OPTIMIZATION ISSUES WITH COMPLEX ROTORCRAFT COMPREHENSIVE ANALYSIS

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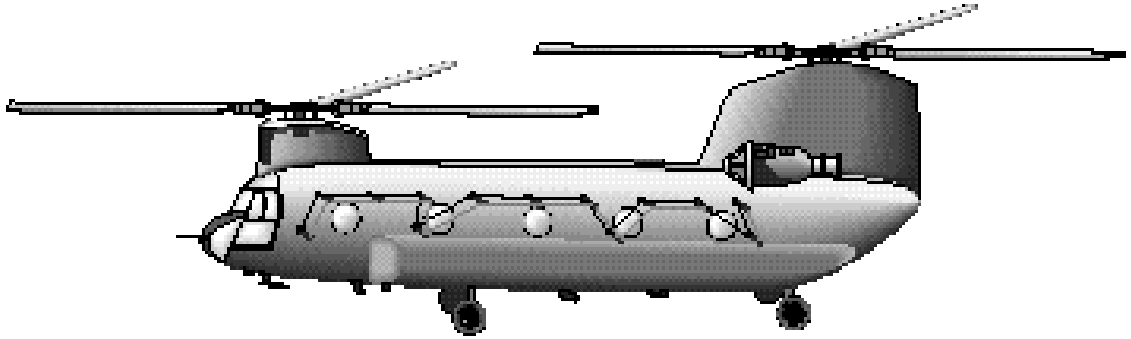
Outline

- **Low vibration rotor blade design**
- **Derivative calculations**
- **Optimization results**
- **Lessons learned**
- **Summary**

Low Vibration Rotor Blade Design



- Typical 3-bladed tandem rotor helicopter with advanced blade tip sweep
- Rotor blade has 13 bays with airloads on the outboard 10 bays
- Airloads applied for 2 flight conditions
- Goal - Reduce fixed system vibratory hub loads by tailoring blade properties

Low Vibration Rotor Blade Design Related Research

- Boeing Helicopter overview paper (AIAA-98-4733)
  - Session 7 at MA&O Conference
  - Gradient and nongradient-based optimization
- Nongradient-based optimization
  - Evolutionary Programming methods
    - 1998 Paper by Hirsh and Young of Boeing Helicopter Philadelphia
  - Approximation management
    - Session 4 at MA&O Conference
    - Boeing/IBM/Rice University Collaboration
  - Genetic algorithm with neural network
    - Rensselaer Polytechnic Institute
- Gradient-based optimization
  - Current talk

