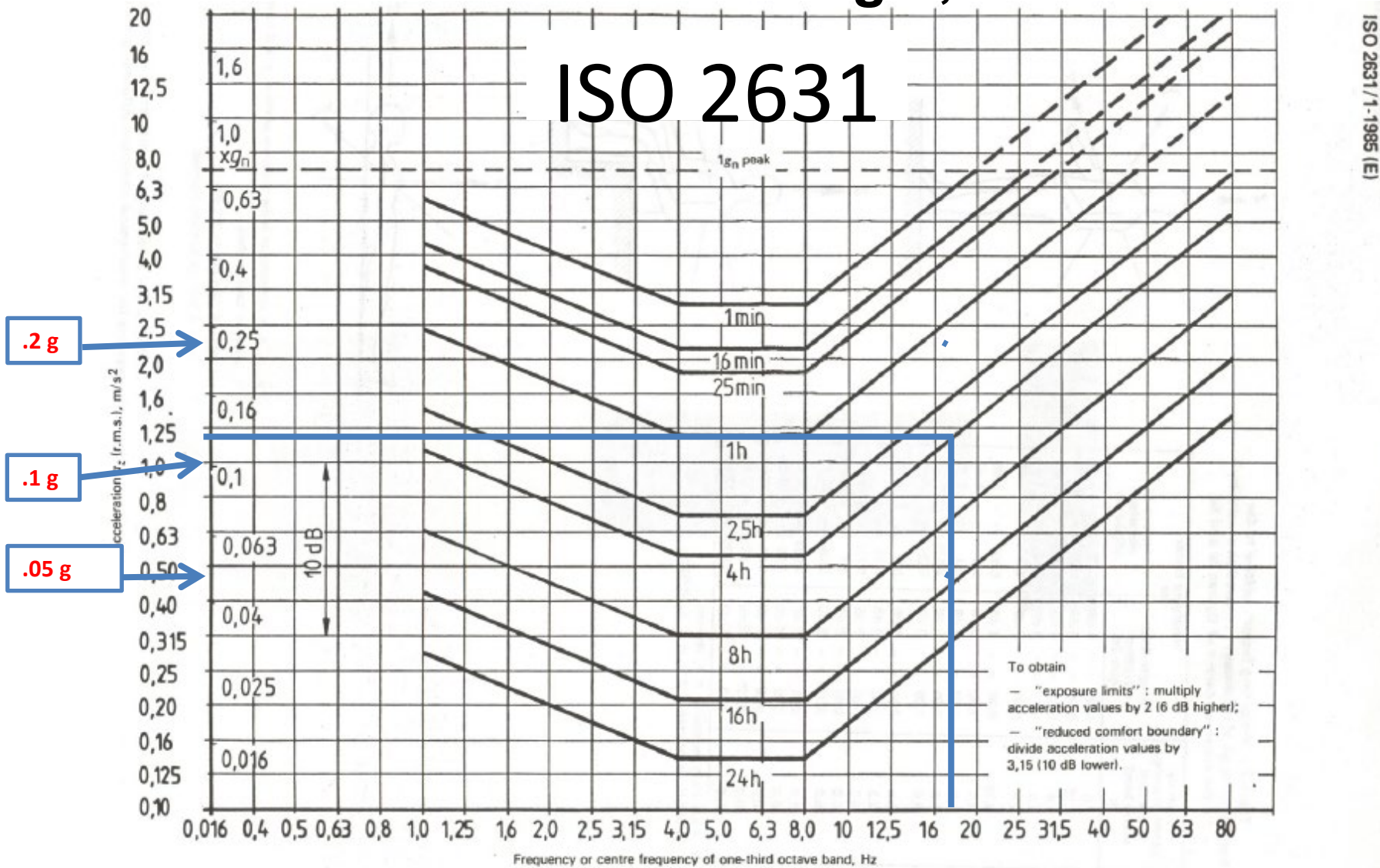


Figure 2a — Longitudinal (a_z) acceleration limits as a function of frequency and exposure time :
"fatigue-decreased proficiency boundary"

Vibration reductions have potential to yield operating cost reductions

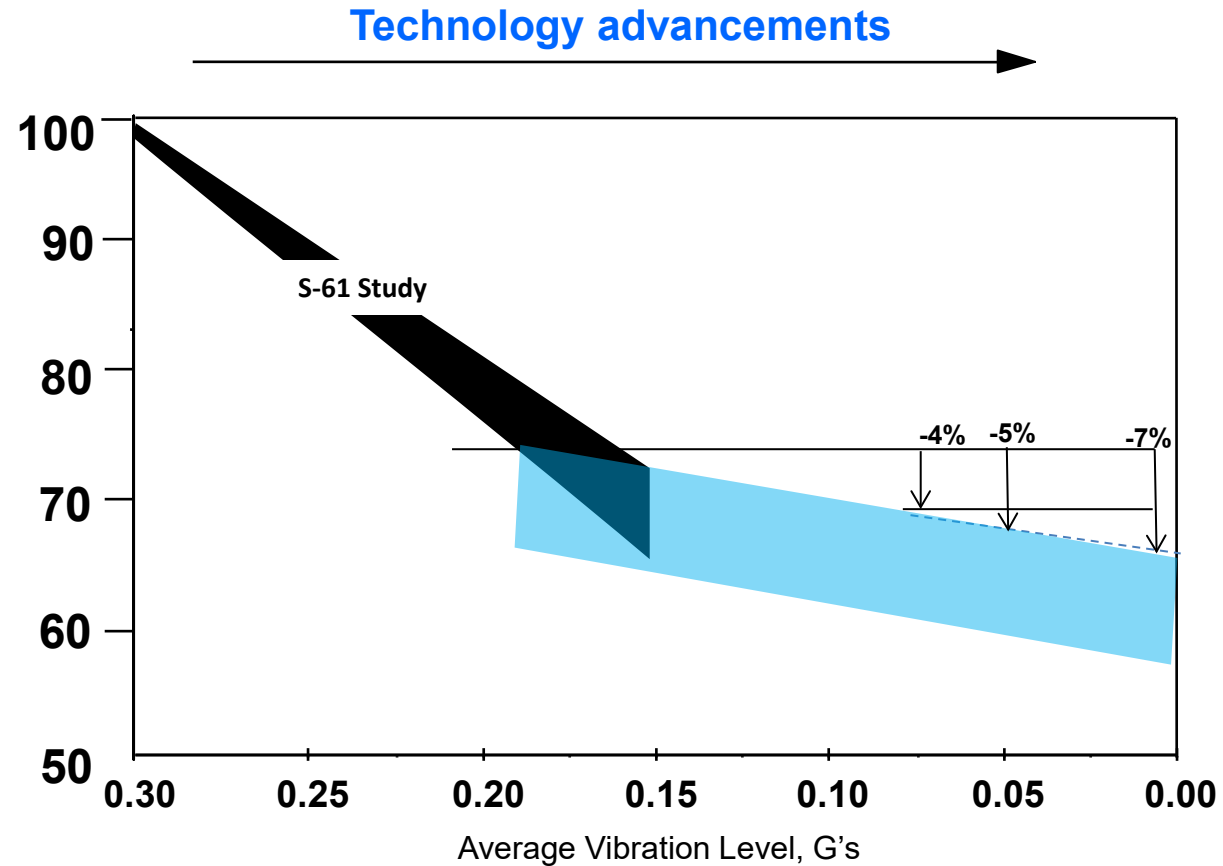
USAAMRDL TECHNICAL REPORT 73-11

VIBRATION EFFECTS ON HELICOPTER
RELIABILITY AND MAINTAINABILITY

By
Angelo C. Veca

April 1973

% of Direct
Maintenance
Cost



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Decreasing Vibration Enables Decreases in Avionics Weight

Stress in a solder joint of a circuit board decrease with decreases in vibratory acceleration

Steinberg's Fatigue Limit Equation

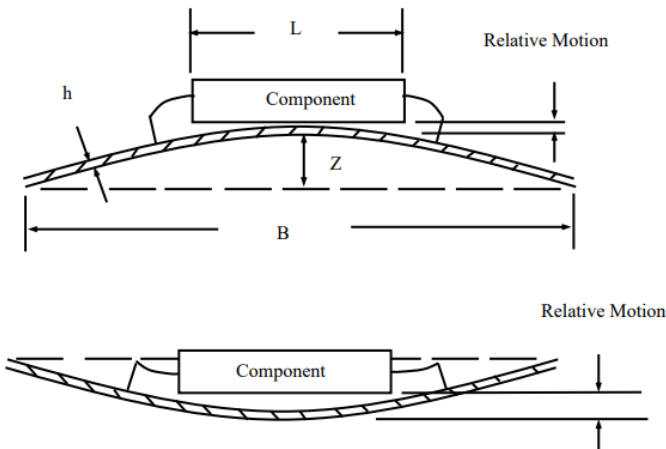


Figure taken from :
https://www.vibrationdata.com/tutorials2/electronic_rd_n.pdf

3σ relative vibration limit :

$$Z = \frac{0.00022 B}{C h r \sqrt{L}} \quad (\text{maximum desired PCB displacement})$$

where B = length of PCB edge parallel to component (in.)

L = length of electronic component (in.)

h = height or thickness of PCB (in.)

C = constant for different types of components (see Eq. 9.50)

r = relative position factor for components (see Eq. 9.50)

$$Z_{\text{vibe}} = \alpha p h G a^4 / D$$

$$D = E h^3 / 12 (1 - \nu^2)$$

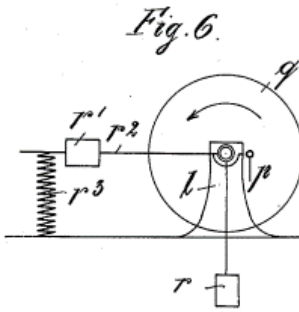
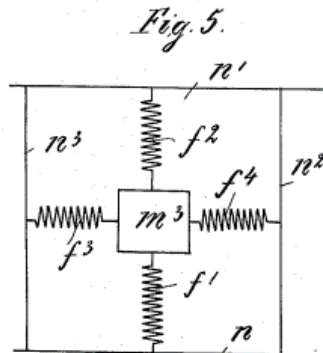
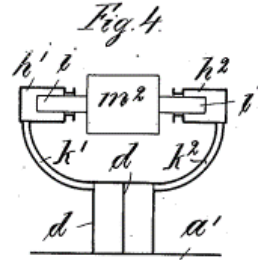
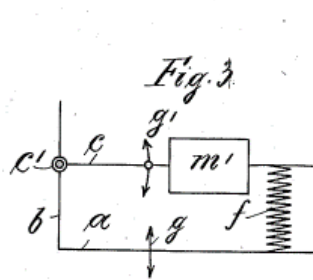
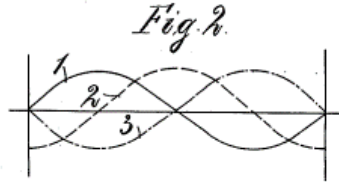
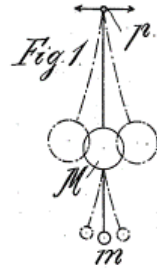
$$Z_{\text{vibe}} < Z$$

$$\alpha p h G a^4 / D < .00022 B / (C h r \sqrt{L})$$

$$G/h < (1.83 \times 10^{-5}) B E / (C r \sqrt{L} \alpha p a^4 (1 - \nu^2))$$

As G is decreased, h can also be decreased proportionally

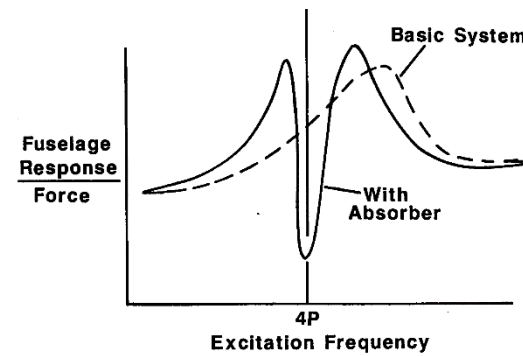
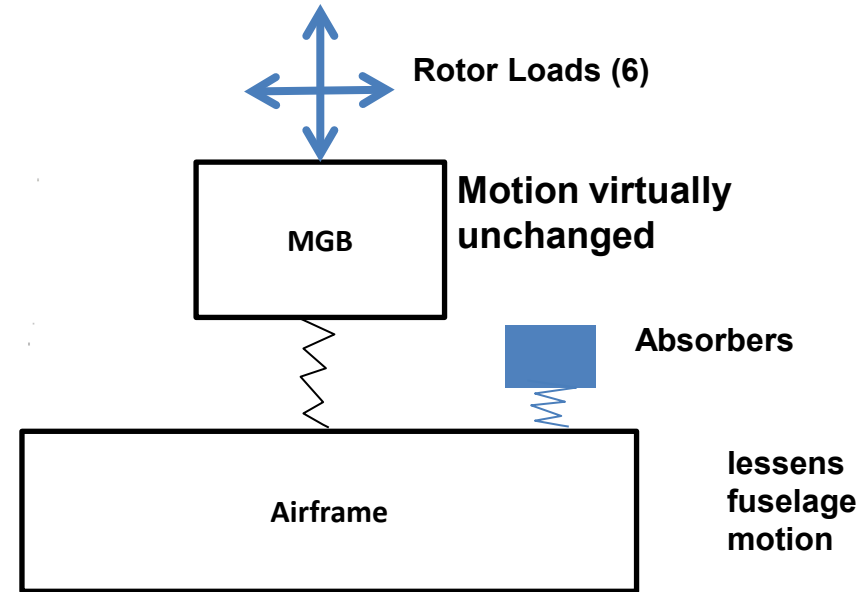
20% reduction in electronics weight ~ 100-200 lb empty weight reduction



Witnesses:
Alfred Lyons
James V. Suggs

Inventor:
Hermann Frahm
 by *L. K. Schmitt*
 Attorney

Patent For Vibration Absorber, Hermann Frahm, Hamburg, Germany, 1911



UH-60L VIBRATION ABSORBER SUITE

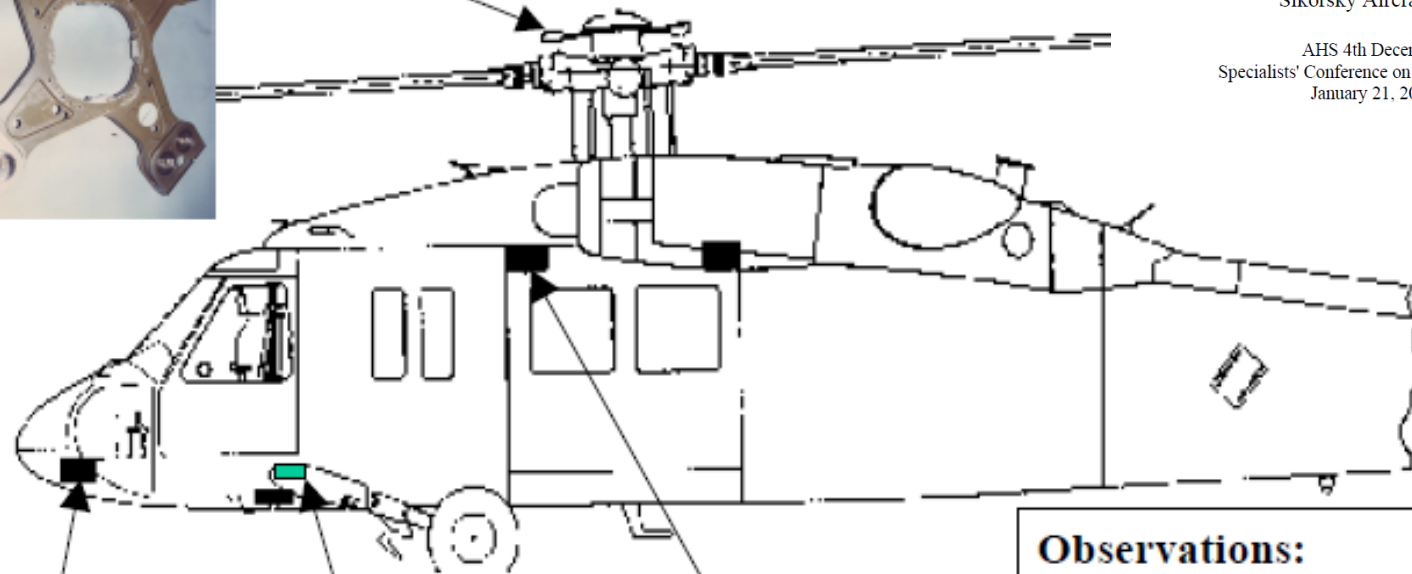
Evolution of Active Vibration Control Technology

W. A. Welsh
Sikorsky Aircraft Co.

AHS 4th Decennial
Specialists' Conference on Aeromechanics
January 21, 2004



Bifilar



Nose Vertical
4P Absorber



Stub Wing
4P Absorber



Forward Cabin Vertical
4P Absorber



Observations:

- Weight reduction limited by material strength
- Weight ~ 1.5 % of GW
- Vib, utility sys ~.15 g
- Performance limited by interaction

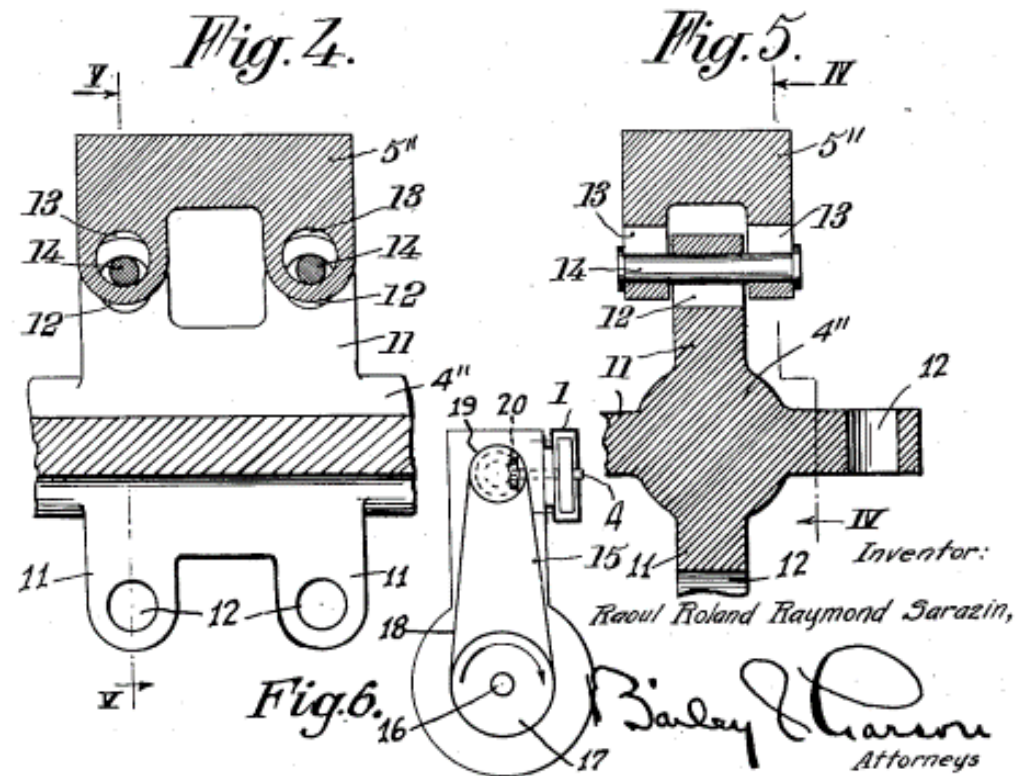
R.R.R. Sarazin Invented the Pendulum and Bifilar Absorber To Reduce Radial Engine Vibration

Nov. 22, 1938.

