Lift-Offset Compound Design Background, X2TD, JMR ME1A

Status and Plans

August 2011

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Topics

- NASA work on lift-offset rotors
  - NASA Heavy Lift System Investigation
  - JHL X2HS analysis
  - Influence of Lift Offset on Rotorcraft Performance

- Correlation: coaxial and lift-offset
  - Harrington
  - XH-59A

- NASA Design and Analysis of Rotorcraft — NDARC
  - Development and process

- X2TD Analysis
  - Geometry, aerodynamics, dynamics model
  - Flight test data and correlation
  - Performance calculation

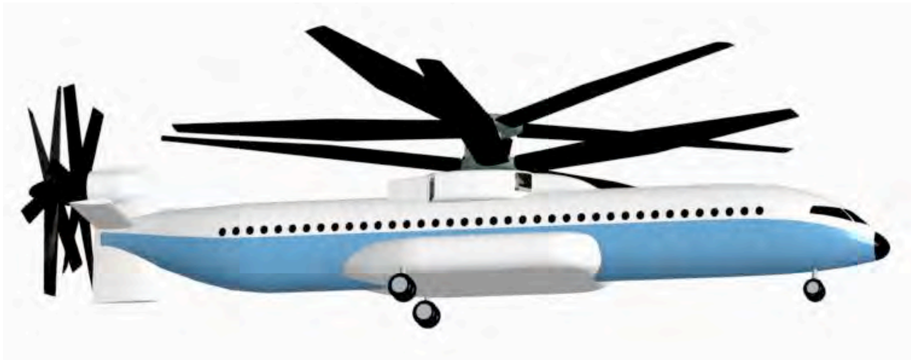
- JMR design
  - JMR-X-ME1A-00

- Plans

NASA Heavy Lift Rotorcraft Systems Investigation

- NASA TP 2005-213467, December 2005

- Configurations selected by industry
  - Sikorsky: Large Advancing Blade Concept (LABC)

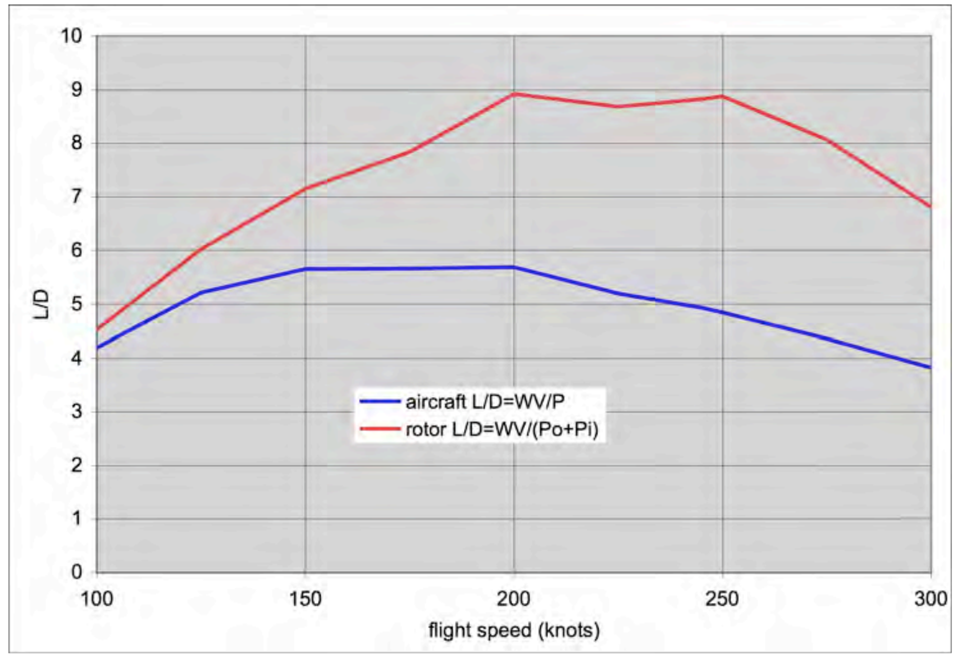


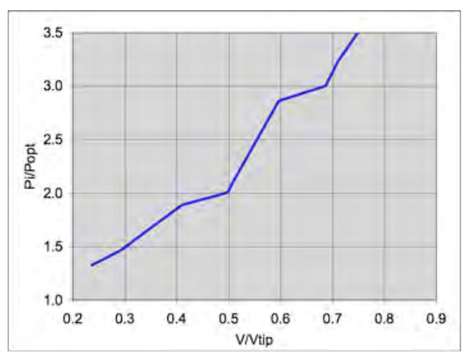
- NASA technology goals and mission intended to identify enabling technologies for civil application of heavy lift rotorcraft
  - Range 1200 nm, 120 passengers
  - Cruise 350 knots at 30000 ft
  - 5k ISA+20°C takeoff and landing, hover OEI