Methods of Derivative Calculation

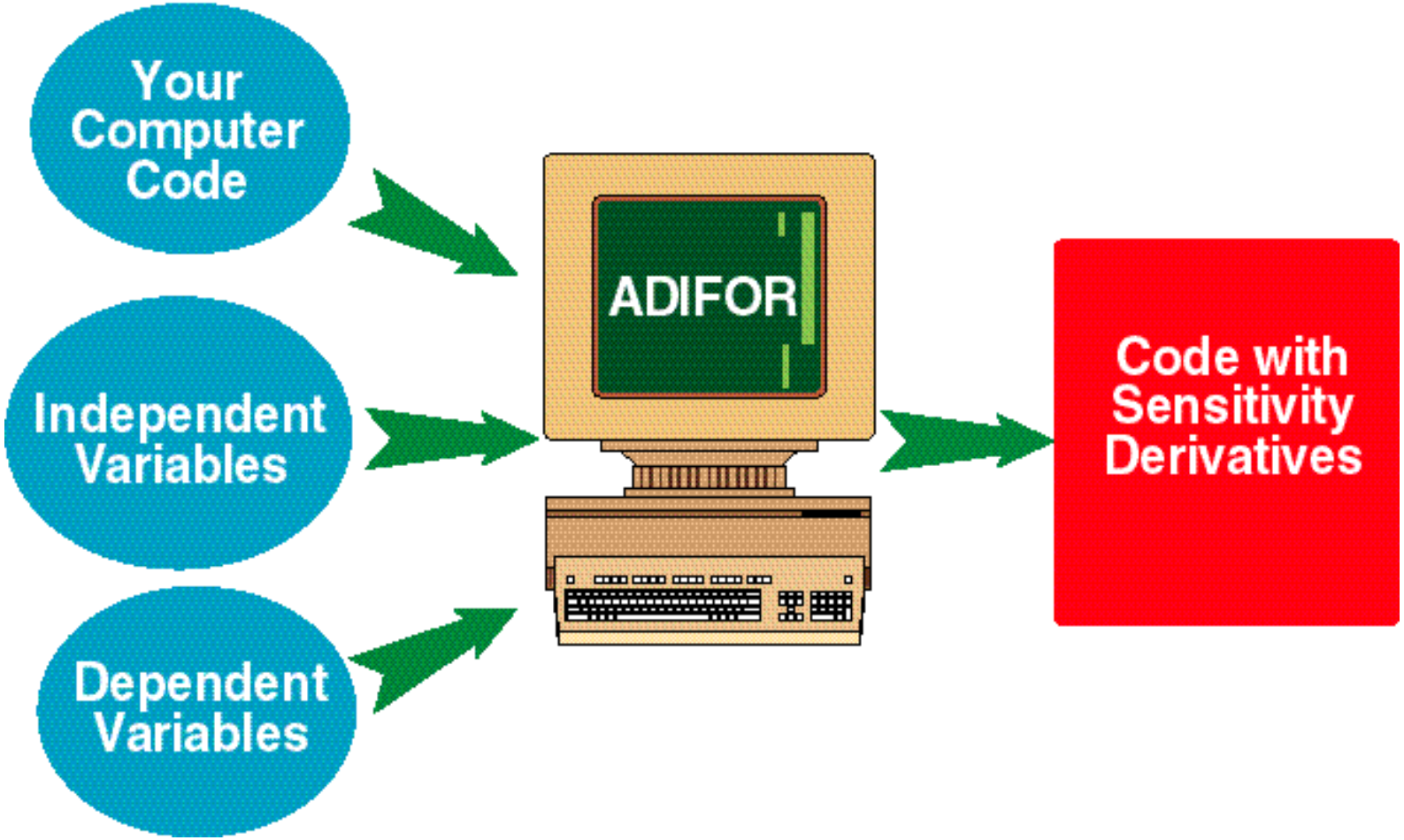
- **Finite difference (FD)**
  - **Costly to compute**
  - **Step-size dependent**
  - **Easy to implement**
- **Analytical**
  - **Fast to compute**
  - **Step-size independent**
  - **Hard to implement**
- **Automatic Differentiation (AD)**
  - **Comparable to FD**
  - **Exact method**
  - **Easy to implement and add new variables**

ADIFOR
Automatic Differentiation of FORTRAN

- General purpose automatic differentiation tool
- Pre-compiler tool for FORTRAN source code*
- User identifies independent and dependent variables in source code
- ADIFOR generates new source code with exact derivatives via the chain rule
- User compiles and executes new source code (analysis and derivatives) on machine of choice

*ADIC - AD tool for C programs

ADIFOR Process



ADIFOR Roles

- Developed at Argonne National Laboratory (Bischof, et. al.) and Rice University (Carle, et. al.) with NASA LaRC, DOE, and NSF funding
- Rice University and Argonne National Laboratory
  - Develop mathematical foundation for tool
  - Develop software tool
    - (e.g. ADJIFOR see Paper AIAA 98-4807)
- NASA LaRC
  - Direction for development and research
  - Testing and feedback from user perspective
  - Identify specific needs
  - In-house applications
  - Transfer techniques to industry