R. R. R. SARAZIN
VIBRATION DAMPING DEVICE
Filed July 18, 1936

2,137,591

2 Sheets-Sheet 1



V-22 In-Plane Pendulum Absorbers



<https://www.flickr.com/photos/129448336@N07/20025271400/>

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Vertical Pendular absorbers



Bell 412 pendular absorbers

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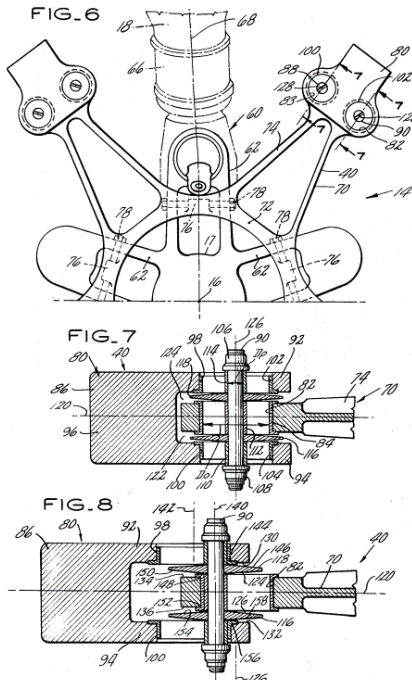
United States Patent Office

3,540,809
Patented Nov. 17, 1970

1
3,540,809
VIBRATION DAMPED HELICOPTER ROTOR
William F. Paul, Trumbull, and Kenneth C. Mard, Stratford, Conn., assignors to United Aircraft Corporation, East Hartford, Conn., a corporation of Delaware
Filed Sept. 20, 1968, Ser. No. 761,187
Int. Cl. B64c 27/32
U.S. Cl. 416—1 20 Claims

2
of rotation, and are tuned to cancel rotor in-plane vibrations.
In accordance with a further aspect of the invention, more than one set of three or more bifilar vibration dampers may be utilized, with each set tuned to damp a different frequency rotor vibration.
In accordance with a further aspect of the present invention a vibration damper is provided which is effective without respect to the number of blades to the rotor and which continues to be effective even when the excitation

Nov. 17, 1970 W. F. PAUL ET AL 3,540,809
VIBRATION DAMPED HELICOPTER ROTOR
Filed Sept. 20, 1968 4 Sheets-Sheet 2



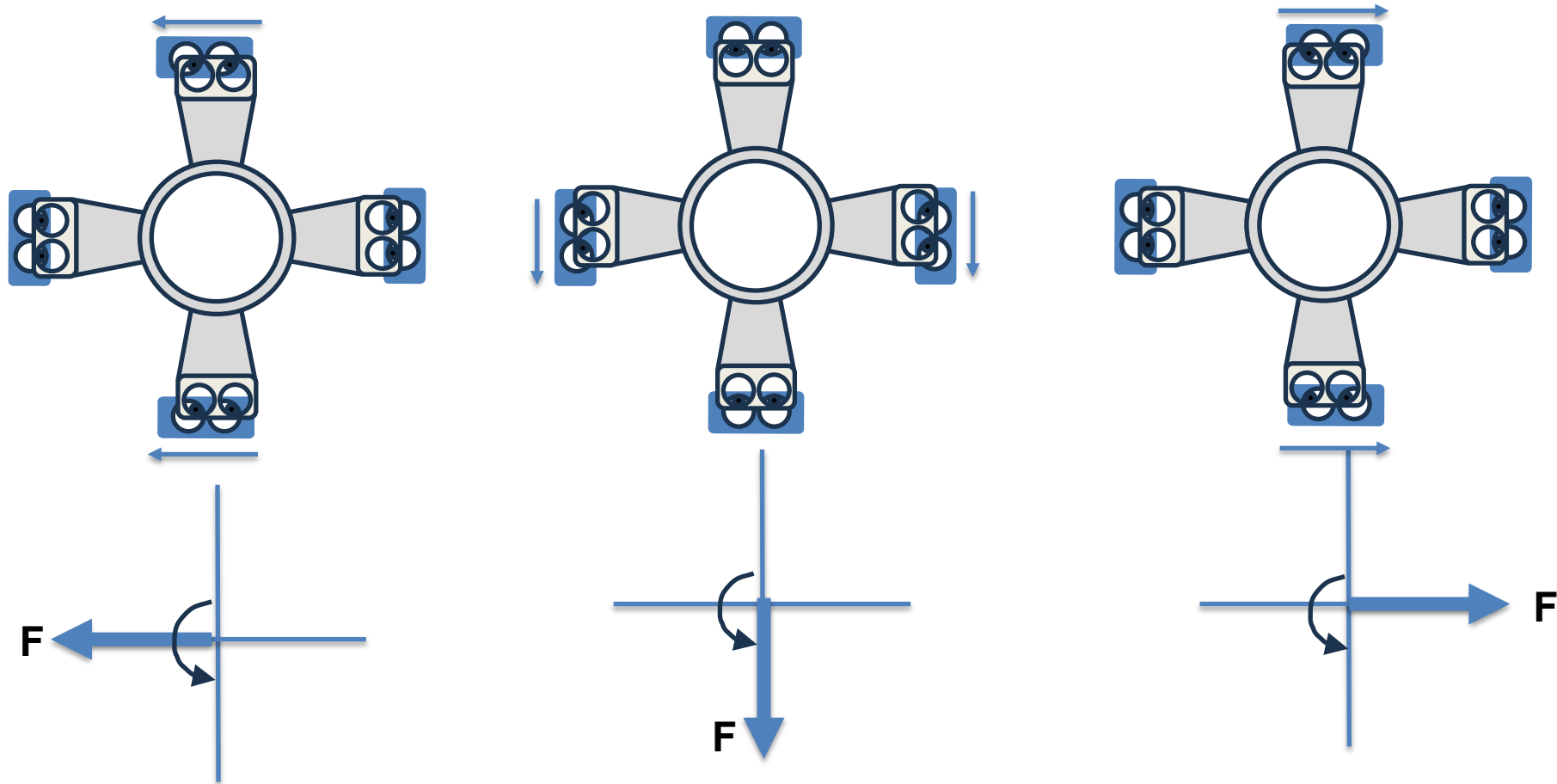
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Bifilar pendular masses
Create progressive i.e. 3/rev in-plane
“circular” load



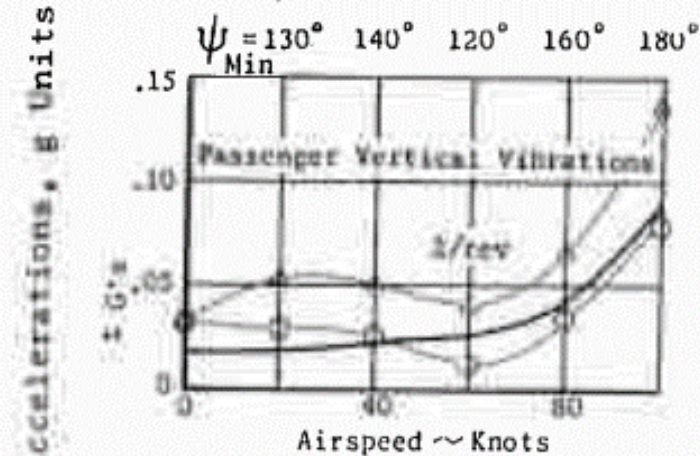
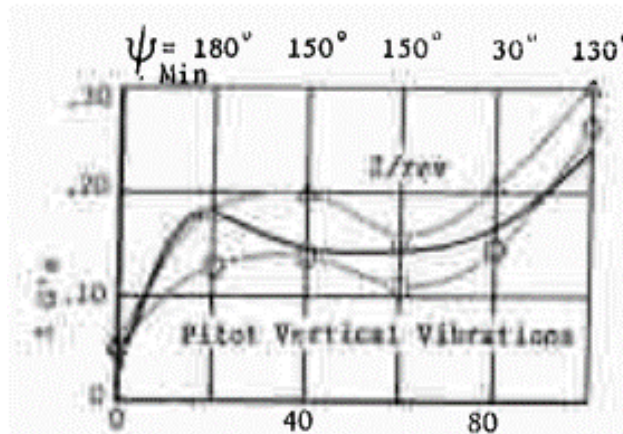
Bifilar absorber produces a “circular” in-plane force at 3P for a 4-bladed rotor



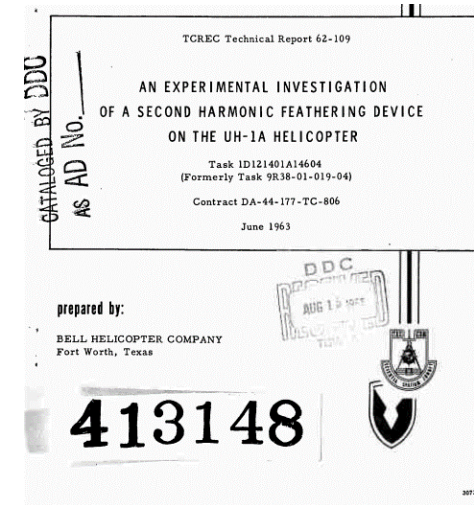
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First Flight Test of HHC was by Bell in 1962 using a mechanical linkage to induce 2P blade feathering



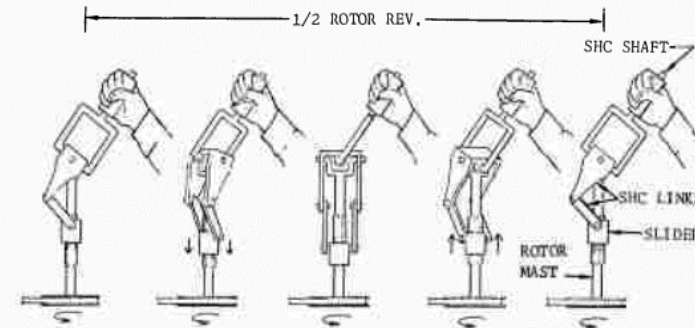
— $\pm 0^\circ$
 ○ $\pm .285^\circ$ @ $\psi_{\min}$ (azimuth phase angle for minimum vibrations and loads)
 △ $\pm .285^\circ$ @ $\psi_{\max}$ ($\psi_{\max} \approx \psi_{\min} \pm 90^\circ$)



B. SECOND HARMONIC CONTROL MECHANISM

1. Description of the Principle

The SHC mechanism was designed to mix into the normal control system of the helicopter, a twice per main rotor revolution oscillation, which could be controlled in amplitude and phasing with respect to blade azimuth. This was accomplished with a mechanism which converts the rotary motion from the rotor mast into a 2/rev vertical slider motion. The operation of the SHC mechanism can be explained with the sketch below.



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First use of T-matrix control was to reduce blade loads on the Dorand Jet Flap rotor during wind tunnel testing, ~1971



MULTICYCLIC JET-FLAP CONTROL FOR ALLEVIATION OF HELICOPTER BLADE STRESSES AND FUSELAGE VIBRATION

John L. McCloud, III* and Marcel Kretz**
Ames Research Center, Moffett Field, California 94035

Blade-Bending Stresses

As discussed in Reference 5, the relationships between the time histories of jet-flap deflections and the resulting blade bending stresses can be expressed by a transfer matrix.* The time histories

*This method of analysis was first suggested and developed by Dr. Jean-Noel Aubrun of Giravions Dorand.

https://www.aviastar.org/helicopters_eng/dorand_dh-011.php

*Research Scientist
Ames Research Center, Moffett Field, Calif. 94035

**Chief Engineer
Giravions Dorand, 92150 Suresnes, France

Quasi-Steady *Adaptive* “T-Matrix” Controller

Still used on over 1000 UH-60M, several hundred MH-60R, MH-60S and S-92 helicopters

$$J = \mathbf{z}^T \mathbf{z} + \mathbf{u}^T \mathbf{W}_u \mathbf{u} + \Delta \mathbf{u}^T \mathbf{W}_{\Delta u} \Delta \mathbf{u}$$

where $\mathbf{W}_u$ is a weighting matrix for controls, $\mathbf{W}_{\Delta u}$ is a weighting matrix for rate of change of controls. The relationship between the controls and the n/rev vibration level is given by a linearized relationship

$$\Delta \mathbf{z} = \mathbf{T} \Delta \mathbf{u} + \mathbf{\bar{w}}$$

The control law resulting from minimizing the performance index is given by

$$\begin{aligned} \mathbf{\bar{u}}_{k+1} &= \mathbf{\bar{u}}_k - \mathbf{Y}_k (\mathbf{W}_u \mathbf{\bar{u}}_k + \mathbf{T}_k^T \mathbf{\bar{z}}_k) \\ \mathbf{Y}_k &= (\mathbf{T}_k^T \mathbf{T}_k + \mathbf{W}_u + \mathbf{W}_{\Delta u})^{-1} \end{aligned}$$

where the subscript k has been added to indicate the recursive implementation of the control algorithm. Controller stability is augmented when a step-size multiplier, $\beta \leq 1.0$, is introduced so that

$$\mathbf{\bar{u}}_{k+1} = \mathbf{\bar{u}}_k - \beta \mathbf{Y}_k (\mathbf{W}_u \mathbf{\bar{u}}_k + \mathbf{T}_k^T \mathbf{\bar{z}}_k)$$

The matrix, $\mathbf{T}$, may vary with flight condition so the control algorithm employs a Kalman filter based, on-line parameter estimation procedure to keep the transfer function current.
[1]

This algorithm works well in steady flight but not in transients i.e. pull-ups, flare to hover etc.

NASA CR 152377, Analytical Design and Evaluation of an Active Control System for Helicopter Vibration Reduction and Gust Response Alleviation, Taylor, Zwicke, Gold, Miao, July 1980.

NASA TM 84336, Adaptive Inverse Control for Helicopter Vibration Reduction, Stephen Jacklin 1983

Real-time Adaptation

NASA CR 152377

ANALYTICAL DESIGN AND EVALUATION OF AN ACTIVE CONTROL SYSTEM FOR
HELICOPTER VIBRATION REDUCTION AND GUST RESPONSE ALLEVIATION

By R. B. Taylor, P. E. Zwicke, P. Gold and W. Miao

July, 1980

(NASA-CR-152377) ANALYTICAL DESIGN AND
EVALUATION OF AN ACTIVE CONTROL SYSTEM FOR
HELICOPTER VIBRATION REDUCTION AND GUST
RESPONSE ALLEVIATION (United Technologies
Research Center) 165 p HC A08/MP A01

N90-28369

G3/08 26014
Unclass

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East Hartford, Connecticut
and
Sikorsky Aircraft
Stratford, Connecticut

for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

The quantity W_{ji} can be considered the forcing vector for changes in
state (X). Equation (4.7) implies that the state vector (the j th row of
the $n \times m$ T-matrix) at time sequence $i+1$ equals its value at time sequence
 i plus a random change. This random change conveys to the mathematical
formulation that the elements of the T-matrix vary with flight condition.
Equations (4.6) and (4.7) present a well-defined problem, and the Kalman
filter solution provides a real-time identification and tracking of the T-
matrix. The Kalman filter solution as taken from Reference 27, Chapter 12,
is:

$$\hat{X}_{ji+1} = \hat{X}_{ji} + K_i (Z_{ji} - H_i \hat{X}_{ji}) \quad (4.8)$$

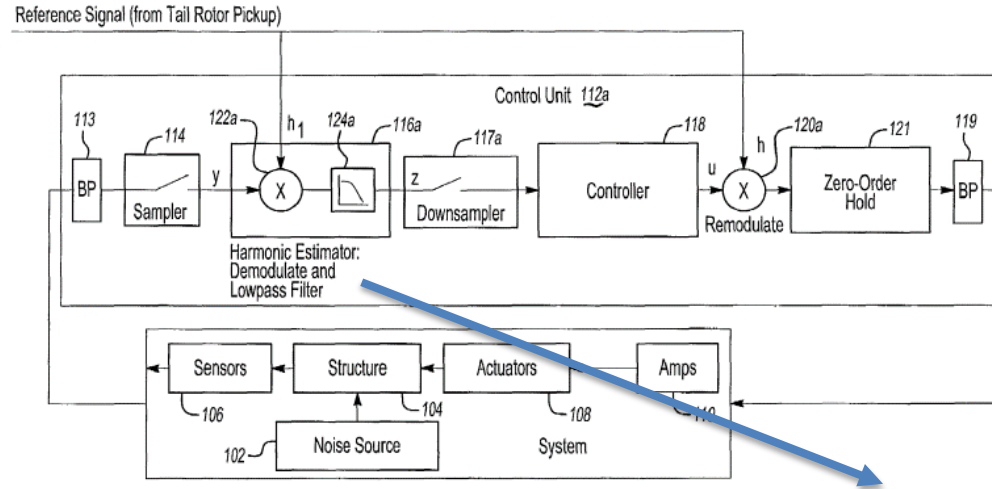
$$K_i = P_i H_i^T R_i^{-1} \quad (4.9)$$

$$P_i = P_{i-1} + Q_i \quad (4.10)$$

T-Matrix is adapted in real time

“Harmonic estimator” eliminates need for real time FFT

Sub-Nyquist sampling is feasible because signal frequency content is completely known



$$H = [1 \cos(f_d t_k) \sin(f_d t_k) \cos(f_x t_k) \sin(f_x t_k); \dots]^T.$$

$$z_{1,k} = z_{1,k-1} + \rho H(y_k - H^T z_{1,k-1})$$

The vector H includes all of the tones that are of interest in the application; the above equation includes the desired disturbance frequency f_d , a second frequency f_x , and also includes DC to estimate the sensor offset. Any number of frequencies can be included in this vector. Not only will this

(10) Patent No.: US 7,224,807 B2
(45) Date of Patent: May 29, 2007

First Closed Loop HHC flight test on OH-6A (~1984)

Demonstrated encouraging vibe reductions

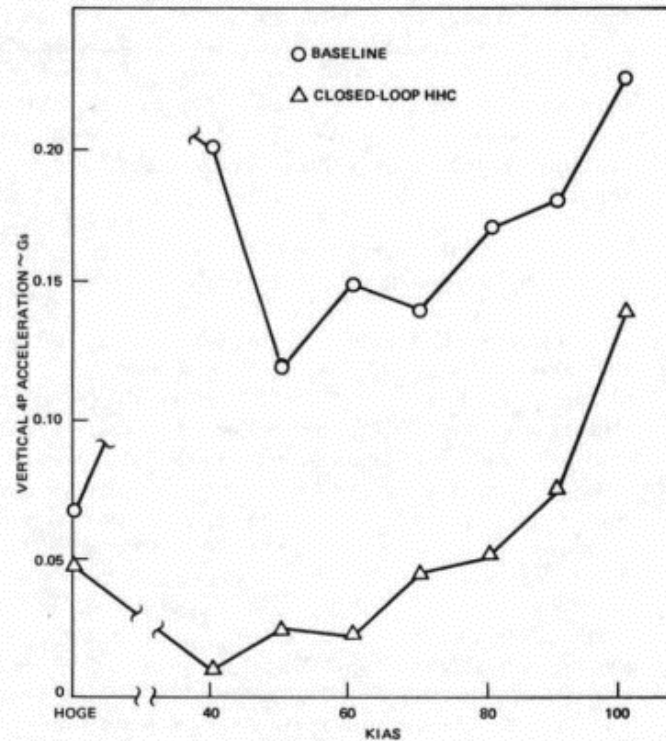


Fig. 24 Closed-loop HHC - 4P vertical pilot seat accelerations versus airspeed.