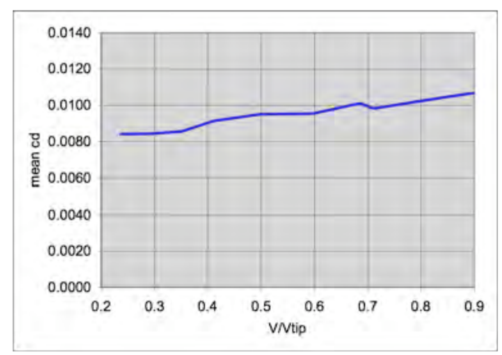
JHL X2HS

X2 High Speed Lifter
245 kt Design Cruise

CAMRAD II Calculation of Performance



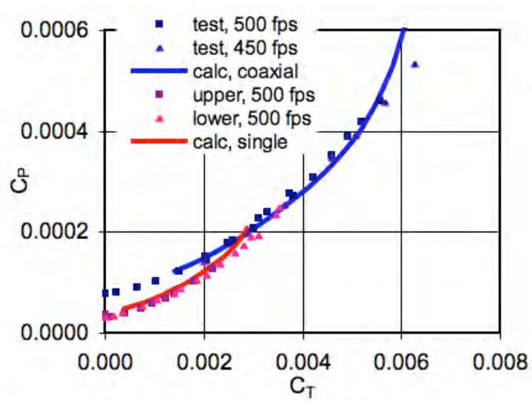


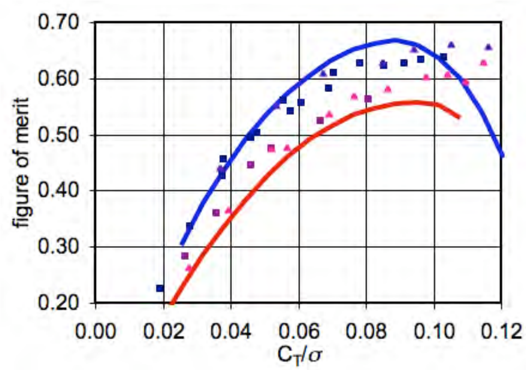


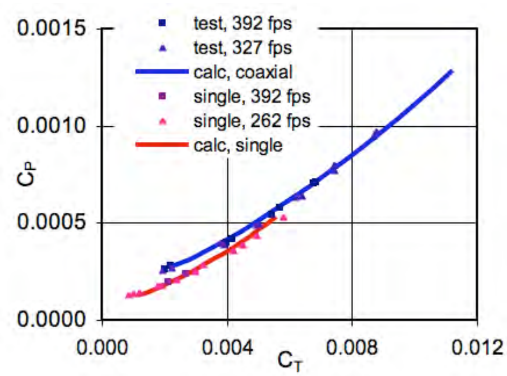
Coaxial Performance Correlation

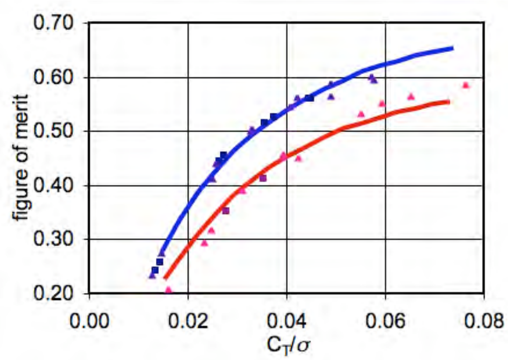
- **Harrington rotors**

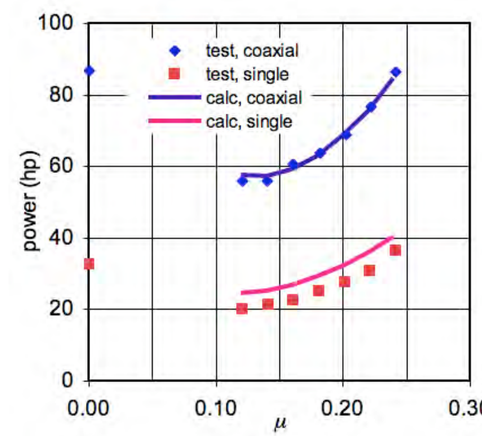
#1 hover	**#2 hover**	**#1 forward flight**