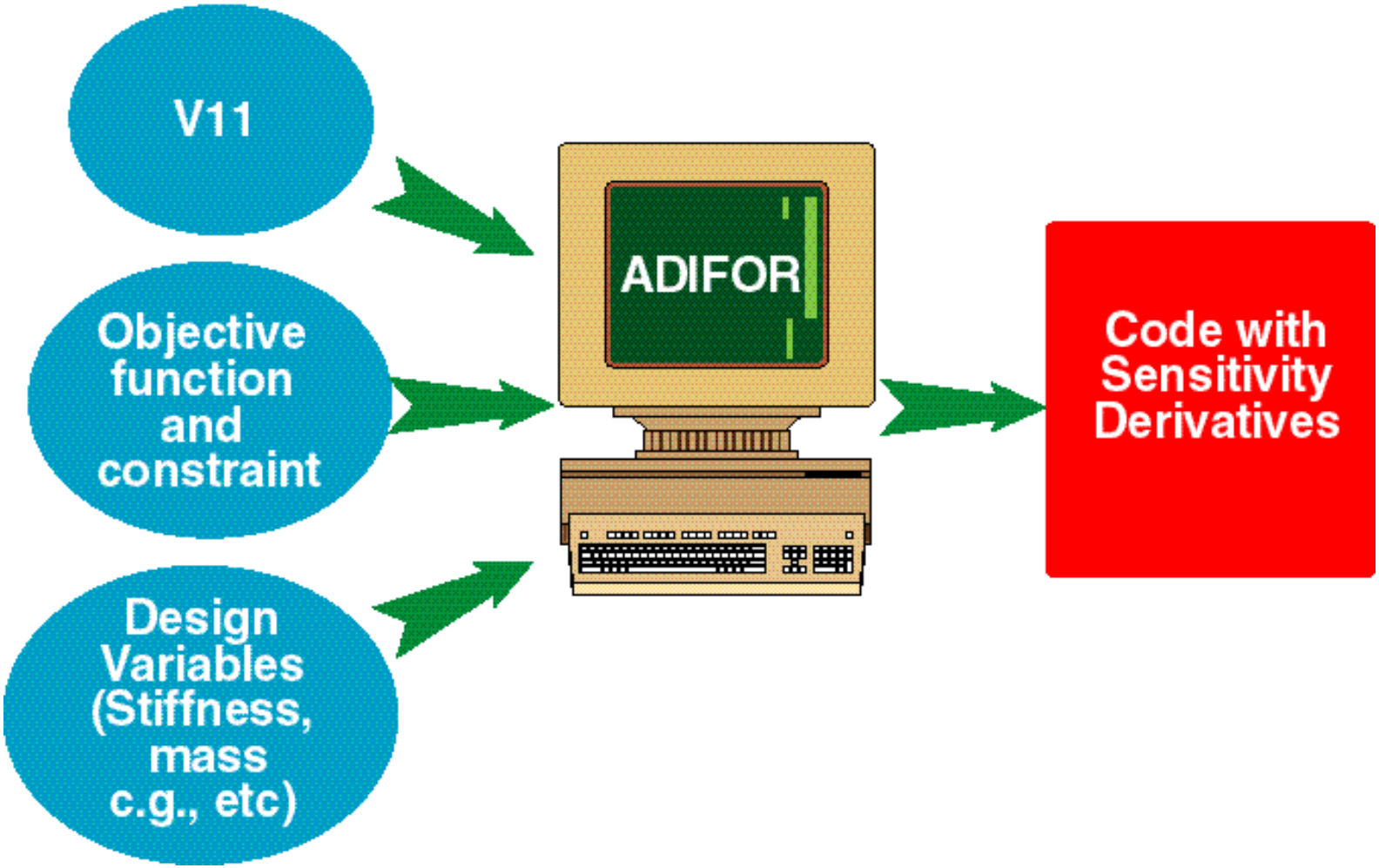
V11 ADIFOR Application

- Joint effort with Boeing Helicopter Philadelphia
  - Apply ADIFOR to proprietary helicopter analysis
  - Use ADIFOR derivatives in optimization
- Boeing provides their V11 code
  - TECH 01 analysis (aerodynamic/dynamic analysis)
  - Gradient-based optimizer - NPSOLN
  - Sample optimization problem used NPSOLN-generated finite-difference (FD) derivatives
- LaRC applies ADIFOR in “Black Box” fashion
  - Compares ADIFOR derivatives with FD derivatives
  - Uses ADIFOR derivatives in 3 optimization schemes

Sample Rotor Blade Optimization Problem

- 56 design variables
  - Section mass
  - Stiffness in flap, chord, and torsion
  - Chordwise c.g. location
- Constraint
  - Nondimensional total blade weight $\leq$ 1.685
- Objective function - Minimize
  - Vibration Function
    - Linear combination of the weighted fixed system 3/rev and 6/rev three hub forces and two hub moments for 2 flight conditions
  - Inplane Function
    - Linear combination of the weighted fixed system 3/rev and 6/rev inplane hub forces for 2 flight conditions

ADIFOR Process for V11 Code



V11 ADIFOR Implementation

- Code size
  - Original code - 139,376 lines
  - Augmented code - 236,531 lines
- Computer memory requirements
  - NOT an issue for V11 code
  - IS an major issue for ADIFOR code
    - 56 DVs requires 56 times original memory
- Due to memory limitations
  - Calculate ADIFOR derivatives in smaller blocks
  - Do 8 blocks 7 design variables at a time
  - Assemble gradients into appropriate locations of gradient arrays