Wood, E.R., Powers, R.W., Cline, J.H., and Hammond, C.E. "On Developing and Flight Testing A Higher Harmonic Control System," Presented at the 39th Annual Forum of the American Helicopter Society, St. Louis, Missouri, May 1983. Also, "HHC Program Review" by Hughes Helicopter, Inc., May 10, 1984, Mesa, Arizona.



Figure 14. OH-6A HHC flight test aircraft.

Higher Harmonic Control - A Historical Perspective

Charles E. Hammond
Retired
Lockheed Martin
Orlando, Florida, U.S.A.

Presented at the AHS International 74th Annual Forum & Technology Display, Phoenix, Arizona, USA, May 14-17, 2018. Copyright © 2018 by AHS International, Inc. All rights reserved.

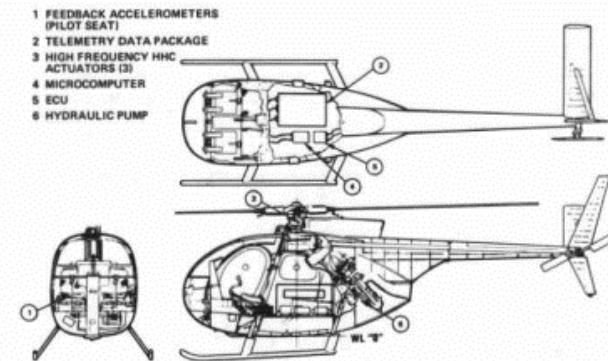


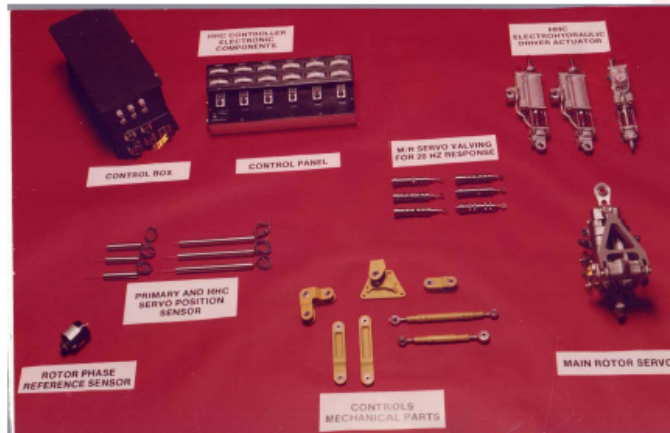
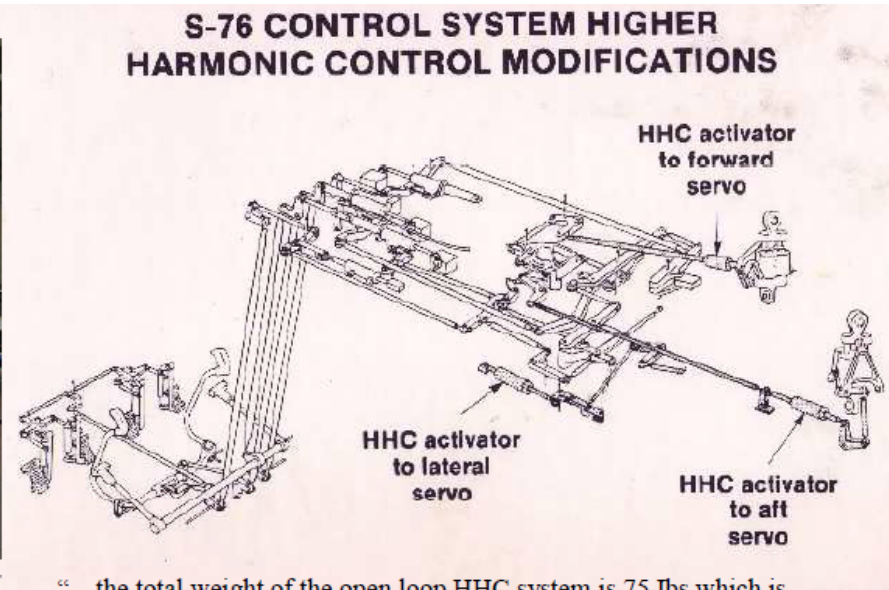
Fig. 5 OH-6A installation of higher harmonic control system.

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Higher Harmonic Control on the S-76[®]

3 controls for 6 loads



“...the total weight of the open loop HHC system is 75 lbs which is 0.75% of the design gross weight of the S-76....” from ADAPTATION OF A MODERN MEDIUM HELICOPTER (SIKORSKY S-76) TO HIGHER HARMONIC CONTROL, O’Leary, Kottapalli, Davis, 1984 AHS forum.

Observations

- Reliability may require redundancy yielding weight risk
- Power requirements are high
- Weight ~.7 % of GW, w/bifilar~1.6
- 2 to 3 actuators, delta pitch limits effectiveness
- Vib for utility ~.2g, VIP potential moderate

Open Loop HHC on an S-76 demonstrated reductions in Mx, My, Fx and Fy and global vibration reductions

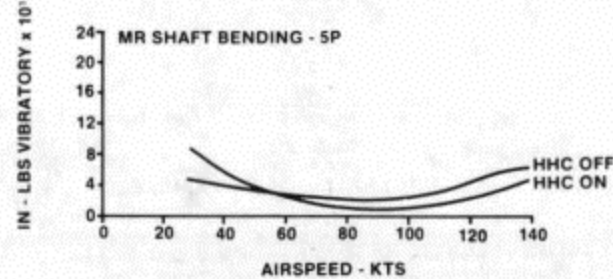
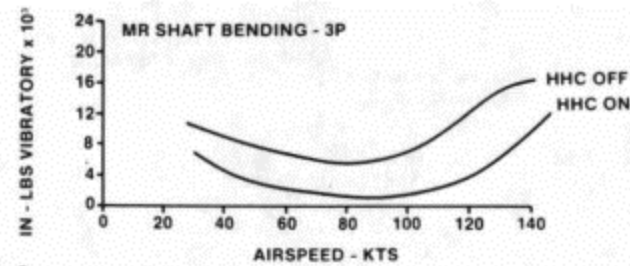


FIGURE 13 MAIN ROTOR SHAFT BENDING VS AIRSPEED FOR OPTIMUM HHC INPUTS

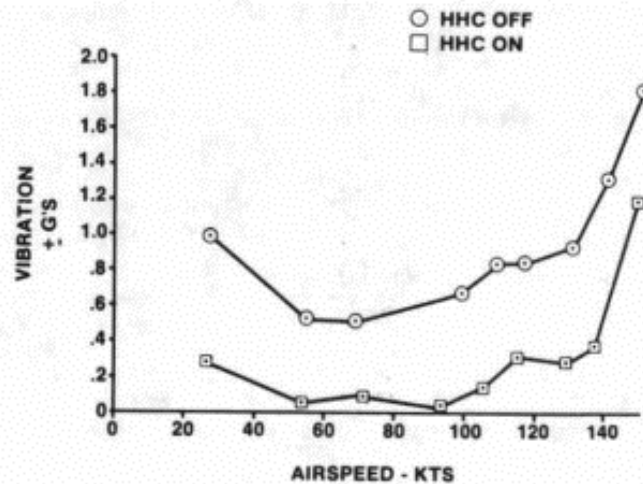


FIGURE 15 NOSE VERTICAL VIBRATION VS AIRSPEED @ 107% Nr

HHC can't, alone, reduce vibration to acceptable levels

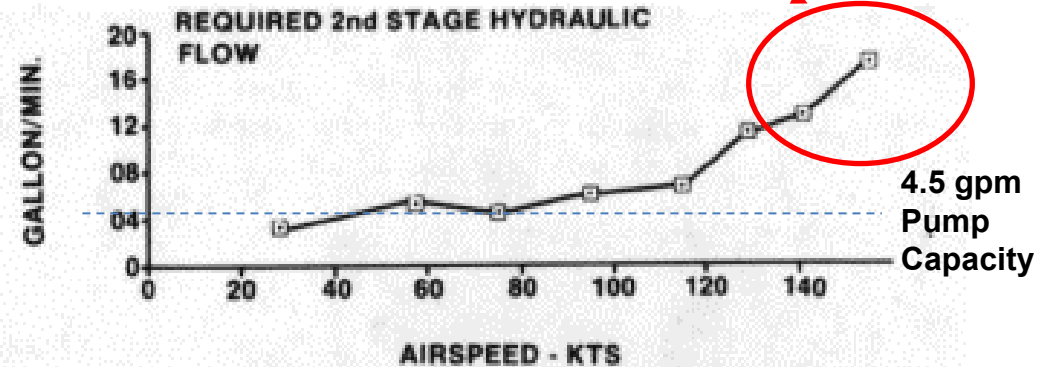


FIGURE 25 S-76A HHC INPUTS REQUIRED TO REDUCE COCKPIT VERTICAL VIBRATION TO LESS THAN 0.1 G'S

FLIGHT TESTS OF AN OPEN LOOP HIGHER HARMONIC CONTROL SYSTEM ON AN S-76A HELICOPTER

by

DAVID M. WALSH

Flight Test Engineer

Sikorsky Aircraft Division
United Technologies Corporation
West Palm Beach, Florida

Presented at AHS Forum 42, 1986

X-Wing HHC on Wind Tunnel Model with Circulation Control Rigid Blades uses multiple, fixed-frame butterfly valves (open-loop)

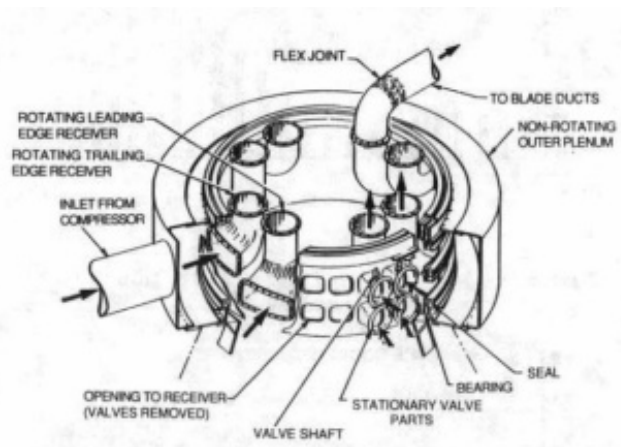


Fig. 2 Pneumatic control system.

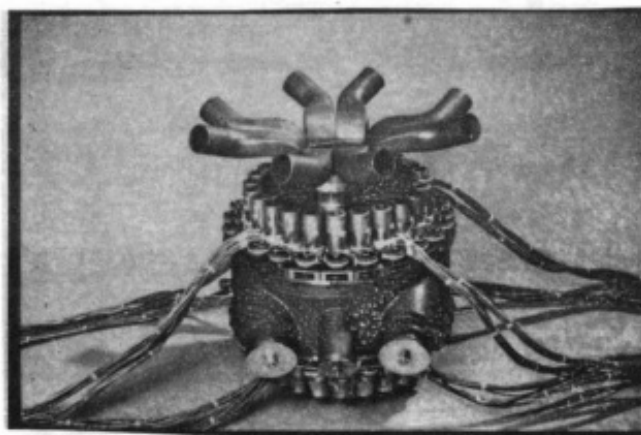


Fig. 3 Model plenum, ducting, receivers and valve motors.

The on-line displays used to monitor valve angle setting and the resultant root pressure for a typical flight condition are illustrated in Figure 4. The angular positions of the trailing and leading edge valves is shown in Figure 4a and the root pressure waveform display is illustrated in Figure 4b.

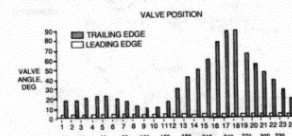


Fig. 4(a) On-line valve position display.

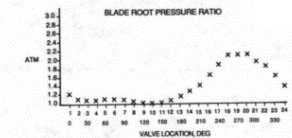


Fig. 4(b) On-line blade root pressure display.

DIAMETER	10 FT
NOMINAL TIP SPEED	470 FT/SEC
TAPER RATIO	1.18:1
	0.134
AIRFOIL THICKNESS RATIO	.3 ROOT
	.15 TIP
TWIST	0 DEG
SLOT PRELOAD	3.2 PSIG
SLOT FULL OPEN PRESSURE	6.0 PSIG

properties of the model.

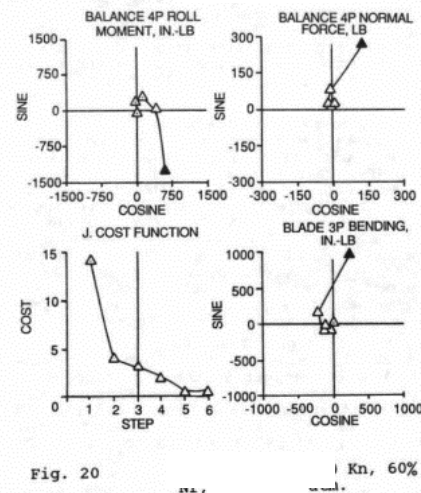


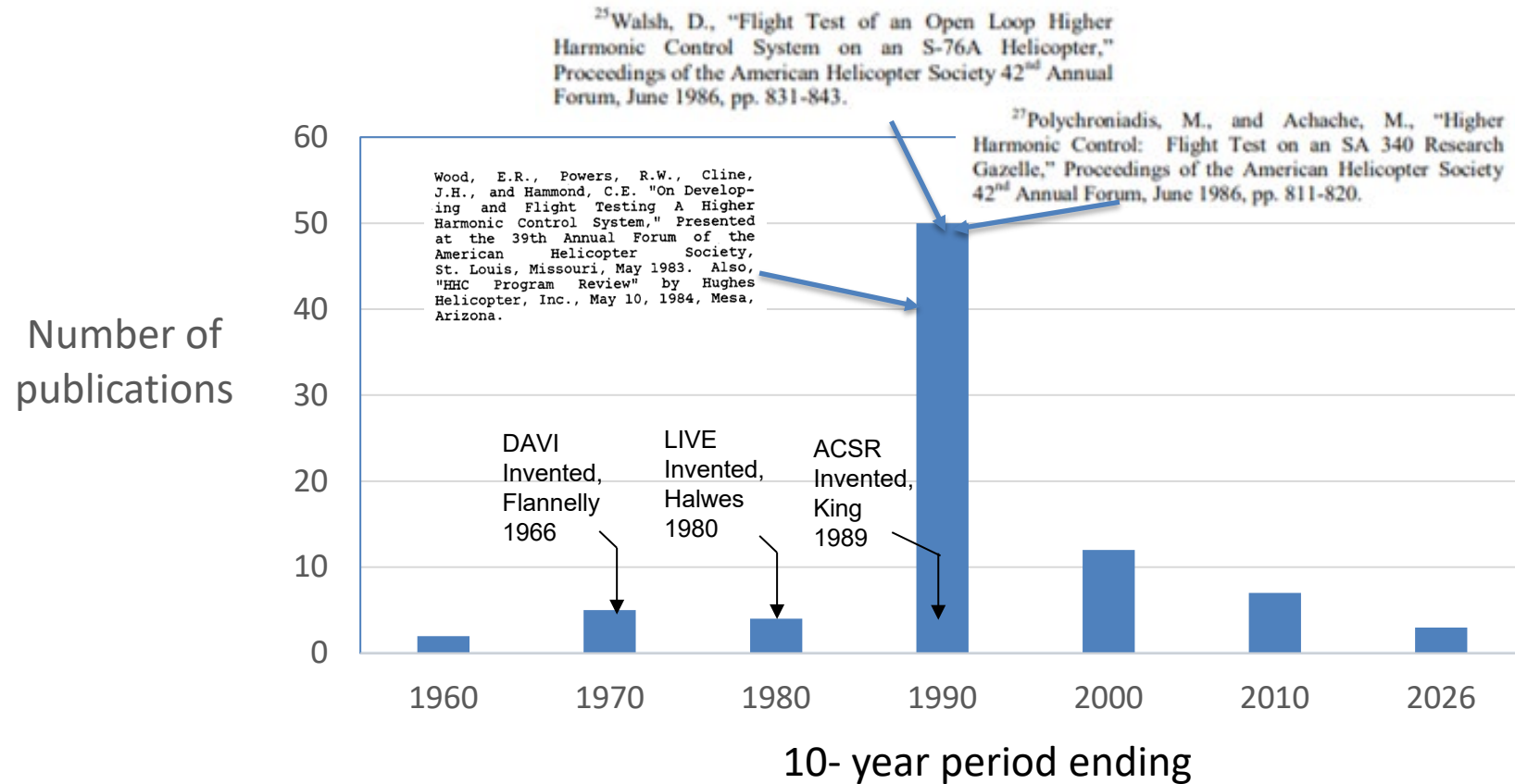
Fig. 20

HIGHER HARMONIC AND TRIM CONTROL OF THE X-WING CIRCULATION CONTROL WIND TUNNEL MODEL ROTOR

W. A. Welsh
and
R. H. Blackwell, Jr.

Presented at the 45th Annual Forum of the American Helicopter Society, Boston, Ma., May, 1989.