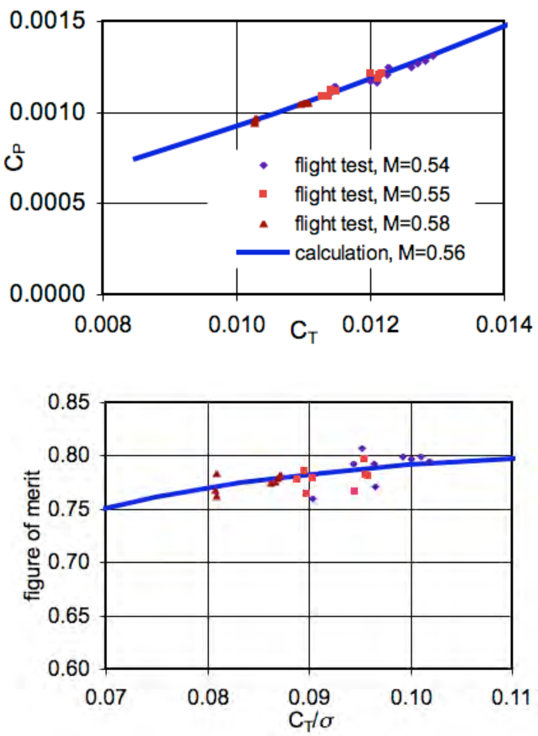


- **CAMRAD II calculations**

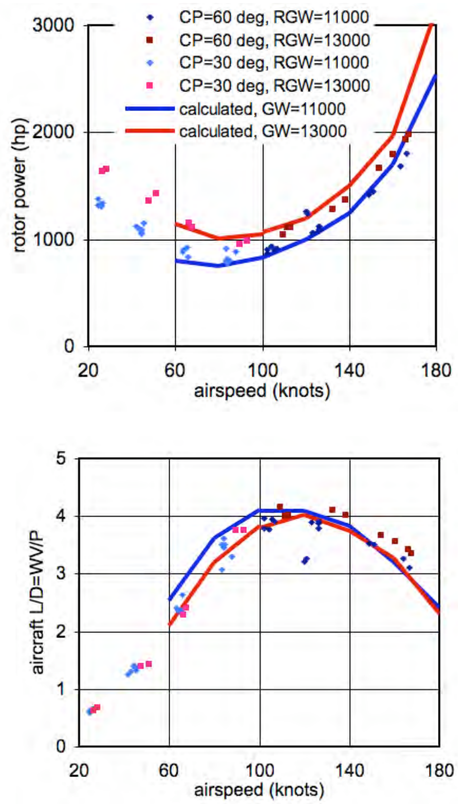
Coaxial Performance Correlation

- **XH-59A**

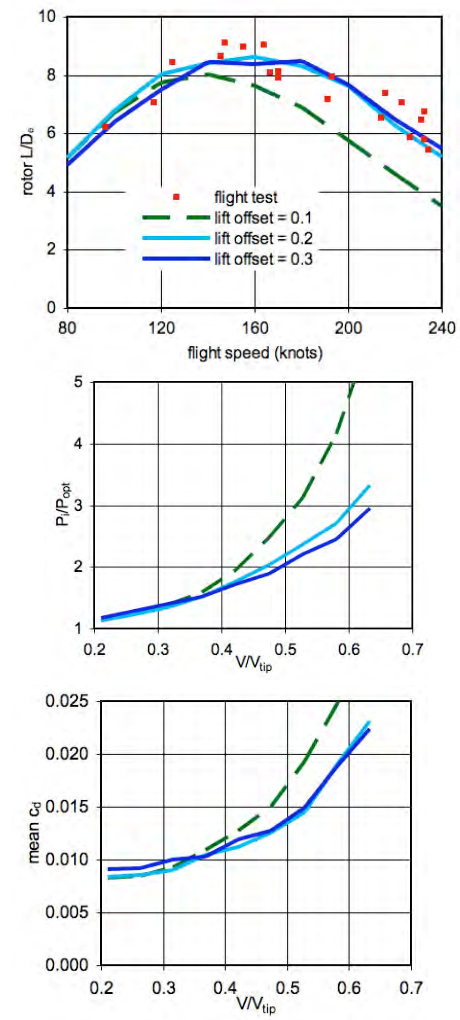
hover



forward flight



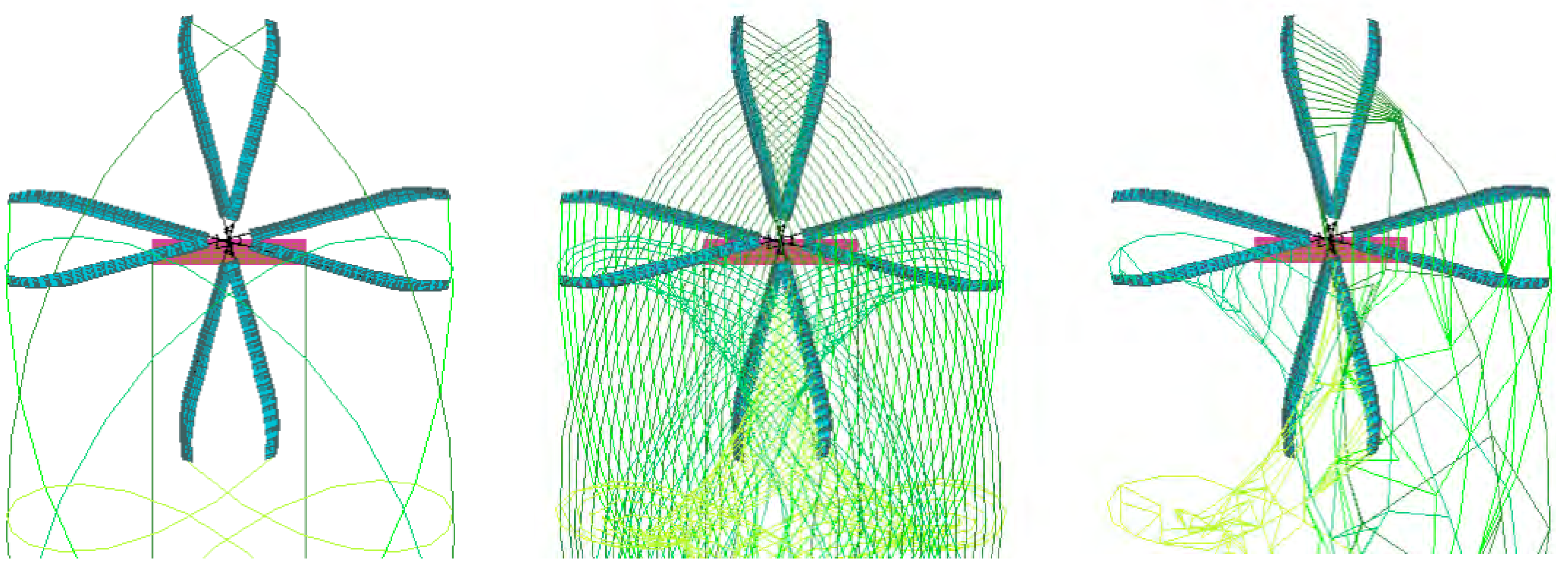
with aux propulsion