Derivative Timing Results

Type of derivative	Design iteration time (min)
Finite difference	209
ADIFOR	366

Notes:

- Design iteration - analysis, derivatives, and line search
- FD uses forward finite-difference
- FD time for a given step-size
- Sun Ultra 2 workstation with 128 megabytes of memory and 877 megabytes of swap space

Comparison of Objective Function Derivatives
Vibration Function (Initial Design - OBJ=1.0)

DV No.	Scaled X	Scaled Objective Function Derivatives				
		Finite difference (step-size)				ADIFOR
		(0.001)	(0.0001)	(0.00001)*	(0.000001)	
1	-1.000000	0.267894	0.264466	0.264996	0.265380	0.265042
2	-0.299511	0.009128	0.009133	0.009194	0.009337	0.009129
3	-0.547333	0.000054	0.000064	0.000061	0.000862	0.000054
4	-1.000000	-0.000302	-0.000301	-0.000260	-0.000176	-0.000302
5	-0.842483	0.000001	0.000006	0.000023	0.000078	0.000001
7	0.017657	0.012525	0.012408	0.011635	-0.007819	0.012547
10	-0.709089	0.000012	0.000012	0.000023	0.000701	0.000012
21	-0.826086	0.030332	0.111996	0.114020	0.114669	0.114294
26	-1.000000	-0.066428	0.004358	0.006627	0.007338	0.006920
35	-0.860322	0.028158	0.028137	0.028161	0.028359	0.028134
53	-1.000000	-0.024887	-0.047656	-0.048948	-0.047871	-0.047964
56	-0.322034	-0.000459	-0.000455	-0.000374	0.000396	-0.000459

↑

default FD step-size

Red indicates more than 10 percent difference in derivative calculation

Comparison of Objective Function Derivatives
Vibration Function
(CONMIN Optimized Design - OBJ=0.56481)

DV No.	Scaled X	Scaled Objective Function Derivatives				
		Finite difference (step-size)				ADIFOR
		(0.001)	(0.0001)	(0.00001)*	(0.000001)	
1	-0.988316	0.020598	0.022351	0.022270	0.018428	0.022890
2	-0.876564	0.001590	0.001559	0.000922	-0.002849	0.001596
3	-0.703650	0.000083	0.000058	-0.000408	-0.006652	0.000093
4	-0.255481	0.000024	-0.000186	-0.000862	-0.012195	0.000033
5	-0.963706	-0.000002	-0.000015	-0.000638	-0.002012	0.000000
7	0.005231	0.002265	0.011723	0.127495	0.123511	0.002292
10	-1.000000	-0.000003	-0.000046	-0.000101	0.000015	0.000002
21	-0.399443	0.035501	0.036102	0.035369	0.035574	0.036175
26	-0.999300	-0.065723	-0.056733	-0.056674	-0.057738	-0.056652
35	-0.959707	0.006113	0.006115	0.005736	0.003701	0.006195
53	-1.000000	0.214883	0.201452	0.202390	0.196713	0.203081
56	-0.931666	-0.001570	-0.001625	-0.001861	-0.003850	-0.001557