After Three Flight Tests Between 1983 and 1986, HHC Interest Declined



Helicopter Seat Isolation using the “Dynamics Antiresonant Vibration Isolator (DAVI) Evolved into Transmission Isolation

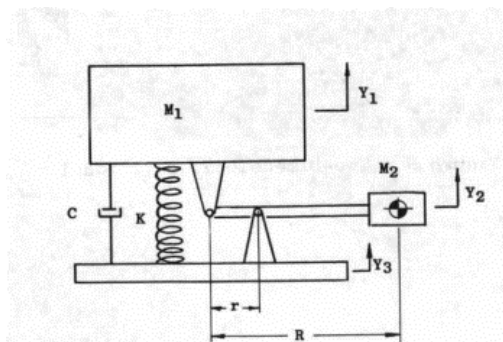


Figure 4. Damped DAVI Schematic

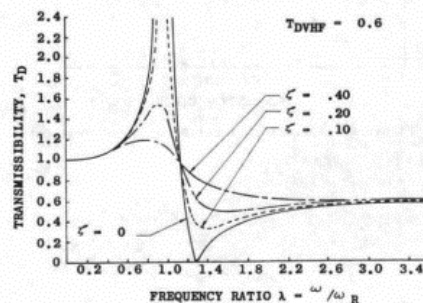


Figure 5. Theoretical Response Curve for DAVI

THE DYNAMIC ANTIRESONANT VIBRATION ISOLATOR
William G. Flannelly
Assistant Chief of Vibrations Research
Kaman Aircraft Corporation
Bloomfield, Connecticut

AHS Forum 22, 1966

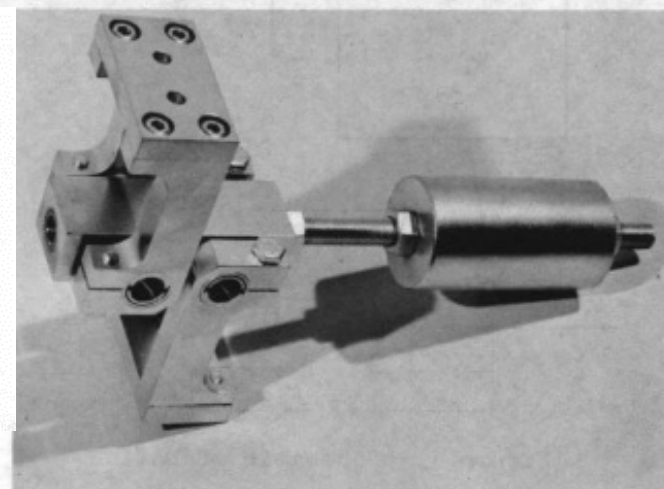


Figure 7. Flexural Pivot DAVI Model

HELICOPTER ROTOR ISOLATION EVALUATION UTILIZING THE DYNAMIC ANTIRESONANT VIBRATION ISOLATOR*

A. D. Rita
Chief of Test Operations
Kaman Aerospace Corporation

J. H. McGarvey
Aerospace Engineer
Eustis Directorate-USAAMRDL

R. Jones
Principal Research Engineer
Kaman Aerospace Corporation

Presented at the AHS Forum 32, 1976

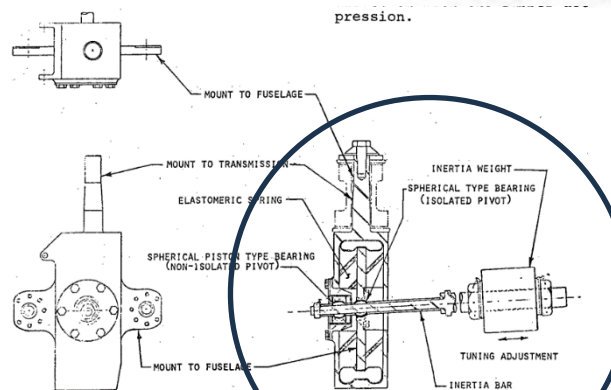


Figure 3. Transmission Mount DAVI

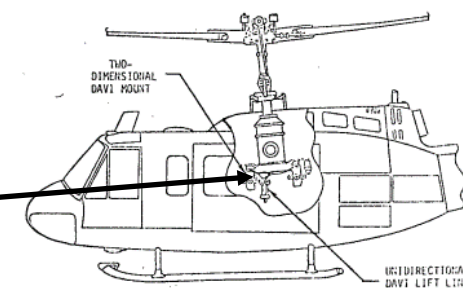
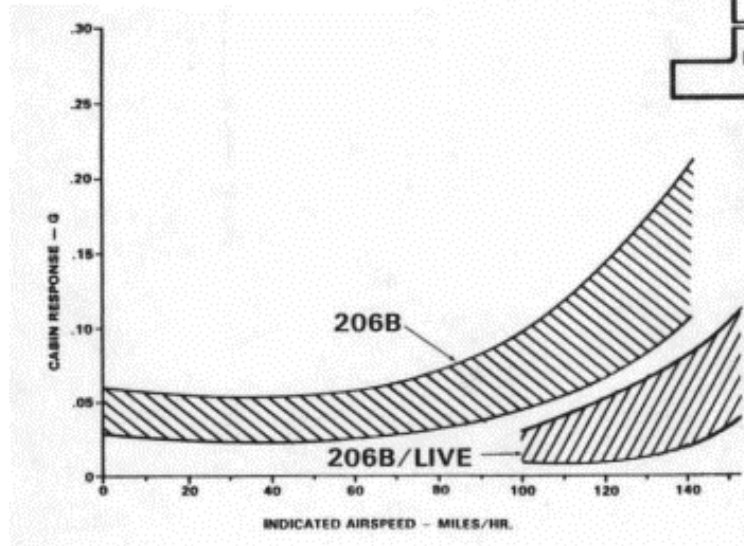
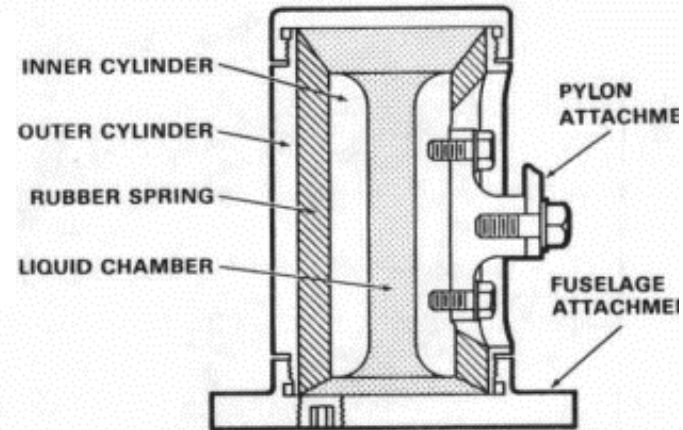
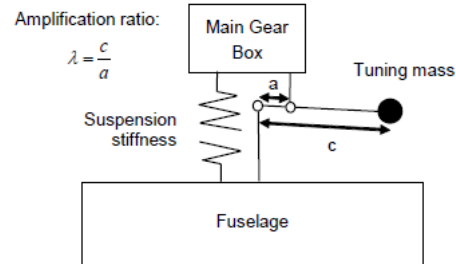


Figure 2. Schematic of the UH-1 DAVI Isolation System

LIVE - LIQUID INERTIA VIBRATION ELIMINATOR

D. R. HALWES
STRUCTURAL DYNAMICS ENGINEER
BELL HELICOPTER TEXTRON



PRESENTED AT THE 36TH ANNUAL FORUM OF
THE AMERICAN HELICOPTER SOCIETY
WASHINGTON, D. C. MAY 1980

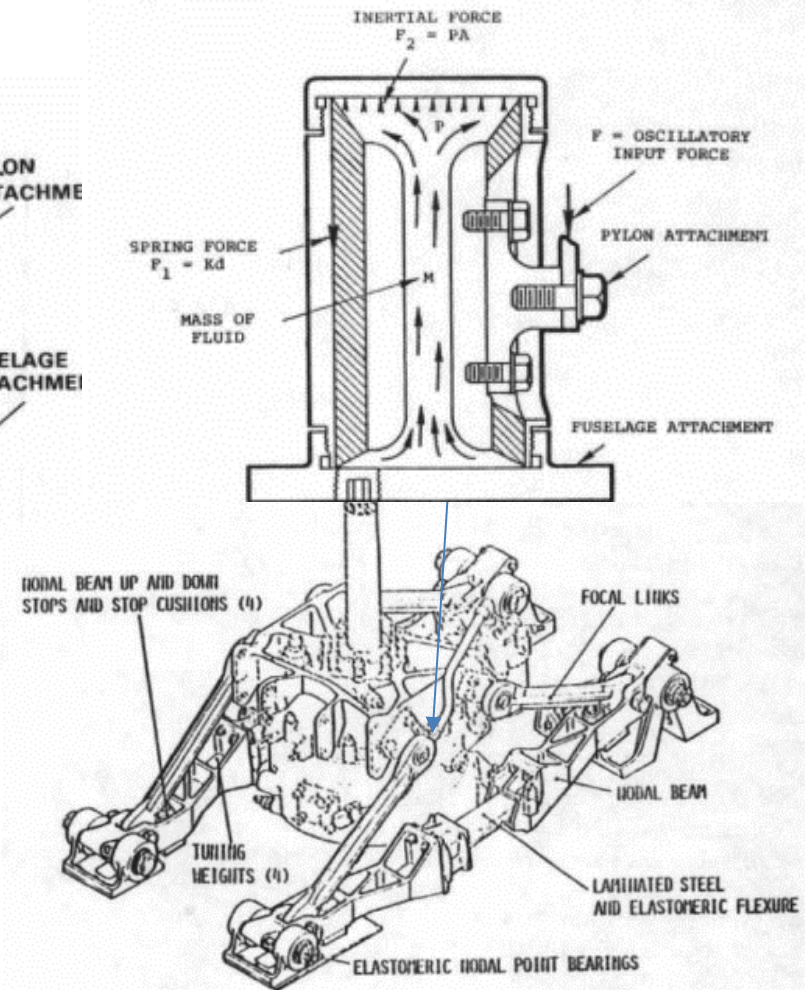


Figure 1. 206L Nodal Beam System Installation.

427 Pylon Isolation System

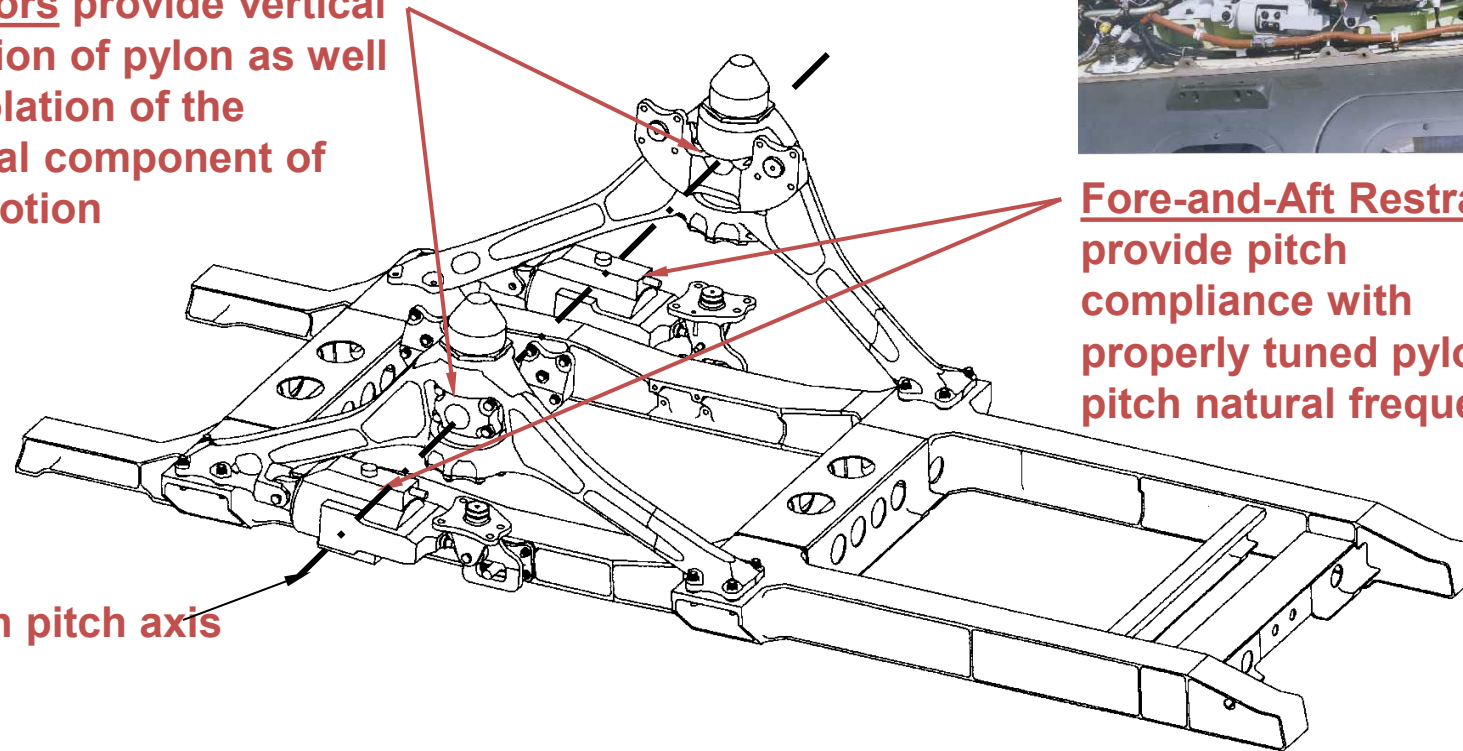
LIVE® (Fluidlastic®)

Isolators provide vertical isolation of pylon as well as isolation of the vertical component of roll motion



Fore-and-Aft Restraints provide pitch compliance with properly tuned pylon pitch natural frequency

Pylon pitch axis



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BELL 429, 7000 lbs

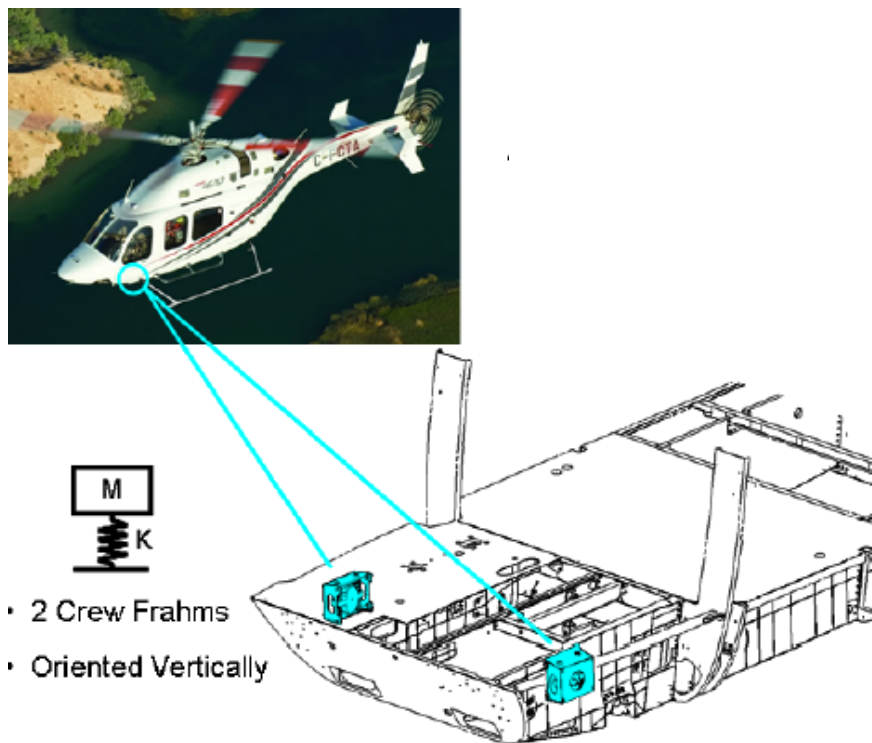


Fig. 7. 429 selected production Frahm locations.

Excerpt from the paper:

4/rev vibrations were minimized with a passive pylon isolation system consisting of two liquid inertia vibration eliminators (LIVE) (Ref. 1). The LIVE isolator pylon mounts are oriented and tuned to isolate 4/rev vibrations along the mast axis. Passive Frahm (aka “tuned mass”) absorbers (Ref. 2) tuned to 4/rev were used to absorb the residual 4/rev cabin vibrations. Two vertically oriented Frahms are mounted to the keel beams under the crew seats of the 429.

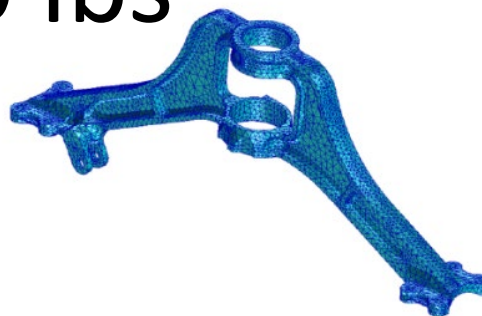
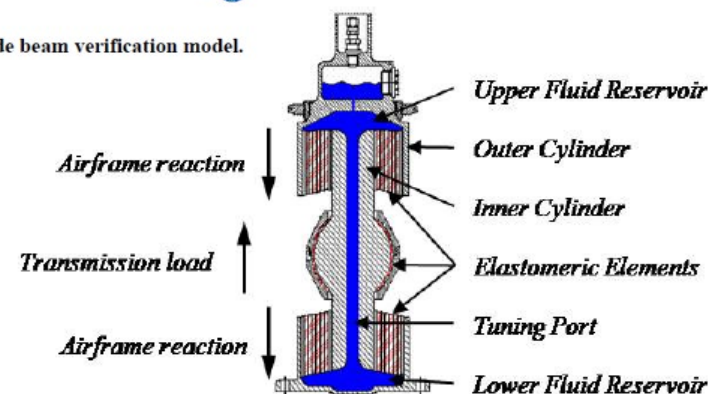


Fig. 17. Pylon side beam verification model.