- **CAMRAD II calculations**

Coaxial Rotor Model

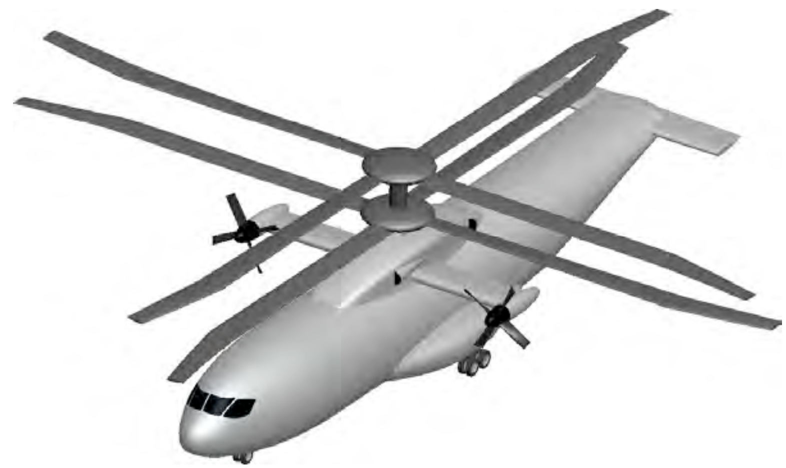
- Wake
  - Rolled up, free wake, multiple trailer, with consolidation
  - With and without shed wake
- Drag
  - With and without radial drag
  - With and without yawed flow corrections