↑

default FD step-size

Red indicates more than 10 percent difference in derivative calculation

Optimization Techniques

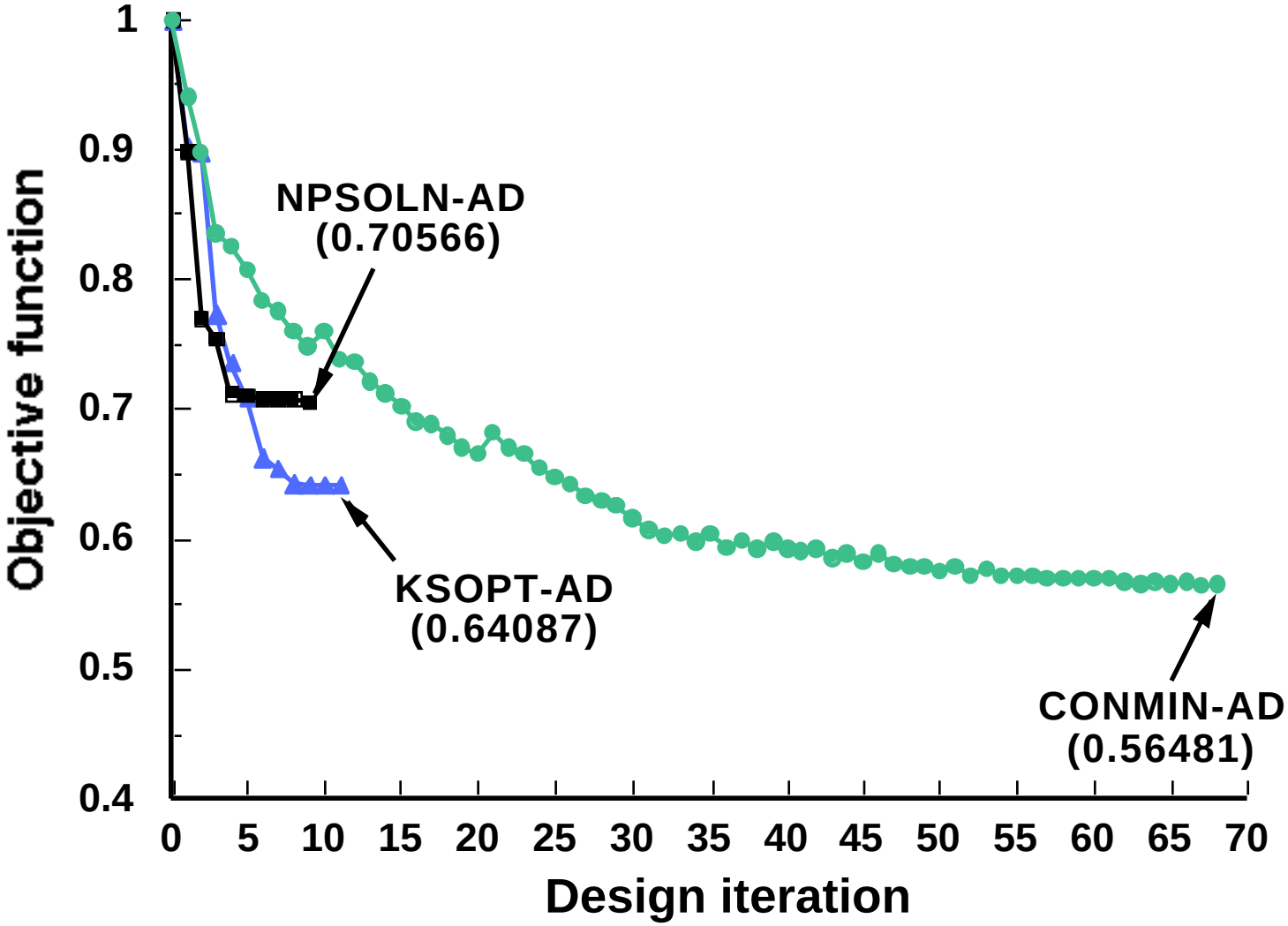
- **Sequential Linear Programming (SLP)**
  - **CONMIN and approximate analysis using linear Taylor series**
- **Sequential Quadratic Programming (SQP)**
  - **NPSOLN**
- **Sequential Unconstrained Minimization Technique (SUMT)**
  - **KSOPT**

Vibration Function

Minimize

- **Linear combination of the weighted fixed system 3/rev and 6/rev three hub forces and two hub moments for 2 flight conditions**