VIBRATION ANALYSIS AND TESTING OF BELL 429 HELICOPTER

Kyle Riedel

kriedel@bellhelicopter.textron.com

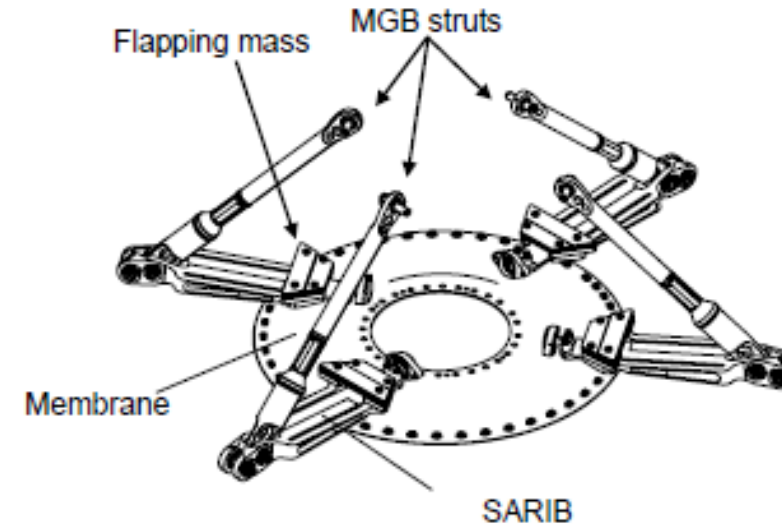
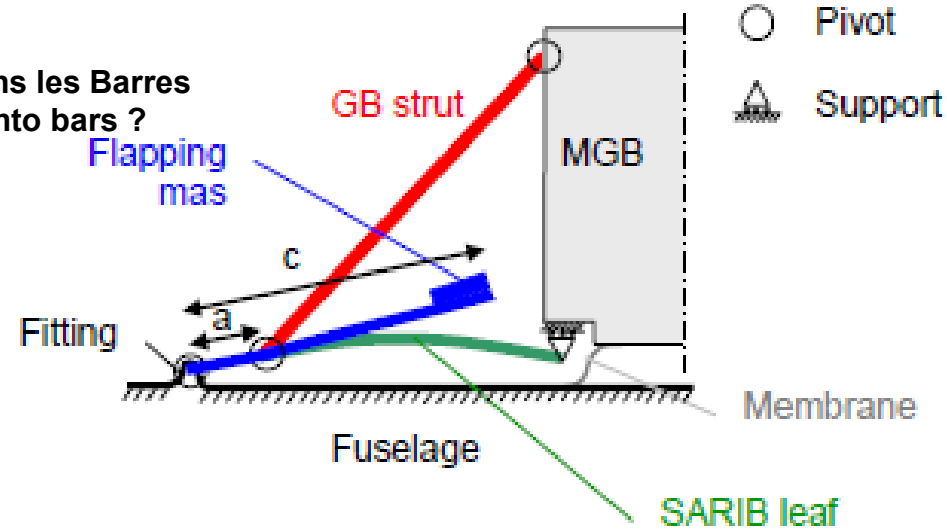
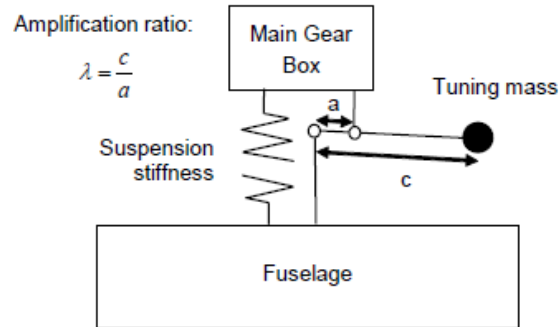
Engineer

Bell Helicopter Textron Inc., Fort Worth, Texas

Presented at the American Helicopter Society 66th Annual Forum, Phoenix, Arizona, May 11 – 13, 2010. Copyright © 2010 by the American Helicopter Society International, Inc. All rights reserved.

Eurocopter's (now Airbus) SARIB gearbox isolation (NH-90)

SARIB = Systeme a Resonateurs Integres dans les Barres
System with resonators integrated into bars ?



Boeing Vertol's IRIS: Improved Rotor Isolation System

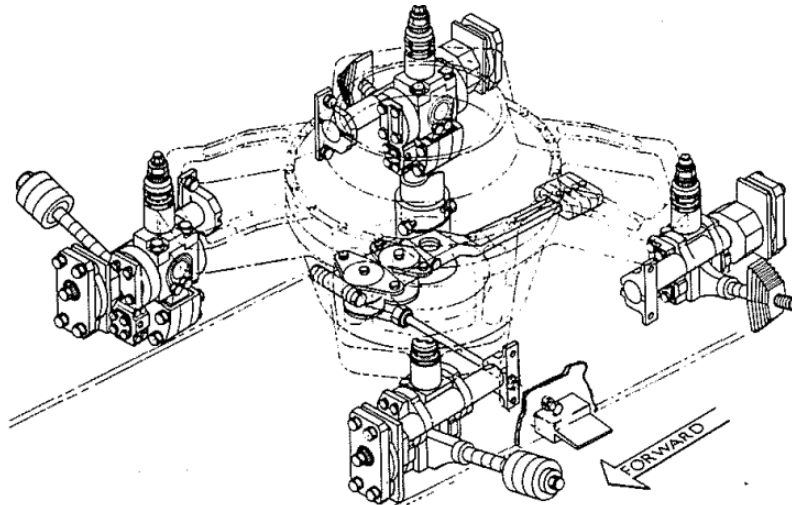


Figure 30. Arrangement of the YUH-61A Rotor-Isolation System

SECOND EUROPEAN ROTORCRAFT AND POWERED
LIFT AIRCRAFT FORUM

(1976)

ROTOR ISOLATION OF THE HINGELESS ROTOR
BO-105 AND YUH-61A HELICOPTERS

Rene A. Desjardins
Manager, Rotor Head, Controls and Vibration Design

W. Euan Hooper
Director of Technology
The Boeing Vertol Company

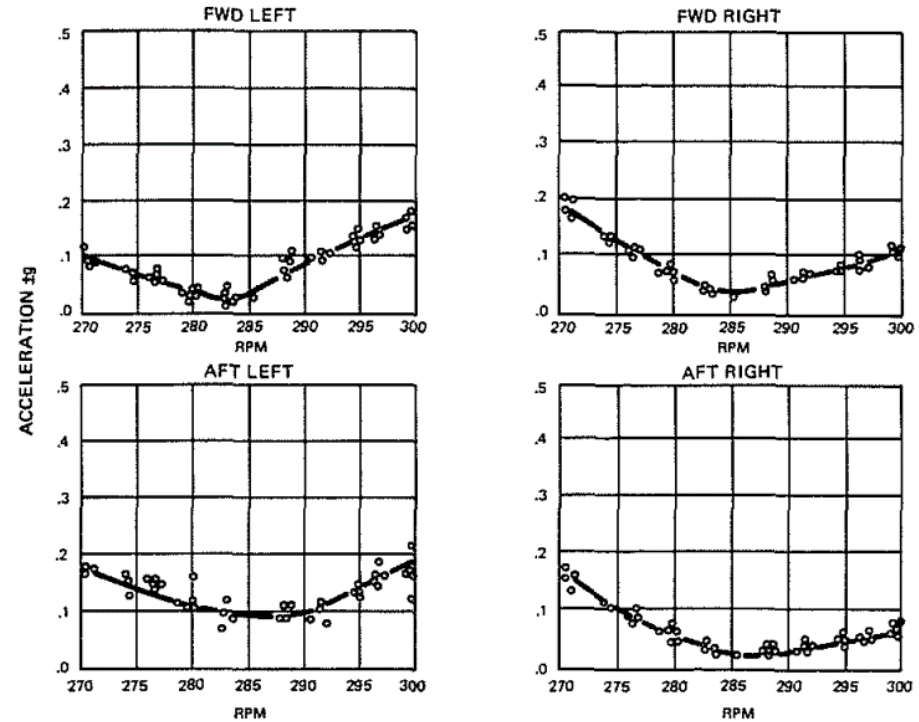
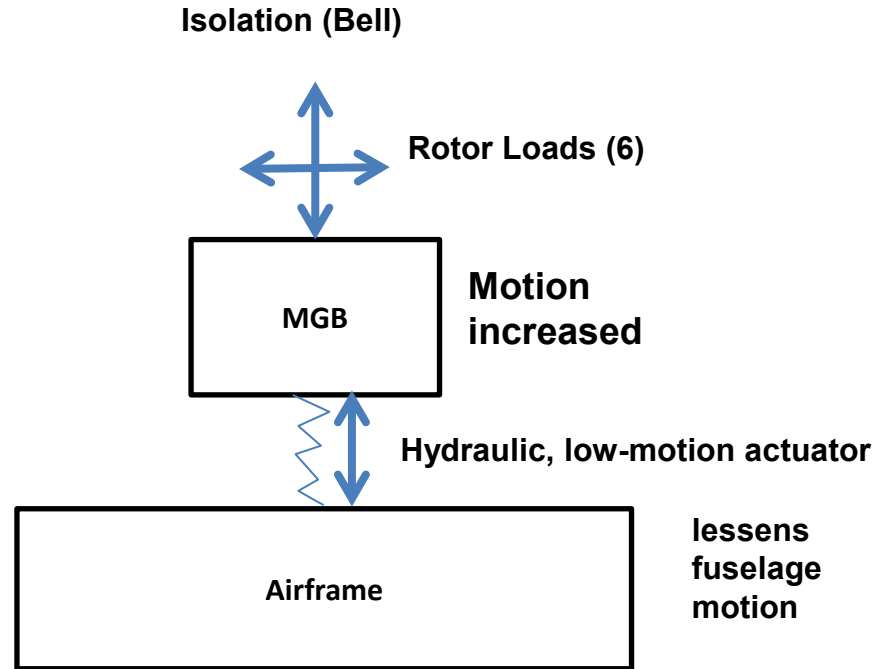


Figure 34. YUH-61A Vertical Airframe Vibration Under Isolators at 150 Kts

ACSR: Active Control of Structural Response



Westland W-30

FIGURE 5. Vibration Control Algorithm Performance - Manoeuvre Response

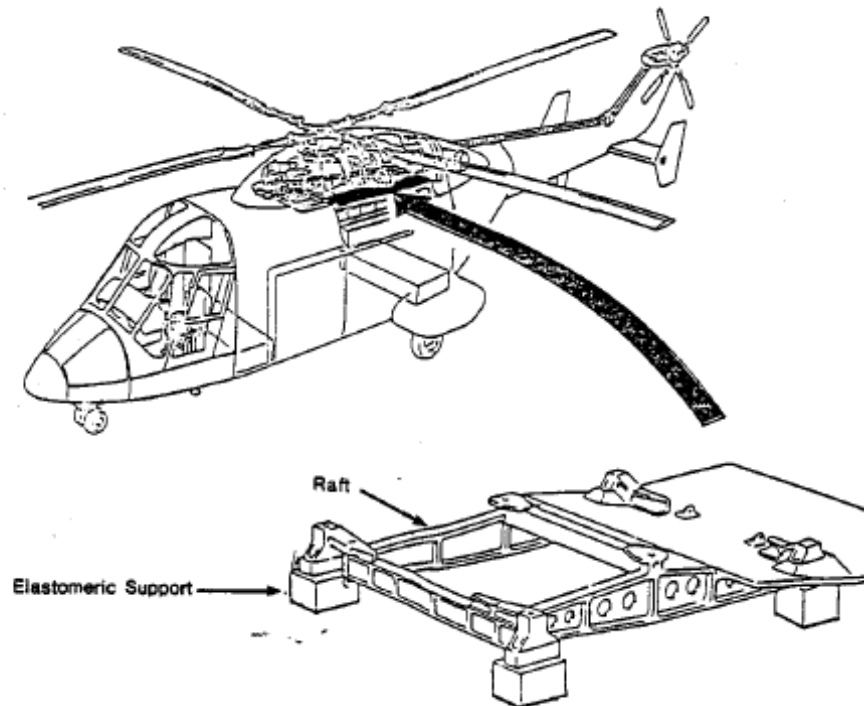


FIGURE 6. Westland 30 Series 100 Raft Construction and Location

King, S. P., and Staple, A. E., "Minimization of helicopter vibration through active control of structural response," Proceedings of the 12th European Rotorcraft Forum, October 1986, Paper 14 (also published in AGARD-CP-423, Rotorcraft Design for Operations, October 1986, pp 14-1-14-13).

MINIMISATION OF HELICOPTER VIBRATION THROUGH ACTIVE CONTROL OF STRUCTURAL RESPONSE

by

Dr S P King
Chief Dynamicist

and

A E Staple
Principal Engineer

Westland Helicopters Limited
Yeovil, Somerset, England

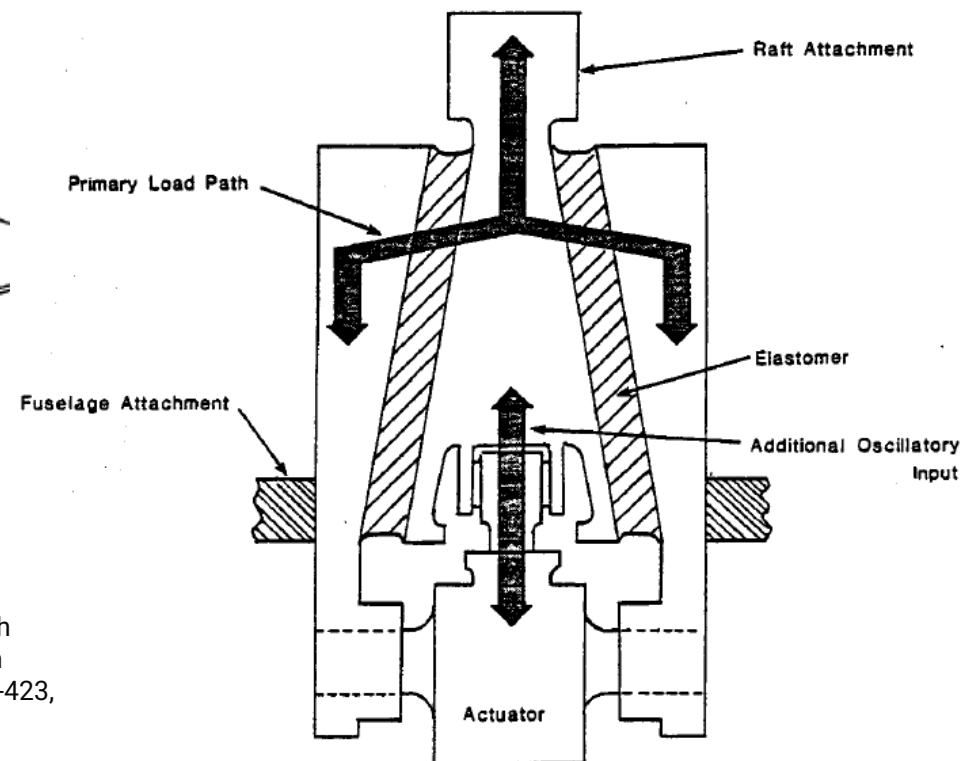


FIGURE 8. Modified Elastomeric Support (including Force Actuator)

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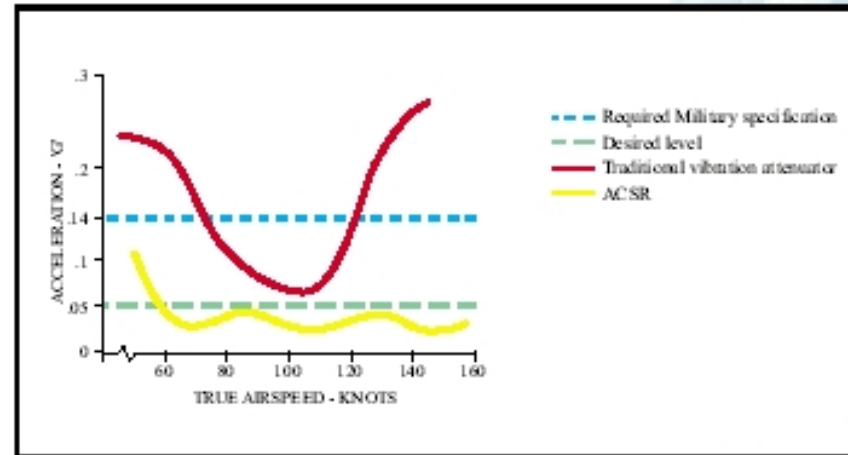
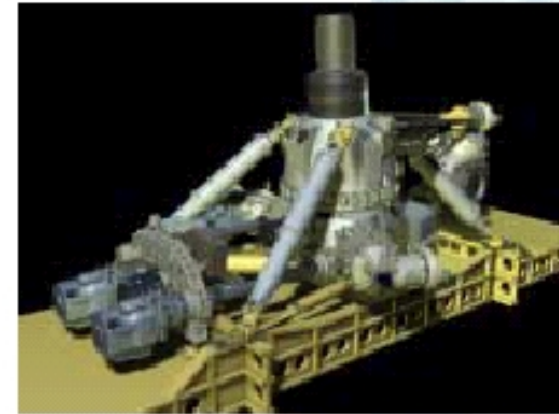
Westland

EH101 Active Control Response System

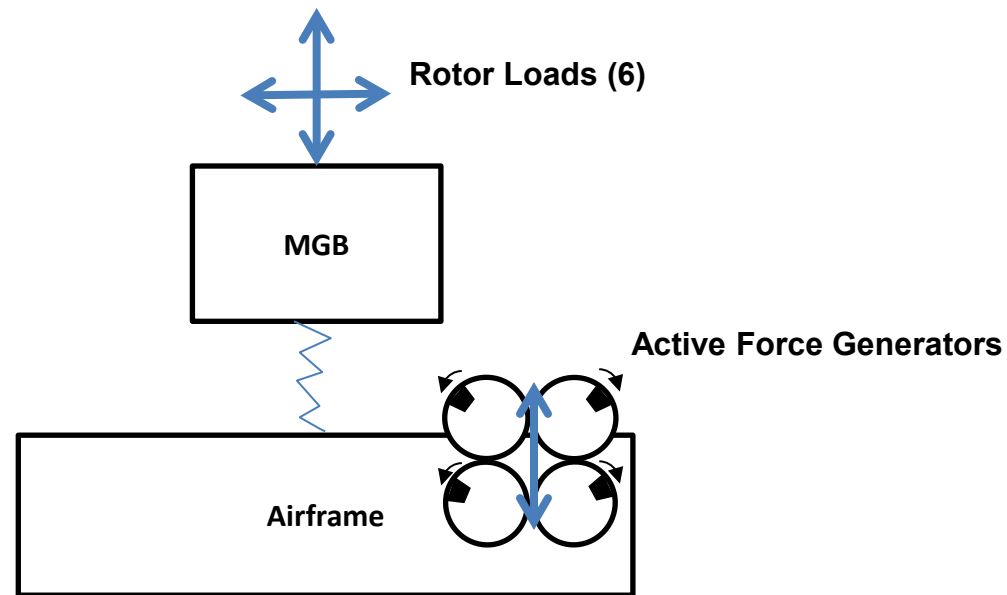
ACSR (Active Control of Structural Response)