Influence of Lift Offset on Rotorcraft Performance

- AHS Specialist's Conference on Aeromechanics, San Francisco, January 2008; NASA TP 2009-215404

- Performance analysis, no sizing

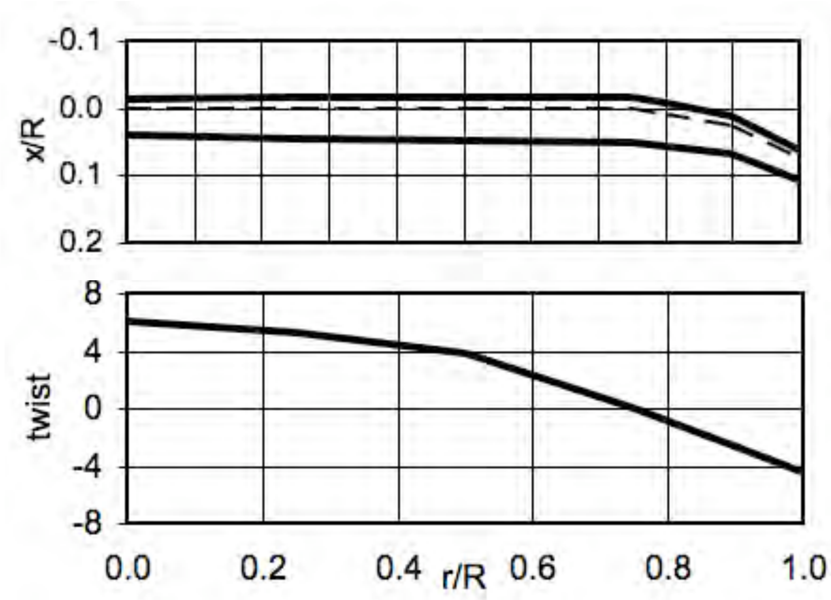


- GW=150000
- Cruise 250 knots, 5k ISA+20°C
- DL = 15 lb/ft^2
- Hover C_W/σ = 0.092, V_{tip} = 700 ft/sec
- Cruise C_T/σ = 0.10, M_{at} = .90, μ = 0.7, V_{tip} = 600 ft/sec (86%)