Optimization Results Using ADIFOR Derivatives
Vibration Function



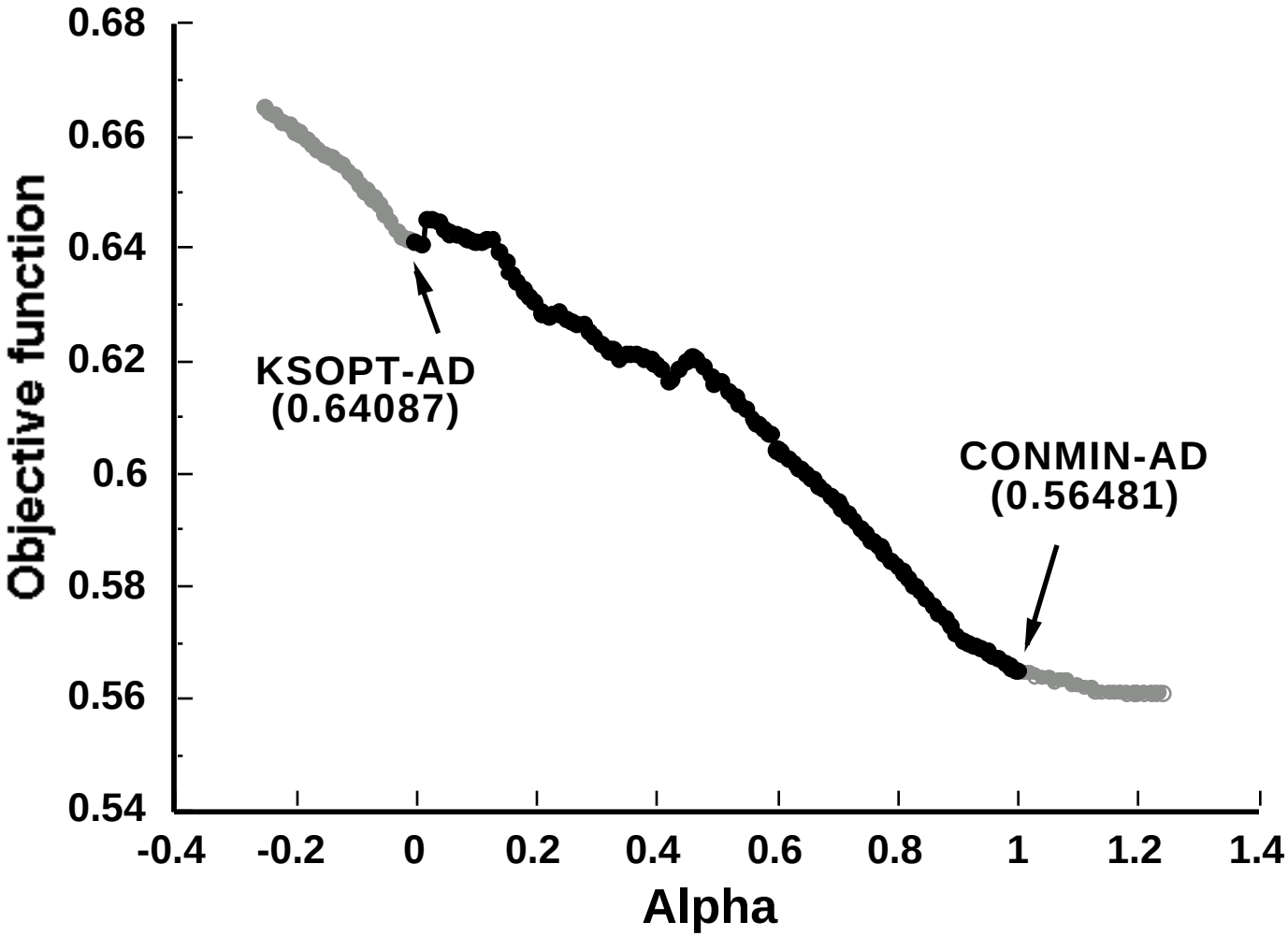
ALPHA Test

- **Suggested to LaRC by Dr. R. Haftka**
- **Can give insight into why there appears to be multiple minima**
- **Choose 2 optimized designs - X_1 and X_2**
- **Evaluate objective function and constraints at various points X on a line between X_1 and X_2**

$$X = \alpha X_2 + (1-\alpha) X_1$$

  - $\alpha = 0$, **X corresponds to X_1**
  - $\alpha = 1$, **X corresponds to X_2**
- **Plot objective function (and/or constraints) as a function of α**
  - **If "bumpy" line, then might be local minimum**

ALPHA Test Results
(Vibration Function)