An award winning system that uses computer controlled forces to reduce the helicopter's basic vibration to very low levels. Effective throughout the flight envelope, ACSR contributes to reduced life cycle costs through:

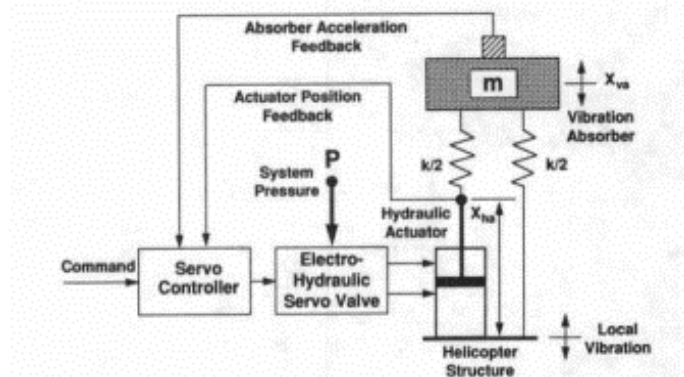
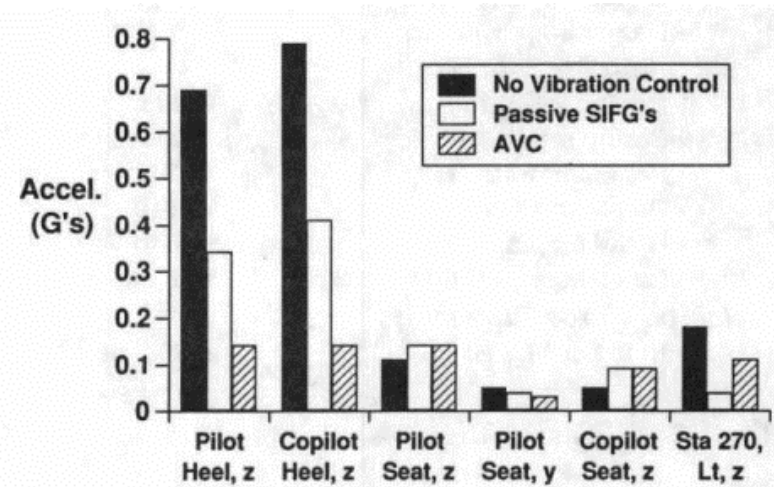
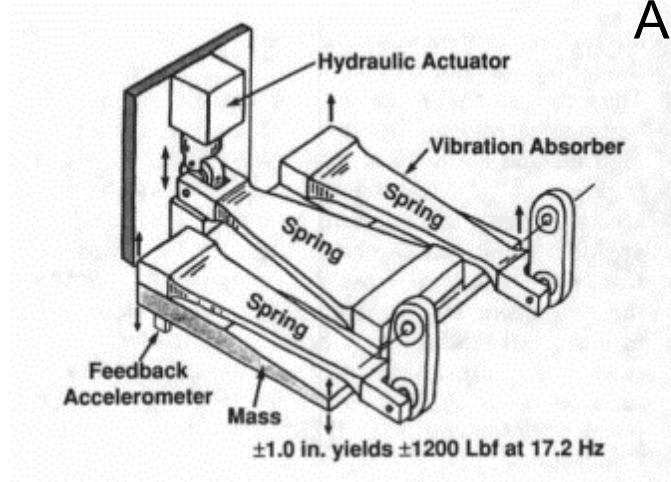
- Reduced structural fatigue
- Greater avionic systems reliability
- Improved crew and passenger comfort



In-Fuselage “Counter-Force” Active Vibe Control



AVC Flight Tested on a Black Hawk: Using Vibration Absorbers with Synthetic Damping (1995)



FLIGHT TEST OF AN ACTIVE VIBRATION CONTROL SYSTEM ON THE UH-60 BLACK HAWK HELICOPTER

W. Welsh
Dynamics Engineer

C. Fredrickson
Flight Test Engineer

C. Rauch
Systems Engineer
Moog Inc.
East Aurora, N.Y.

United Technologies Corp.
Sikorsky Aircraft Corporation
Stratford, Ct.

I. Lyndon
Principal Engineer
Westland Helicopters Ltd.
Yeovil, U.K.

Presented at the American Helicopter Society 51st Annual Forum, Fort Worth, TX, May 9-11, 1995.
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S-92[®] Uses Combined Active + Passive Methods



**Bifilar ,
pendulum
absorber**



**Moog Vibration Control
Actuation System**



**Hamilton Sundstrand
Computer**



Evolution of Active Vibration Control Technology

W. A. Welsh
Sikorsky Aircraft Co.

AHS 4th Decennial
Specialists' Conference on Aeromechanics
January 21, 2004

Zero-Vibe™ using counter-force i.e. force generators grouped around the “choke point” i.e. the main gearbox

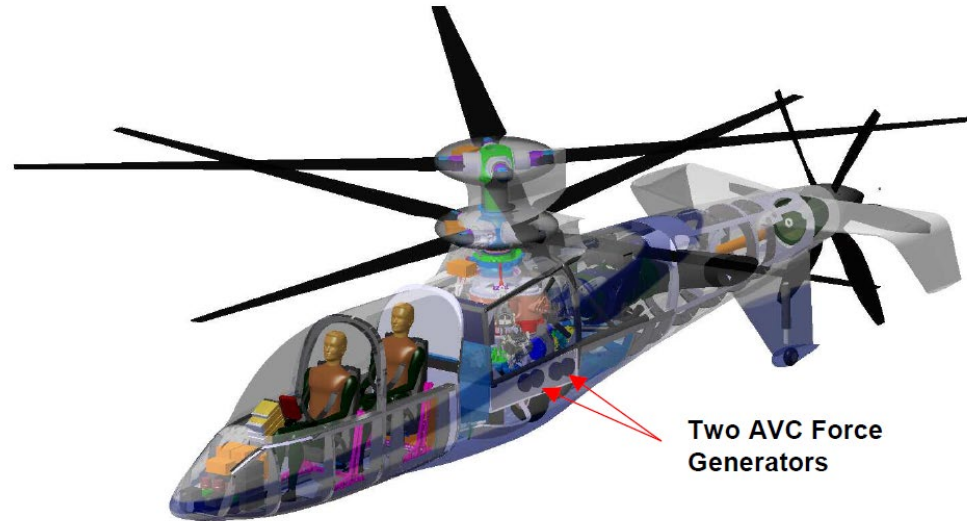


Figure 4. Cutaway view of the X2 Technology™ Demonstrator

Dynamics Design Characteristics of the Sikorsky X2 Technology™ Demonstrator Aircraft

R. Blackwell*

T. Millott**

Sikorsky Aircraft Corporation
Stratford, CT 06615

*Technical Fellow, email: rblackwell@sikorsky.com **Senior Dynamicist, email: tmillott@sikorsky.com Presented at the American Helicopter Society 64th Annual Forum, Montreal, Canada, April 29-May 1, 2008. Copyright © 2008 by the American Helicopter Society.

Force generator produces a uni-axial force

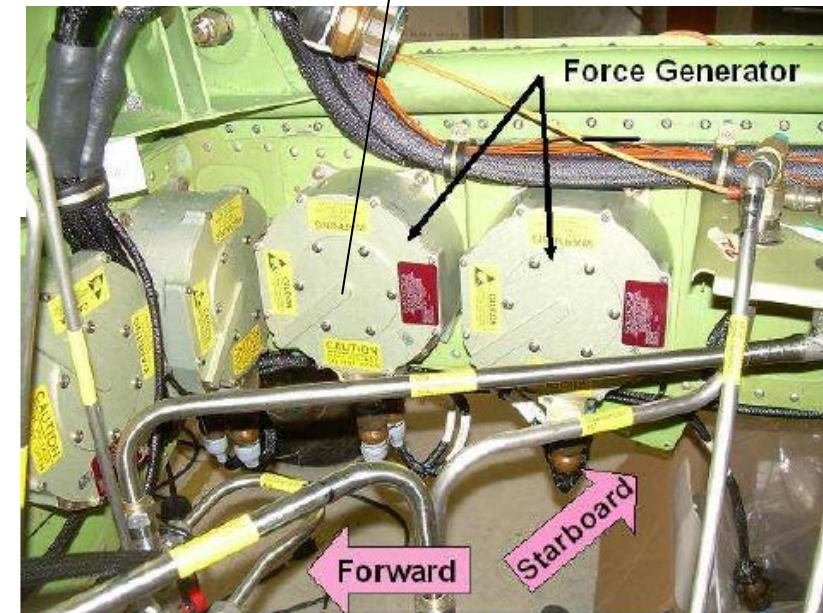
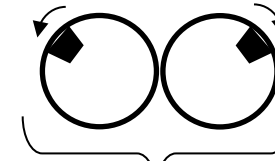
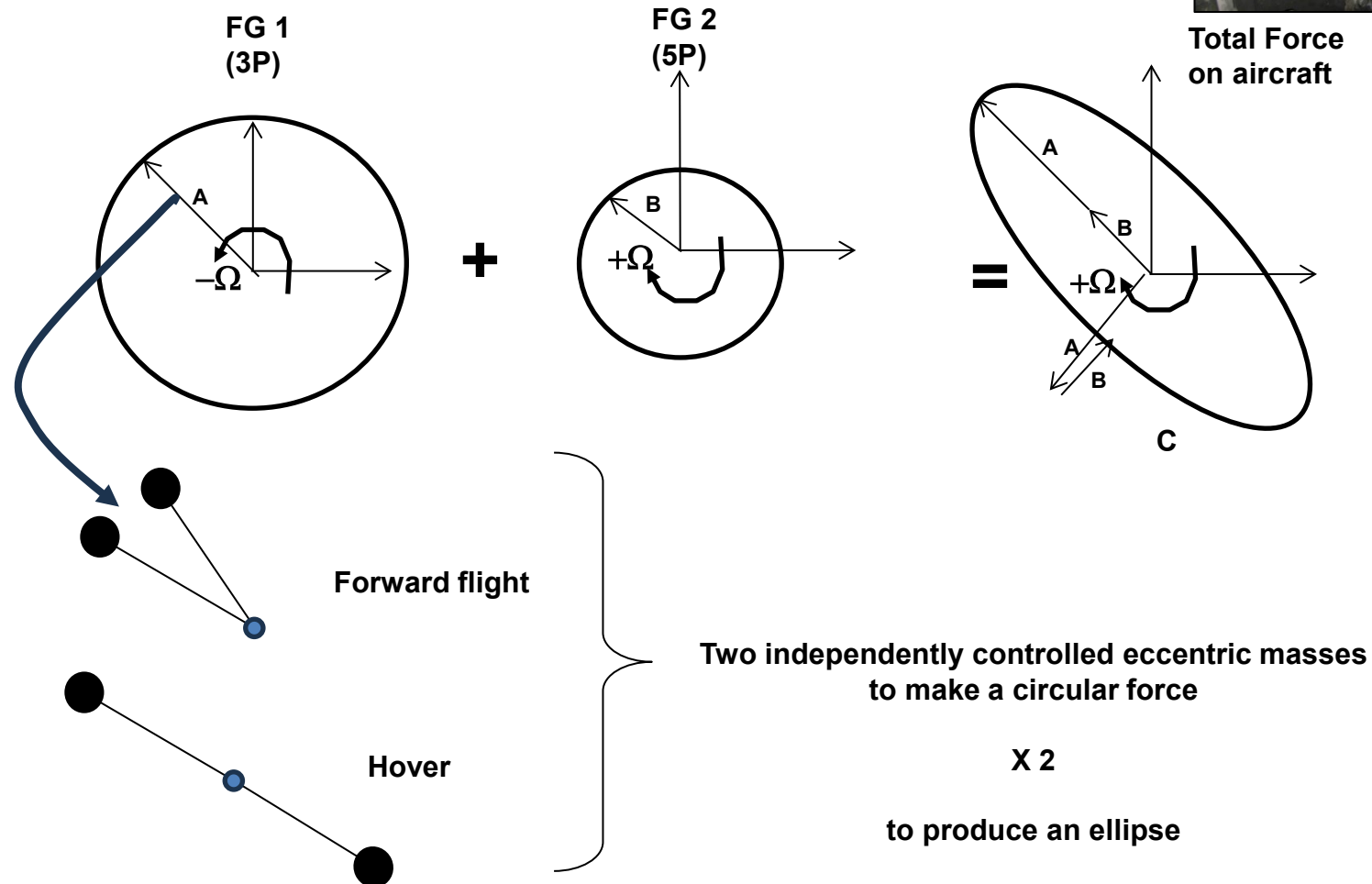


Figure 20. Installation of the FGs on the AVC space frame

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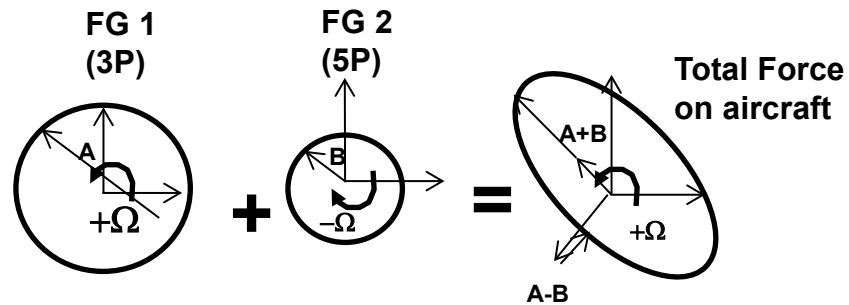
Two Counter-rotating “Force Generators” on the Hub or in the Fuselage Can Produce any Load Shape



ZERO-VIBE™ Ground Demo



HMVS Lab Testing
Lord Corporation Facility
Cary, NC
July-August 2012



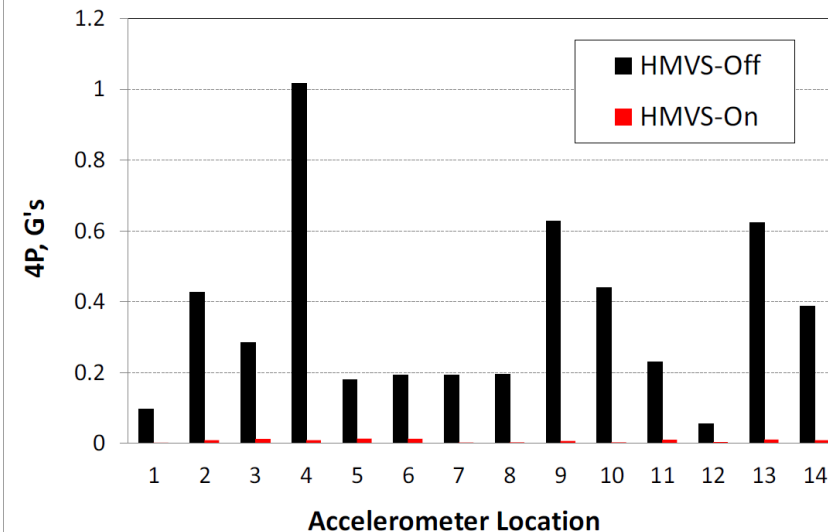
Ground and Flight Testing of a Hub Mounted Vibration Suppression System

Joseph Andrews, William Welsh
 Sikorsky Aircraft Corporation
 Stratford, CT

Russ Altieri
 LORD Corporation
 Cary, NC

James DiOttavio
 US Army Aviation Development Directorate (ADD)
 Ft Eustis, VA

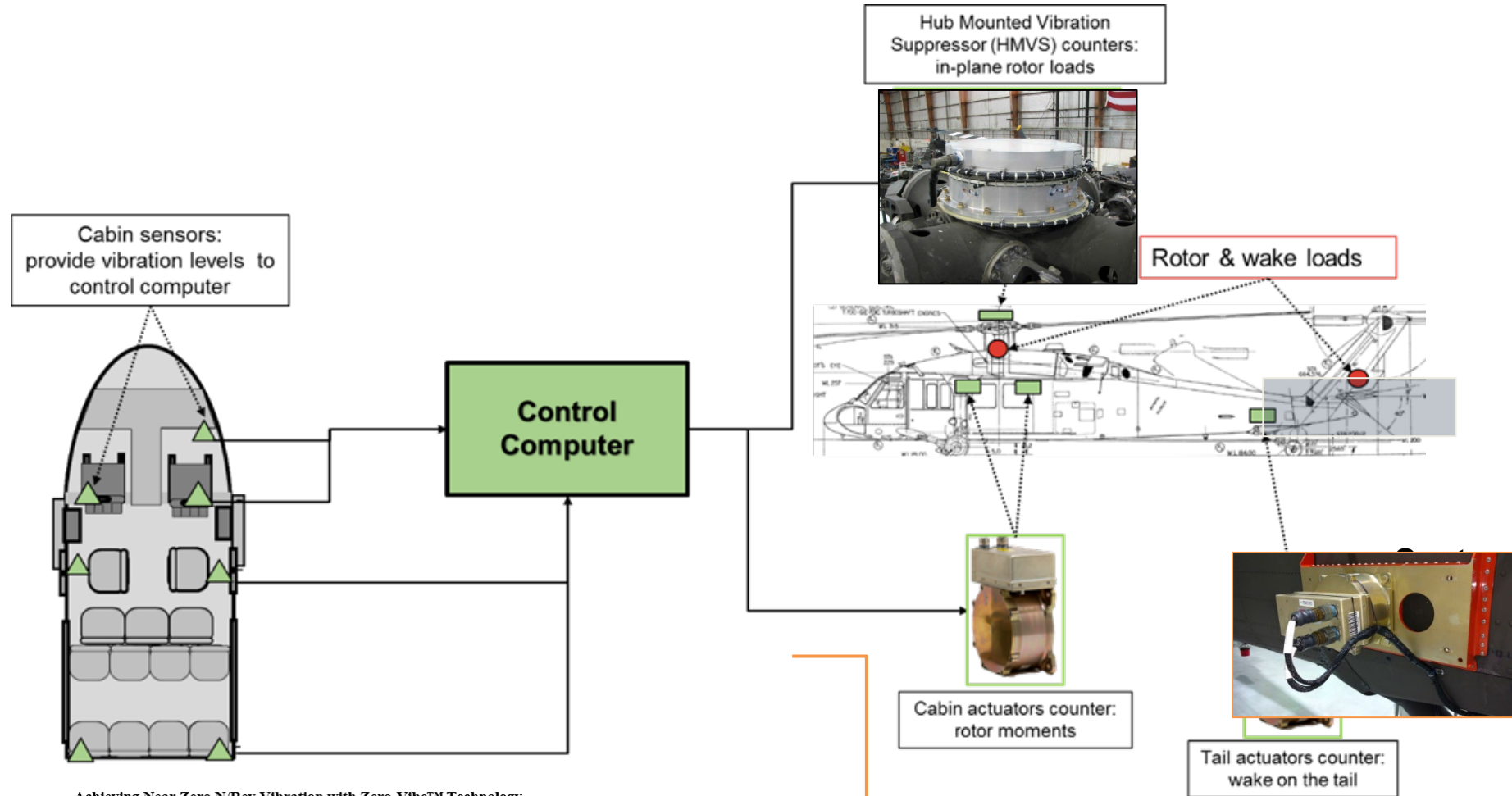
Presented at the American Helicopter Society 70th Annual Forum,
 Montreal, Quebec, Canada, May 20-22, 2014. Copyright © 2014 by the
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Additional Vibration Reductions Were Achieved by Addressing the Secondary Source with Actuators on the Tail (2018)



Achieving Near Zero N/Rev Vibration with Zero-Vibe™ Technology

Michael Monico
Dynamics Engineer
Sikorsky, A Lockheed Martin Company
Stratford, CT

James DiOttavio
Flight Test Engineer
U.S. Army Aviation Development Directorate
Ft Eustis, VA

Daniel Kakaley
Sr. Engineer, Mechanical Research
LORD Corporation
Cary, NC

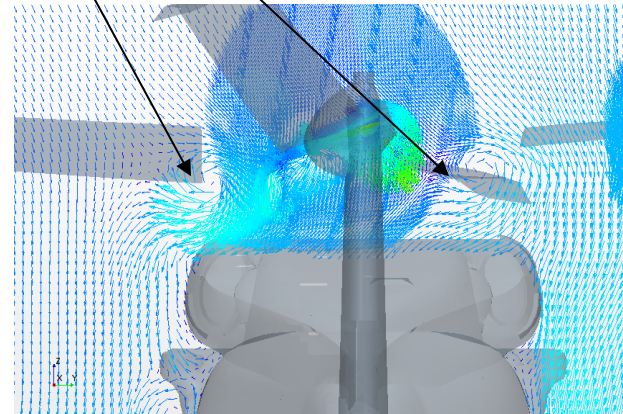
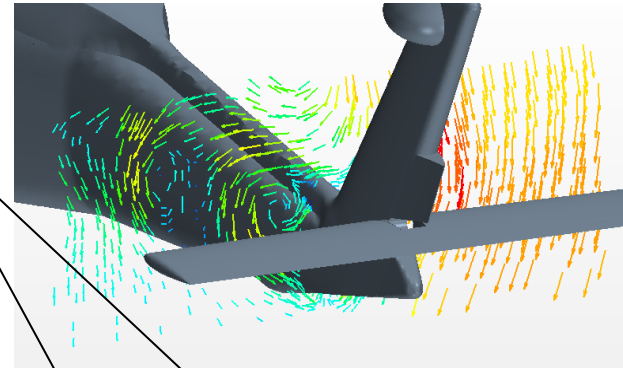
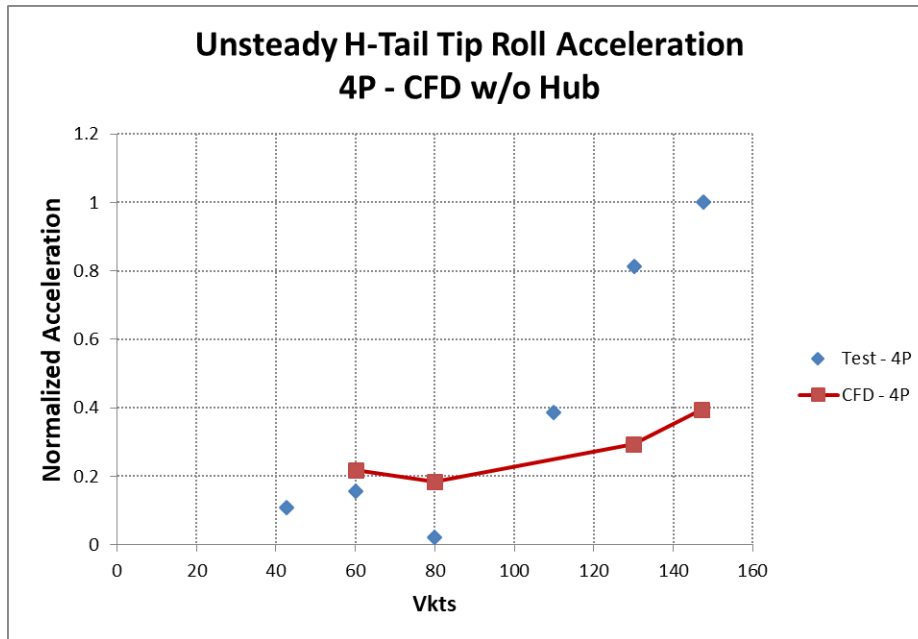
Presented at the AHS International 74th Annual Forum & Technology Display, Phoenix, Arizona, USA, May 14-17, 2018.
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CFD (Star-CCM) shows wake impingement on the tail surfaces can produce another “load path” for NP loads and vibration

- Co-rotating blade root vortices
- Bias hub/blade root disturbances to left side of H-tail



Siemens PLM Software 2018
Simcenter conference-Americas
Detroit, MI, 10-15-2018

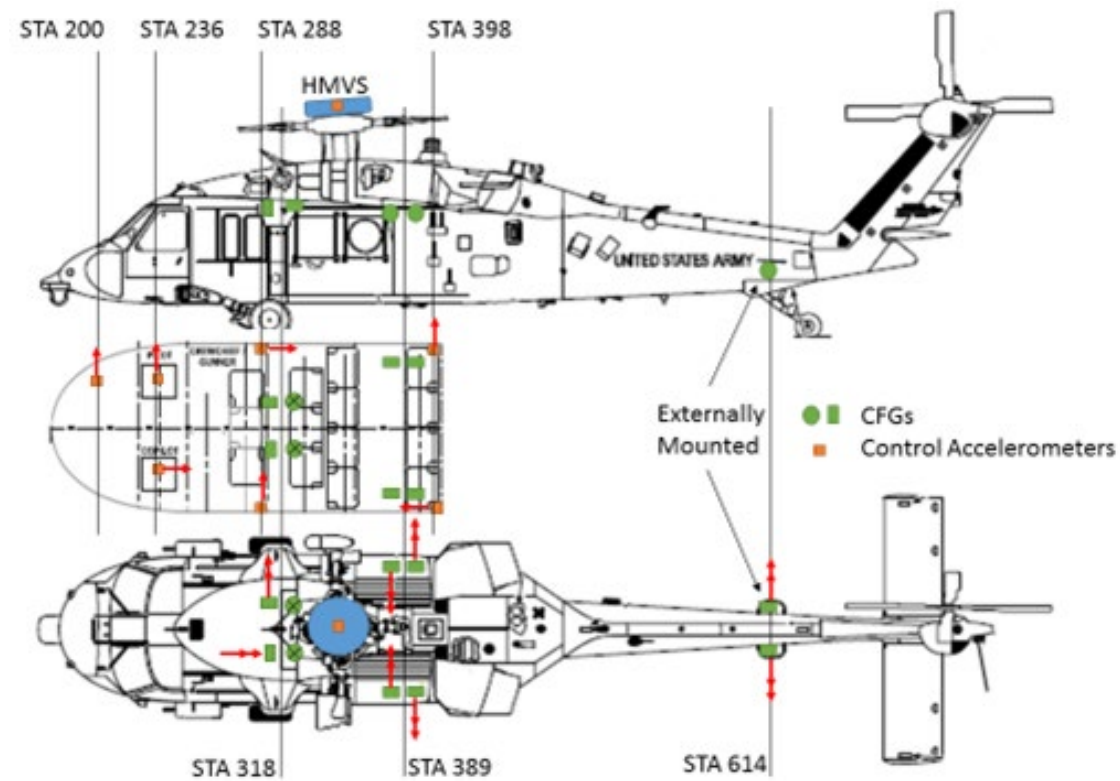
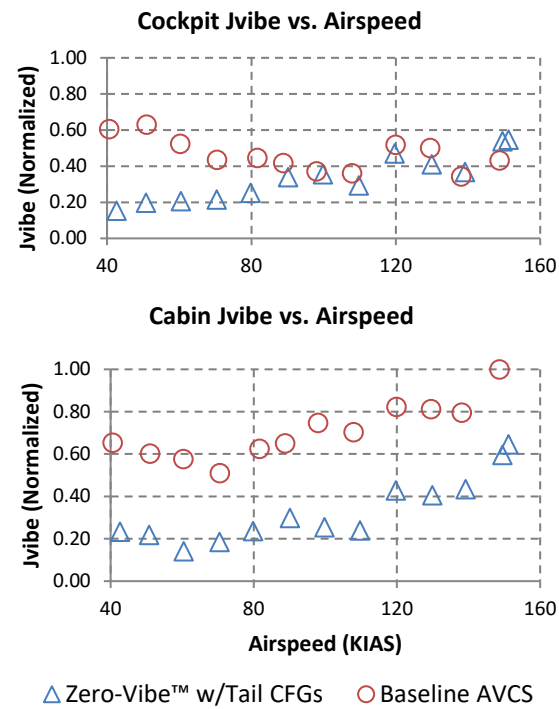
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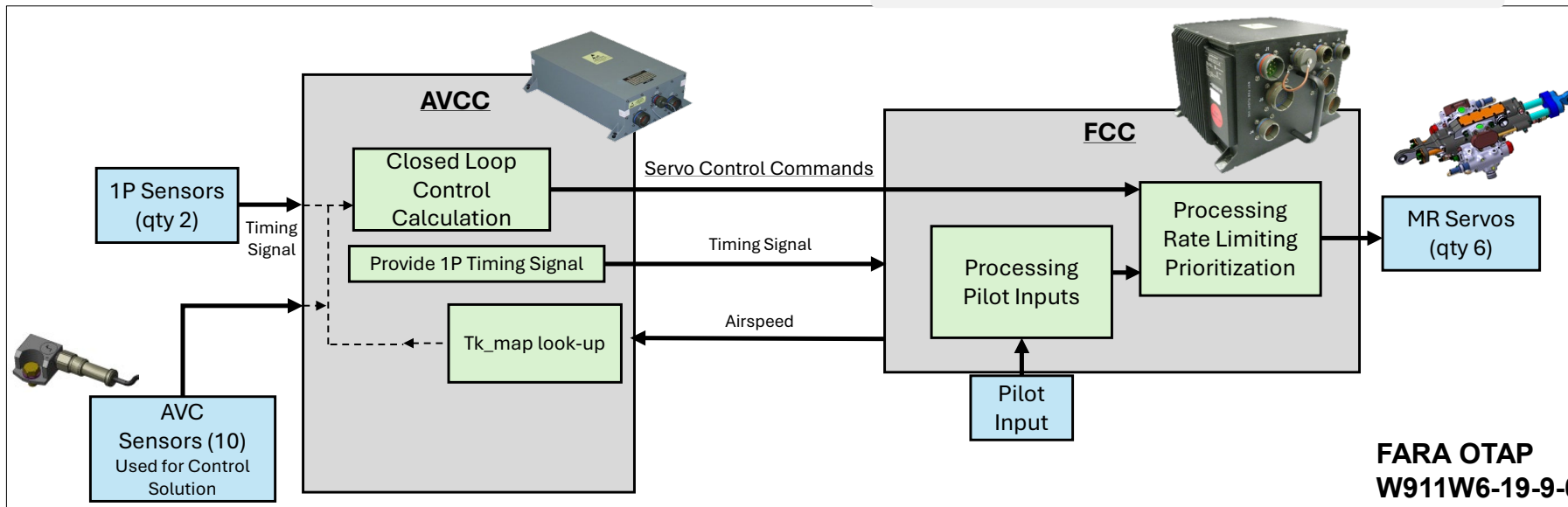
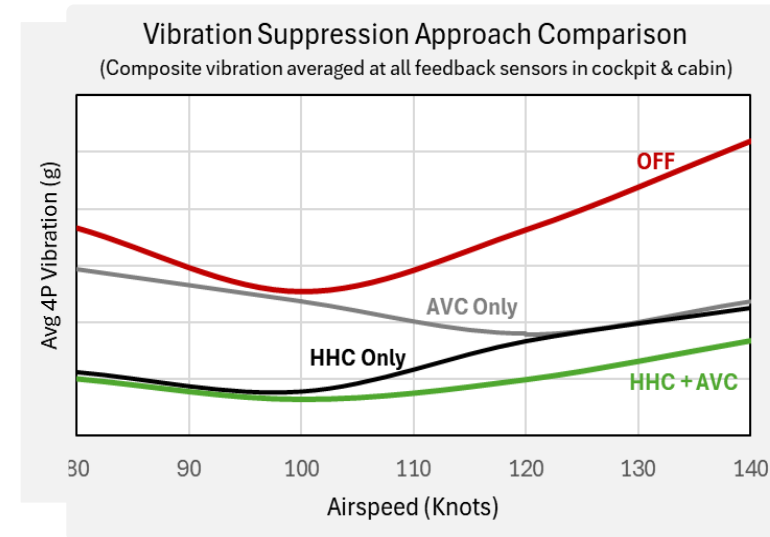
Addressing both the rotor pylon and tail plane load paths can be necessary to achieve very low vibration



Figure 1: UH-60M ASN 07-20034 in the Zero-Vibe™ Configuration



Combined AVC + HHC on the Co-Axial Raider[®] helicopter (2025)



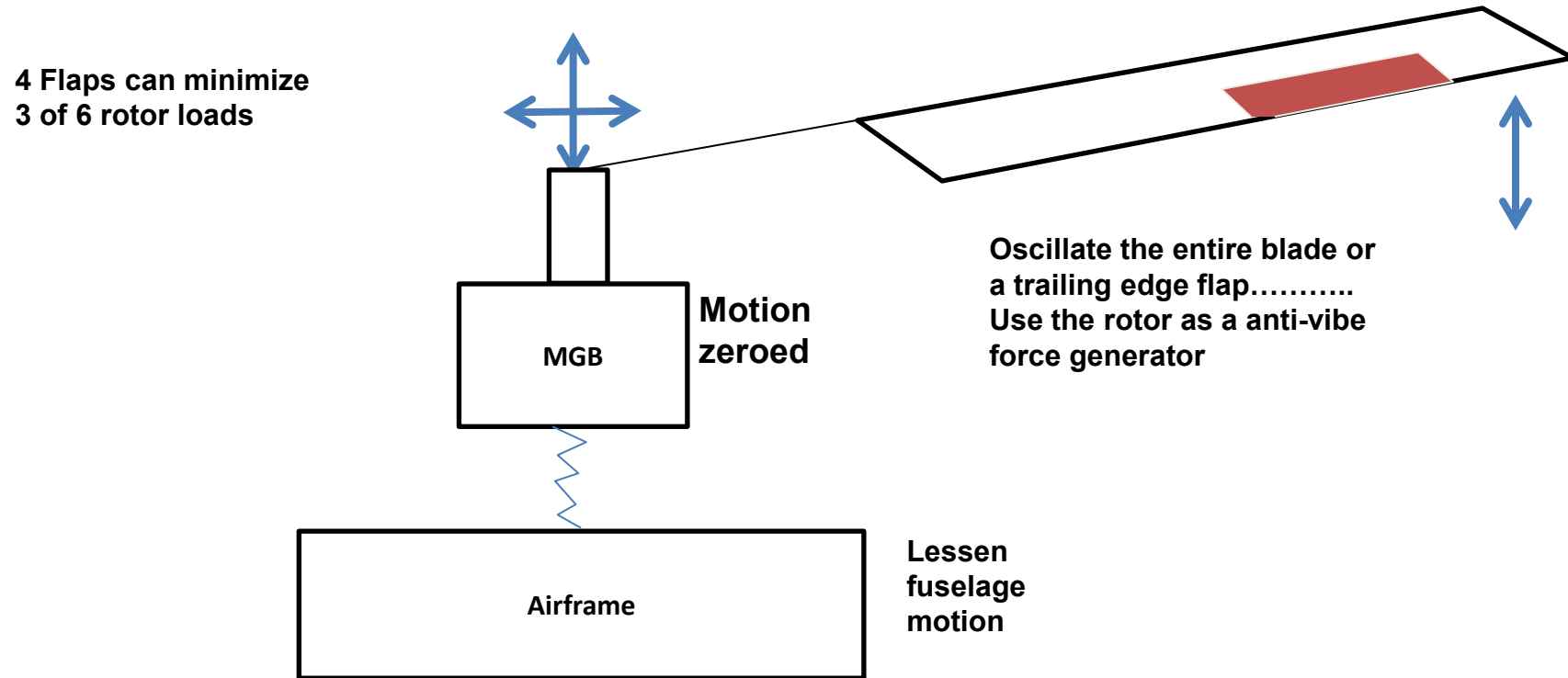
FARA OTAP
W911W6-19-9-0005

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Active Rotor (for both 1P and NP)

Sikorsky, Boeing, Eurocopter



Boeing SMART Rotor

Limited Authority Trailing Edge Flap Piezo material actuators

Wind Tunnel Test of the SMART Active Flap Rotor

Friedrich K. Straub
Boeing Technical Fellow
The Boeing Company
Mesa, Arizona
friedrich.k.straub@boeing.com

Vaidyanathan R. Anand
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The Boeing Company
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Benton H. Lau
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Presented at the American Helicopter Society 65th Annual Forum, Grapevine, Texas, May 27-29, 2009. Copyright © 2009 by the American Helicopter Society International Inc. All rights reserved.