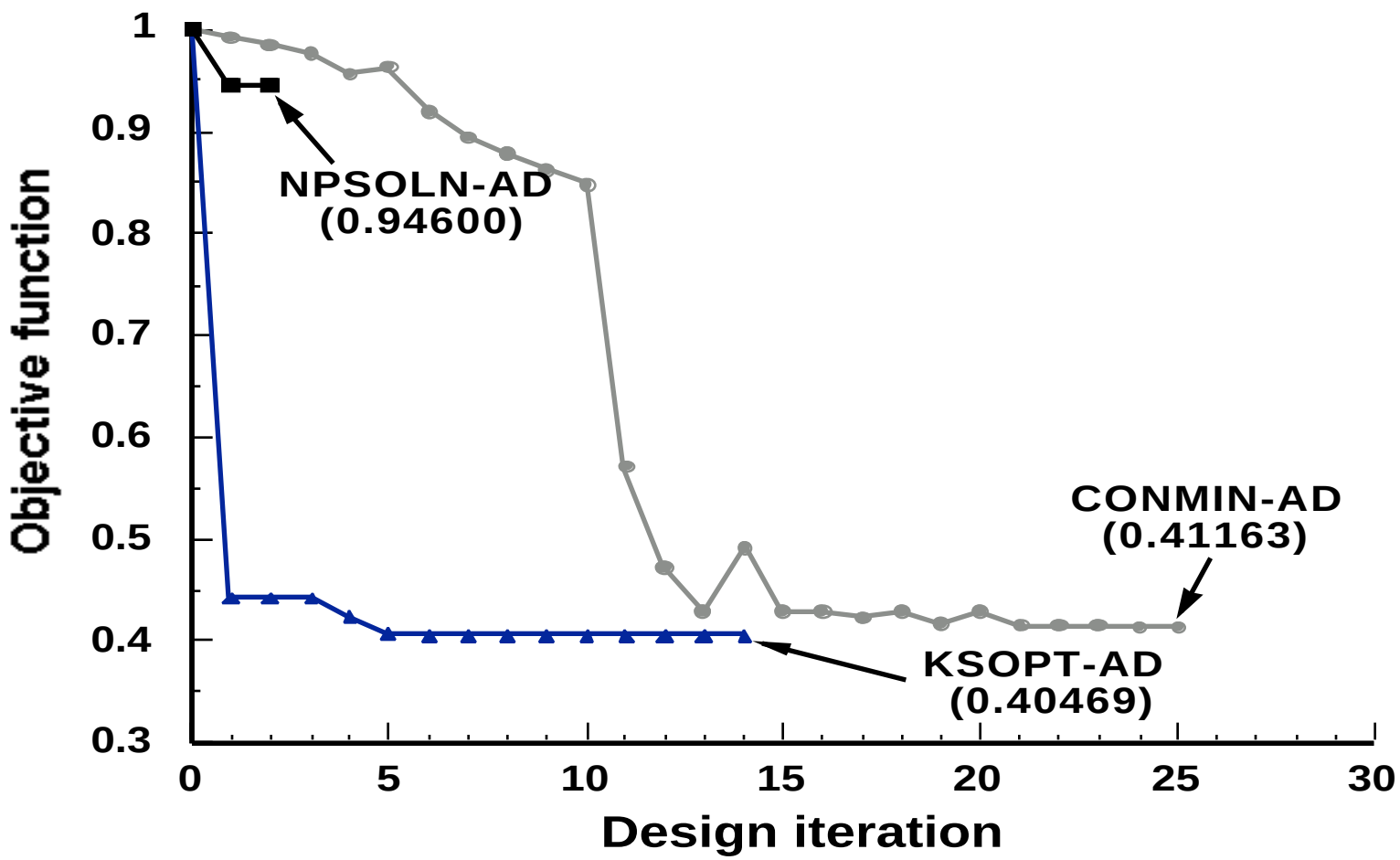


Rotor Blade Optimization Formulation
Inplane Function

Minimize

- **Linear combination of the weighted fixed system 3/rev and 6/rev inplane hub forces for 2 flight conditions**

Optimization Results Using ADIFOR Derivatives
Inplane Function



Lessons Learned

- Relative easy to process V11 through ADIFOR
  - FORTRAN 77 standard
  - About 1/2 day to obtain ADIFOR V11
    - Manual pre-processing
    - ADIFOR processing
    - Manual post-processing
- Applied ADIFOR in “Black Box”
  - R/C analysis included nested iterative loops
  - R/C analysis repeated 8 times to obtain 56 derivatives
- Incorporating ADIFOR derivatives with optimizer
  - Straight forward if optimizer has flag for derivative calculations (e.g., CONMIN and KSOPT)
  - NPSOLN required subroutine rewrite
- Choice of optimizer was important for the Inplane Function

Summary

- Successfully obtained derivatives of V11 code using ADIFOR
- Disadvantages of using ADIFOR derivatives
  - Takes 1.75 times longer to compute ADIFOR derivatives than FD derivatives
  - Requires large amount of computer memory
- Advantages of using ADIFOR derivatives
  - ADIFOR derivatives are exact
  - FD derivatives are step-size dependent
- Obtained optimized designs for 3 optimizers using ADIFOR derivatives
  - NPSOLN, KSOPT and CONMIN
  - Choice of optimizers is important