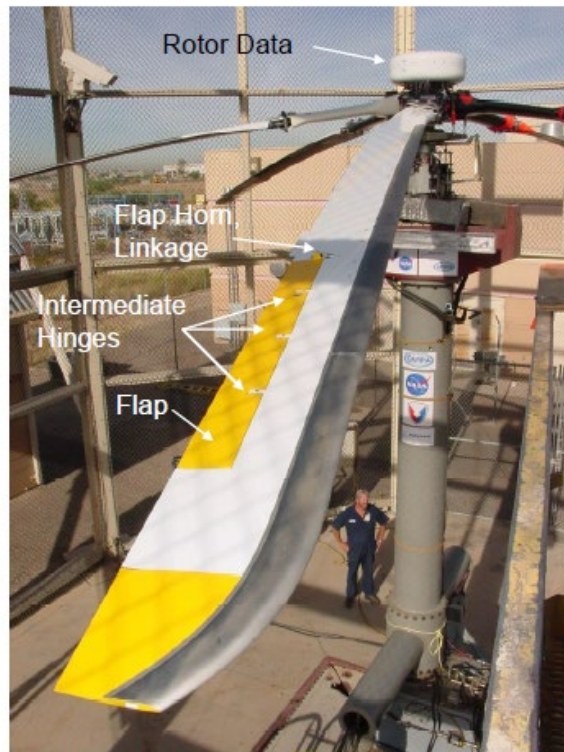


Figure 1b: SMART rotor blade on whirl tower

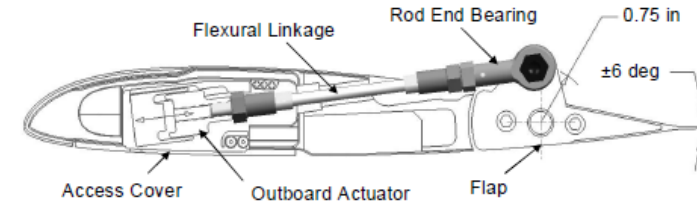


Figure 1c: SMART Blade, flap, actuator cross-section

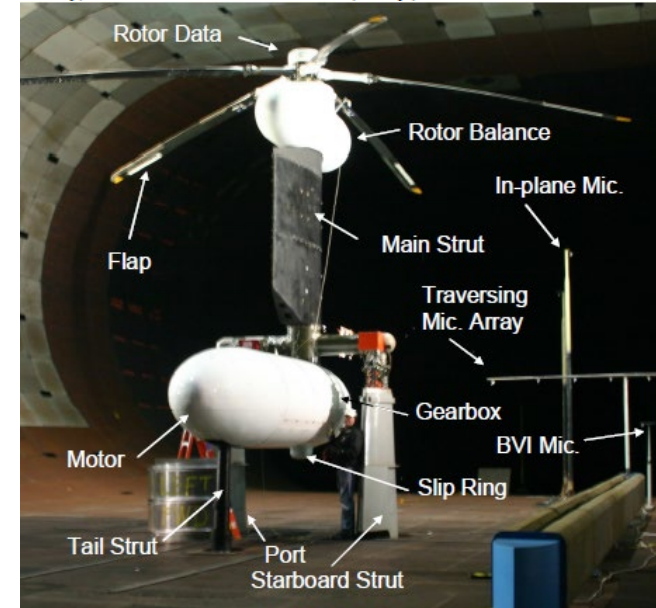


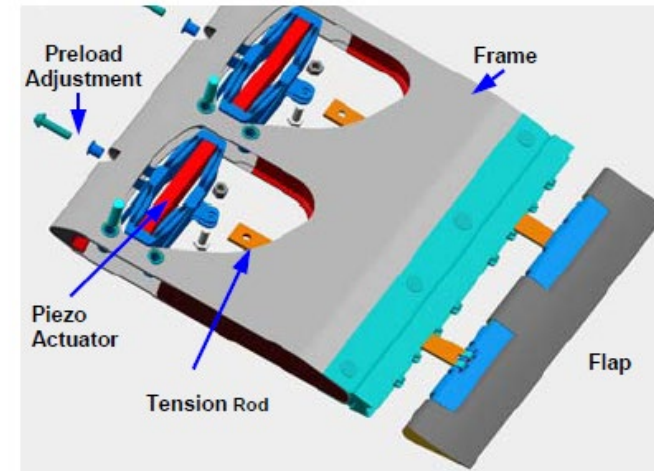
Figure 3a: SMART rotor in the NFAC 40- by 80-foot wind tunnel (looking upstream)

Eurocopter's Trailing Edge Flap With Piezo Electric Actuators



BK117 S7045 with active flaps rotor

Flight Tested 2006



Recent advances in Eurocopter's passive and active vibration control

Peter Konstanzer*
peter.konstanzer@eurocopter.com

Bernhard Enenkl
bernhard.enenkl@eurocopter.com

EUROCOPTER DEUTSCHLAND GmbH, Munich, Germany

Pierre-Antoine Aubourg
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Paul Cranga
paul.cranga@eurocopter.com

EUROCOPTER SAS, Marignane, France

Presented at the American Helicopter Society 64th Annual Forum, Montréal, Canada, April 29 – May 1, 2008. Copyright © 2008 by the American Helicopter Society International, Inc. All rights reserved.

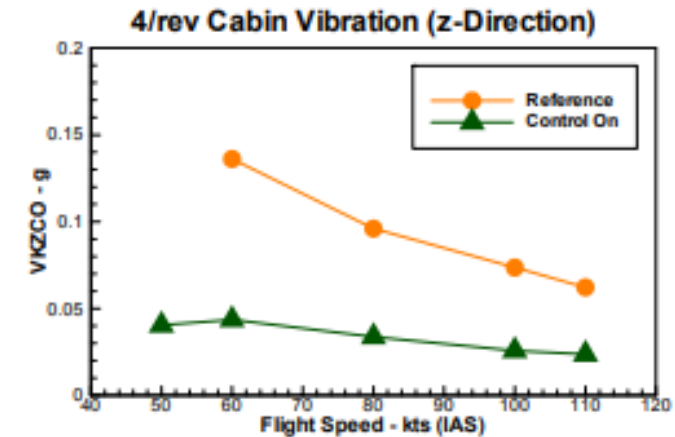


Figure 20: Vertical 4/rev cabin vibration vs. level flight speed



Sikorsky
A United Technologies Company



**United Technologies
Research Center**



Whirl and Wind Tunnel Testing of the Sikorsky Active Flap Demonstration Rotor

Peter F. Lorber

Benjamin Hein

John O'Neill, Benjamin Isabella

Joseph Andrews, Jonathon Wong, Mikel Brigley

Phillip LeMasurier

Sikorsky Aircraft

Flight Sciences

Advanced Concepts

Experimental Aeromechanics

Dynamics & Internal Acoustics

Aero & External Acoustics

United Technologies Research Center

Technical Fellow

Brian E. Wake

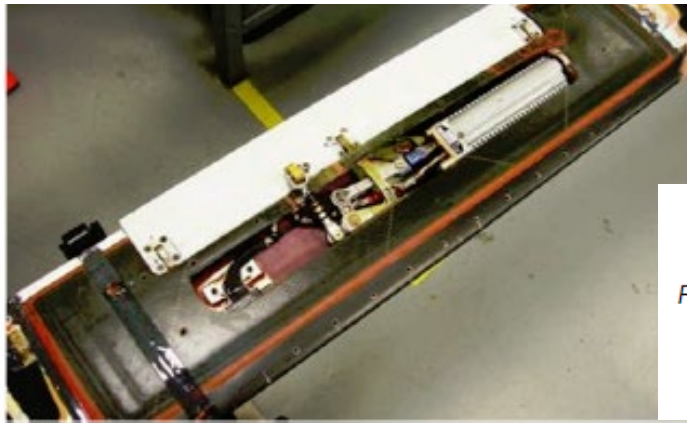


*67th AHS International Annual
Forum and Technology Display*

*Virginia Beach, VA,
May 3-5, 2011*



Sikorsky Active Flap Rotor



67th AHS International
Forum and Technology

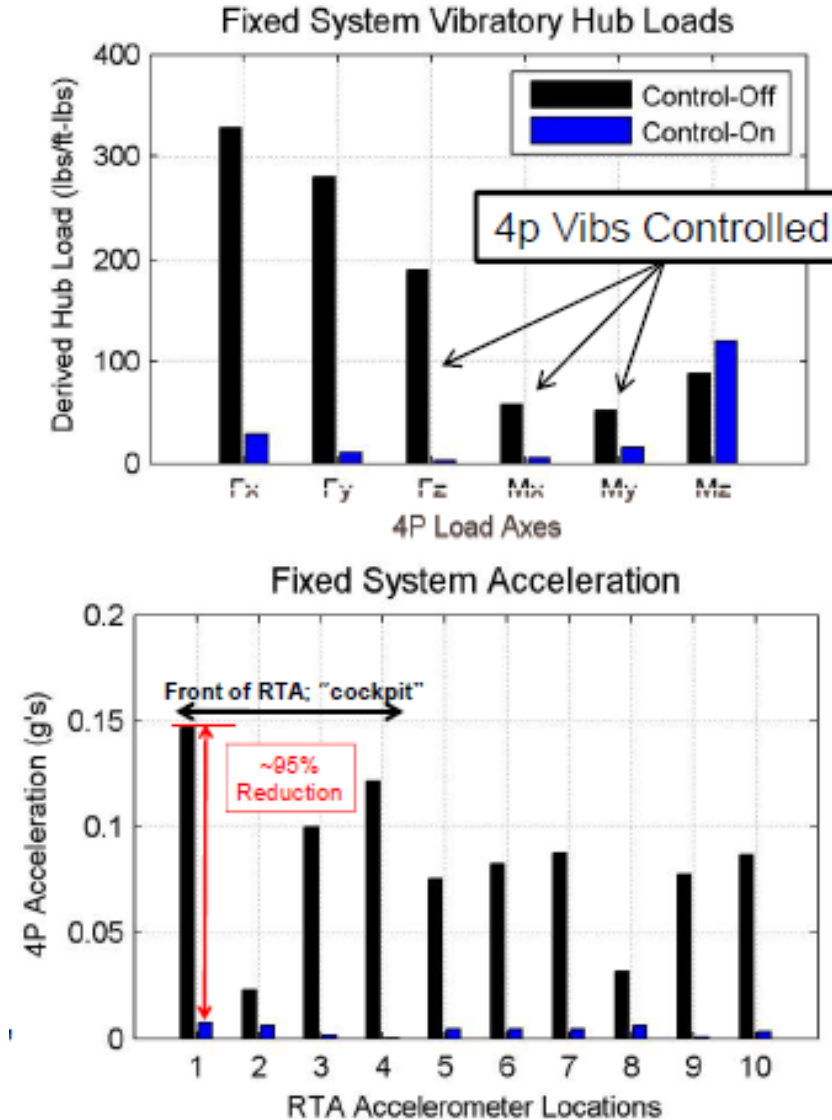
Virginia Beach, VA
May 3-5, 2011



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Sikorsky Active Flap Rotor 95% vibration reductions demonstrated in the “fuselage”



67th AHS International Annual
Forum and Technology Display

Virginia Beach, VA,
May 3-5, 2011

Conclusions

- Technology has developed enough to *Globally* (cockpit, cabin, tailcone) eliminate vibration in helicopters by using combinations of technologies
 - ✓ AVC at choke points + HHC
 - ✓ AVC at choke points + IBC
 - ✓ Isolation at choke points (Main and tail rotors)
 -
 -
 -
- Revive HHC...at least for low amplitudes, it's virtually free !
 - ✓ Seal wear ?
- Develop “Dynamic Controllers” for transient vibration suppression
- “Counter-Force” or “Choke point” approaches show a lot of promise
- Reduce empty weight by reducing equipment qualification vibration levels via MIL-STD-810

Questions?

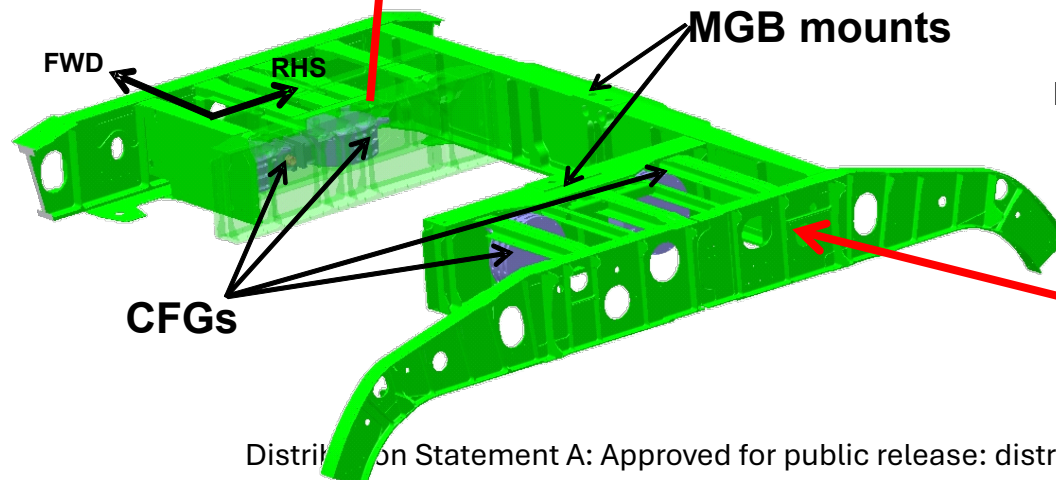
ZERO-VIBE™

Full demonstration in 2014-2015



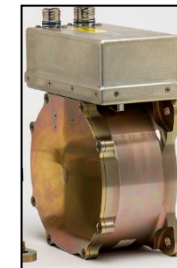
Step 1 – HMVS demo-completed

Replace bifilar with Dual Frequency Hub Mounted Vibration Suppressor (HMVS)



Step 2 – DEMO full Zero Vibe™

Install 4 Lord circular force generators (CFGs), mounted on/near main transmission (MGB)



LORD
AskUsHow™

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ZERO-VIBE™

HMVS flight tests successfully completed

First Flight – July 2013

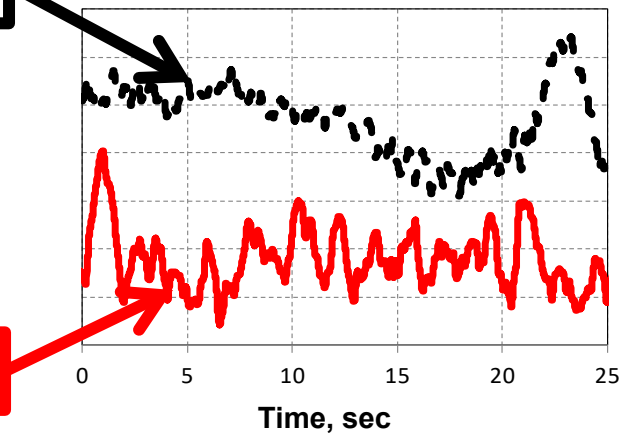
Last Flight – March 2014

Achieved : 150 kts, 45 deg
angle of bank, autorotations

Bifilar Only

Pilot Heel
Vertical
4/rev
(g's)

HMVS On



FELKER AIRFIELD
FT. EUSTIS, VA

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Ground and Flight Testing of a Hub Mounted Vibration Suppression System

Joseph Andrews, William Welsh
Sikorsky Aircraft Corporation
Stratford, CT

Russ Altieri
LORD Corporation
Cary, NC

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Mock-up Model of IBC Actuator on UH-60 Helicopter at Ames



- Mock-up model of IBC actuator machined from aluminum block by ZFL
- No mechanical interference problems found

IBC Actuators Made for LRTA Test Stand



FULL-SCALE WIND TUNNEL TEST OF AN INDIVIDUAL BLADE CONTROL SYSTEM FOR A UH-60 HELICOPTER

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Fig. 1. Large Rotor Test Apparatus and UH-60A rotor installed in 80- by 120-Foot Wind Tunnel.

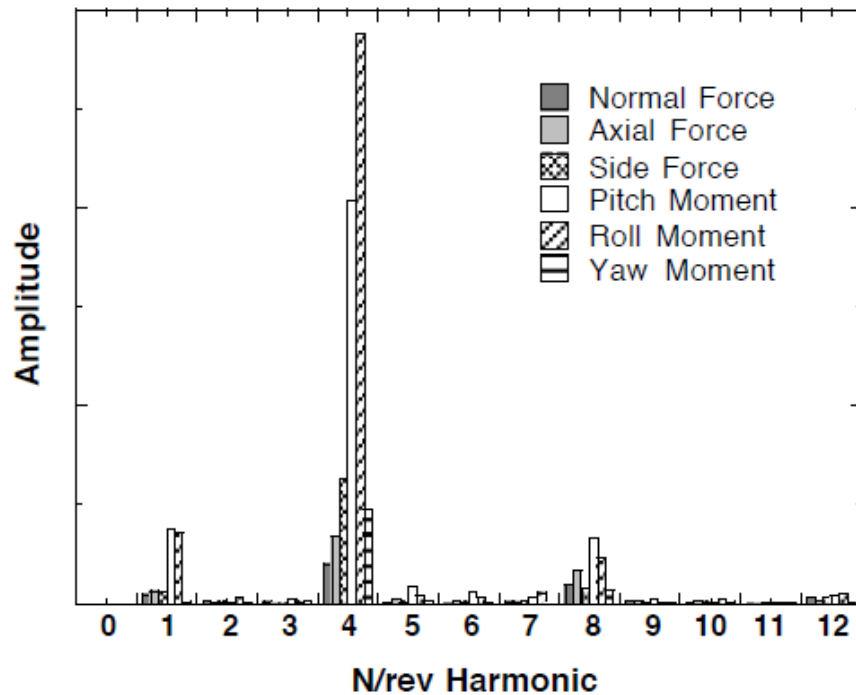


Fig. 5. Vibration spectrum at 46 kts.

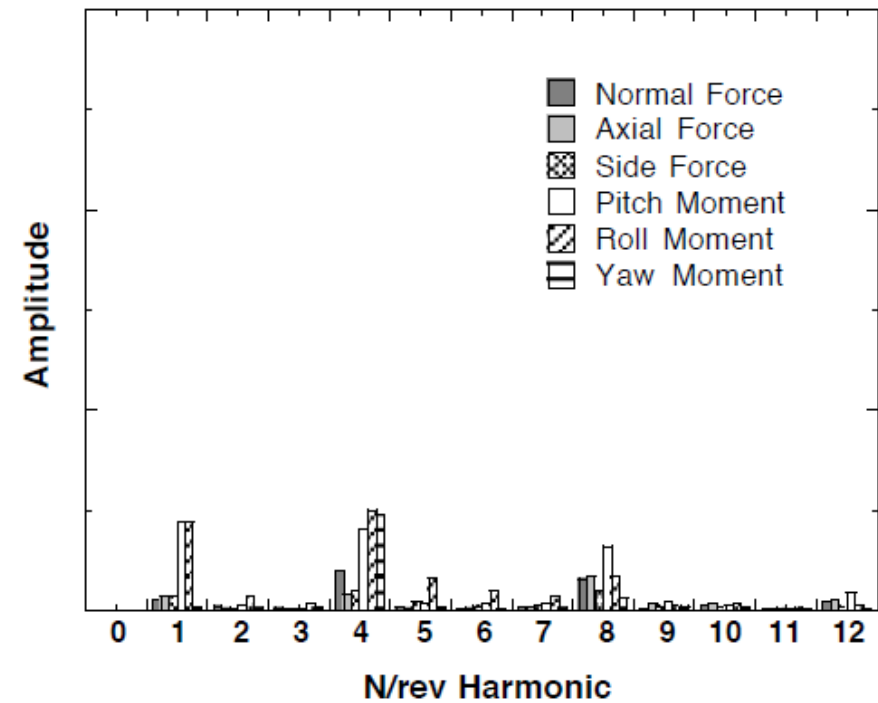


Fig. 13. Vibration spectrum with 1.0° of 3/rev IBC applied at 315° phase angle. (46 kts, baseline levels shown in Fig. 5.)

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