- σ = 2 x 0.0871, N = 4
- Separation z/D = 0.06

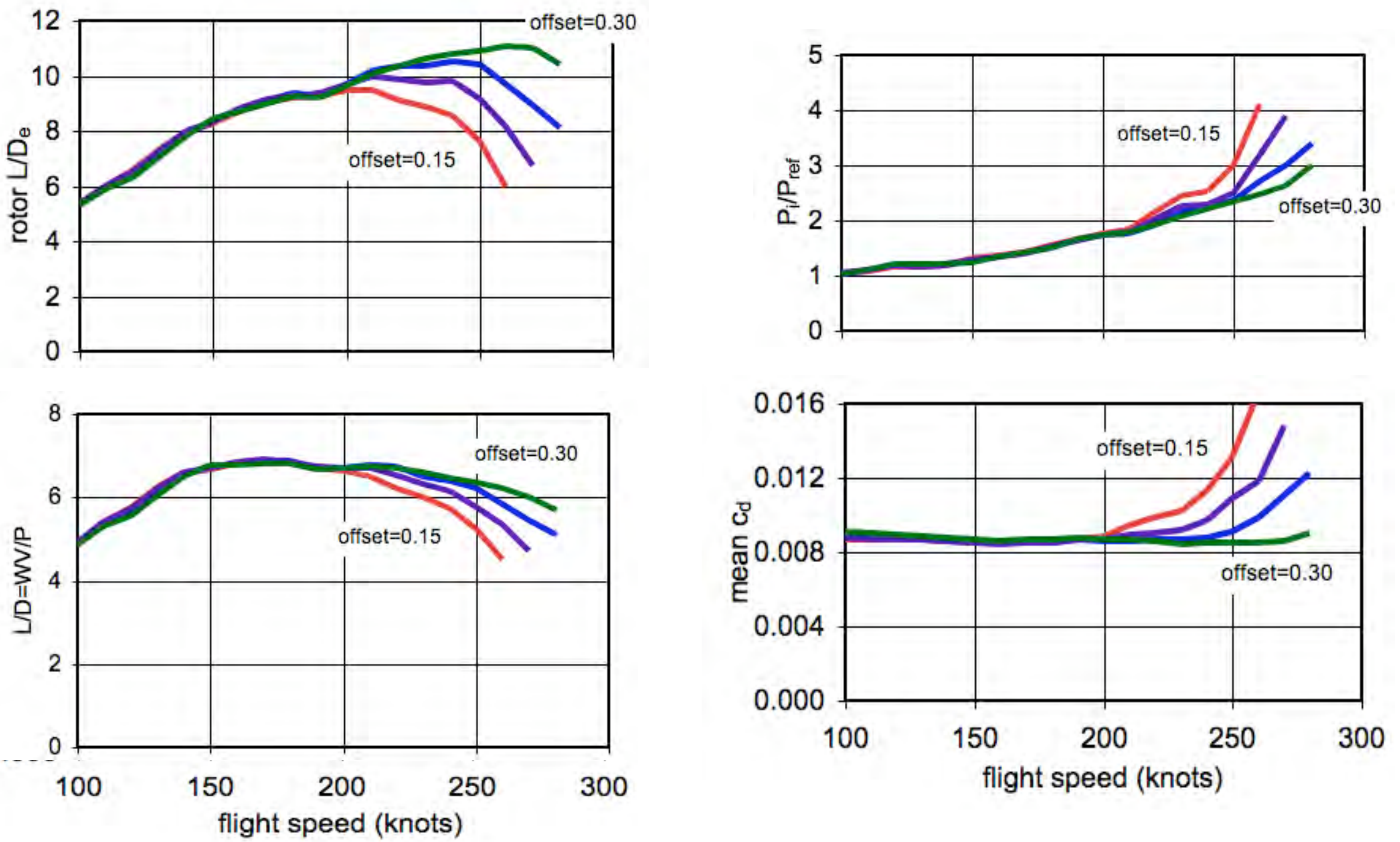
Rotor Optimization

• **Hover FM and 250 knots cruise L/D**

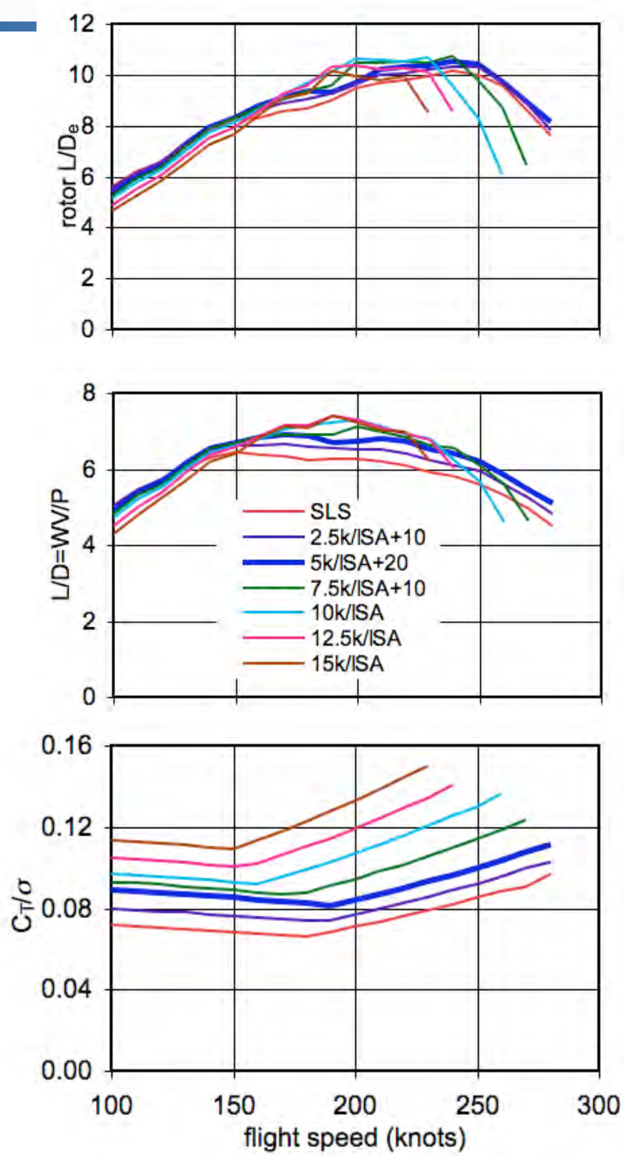


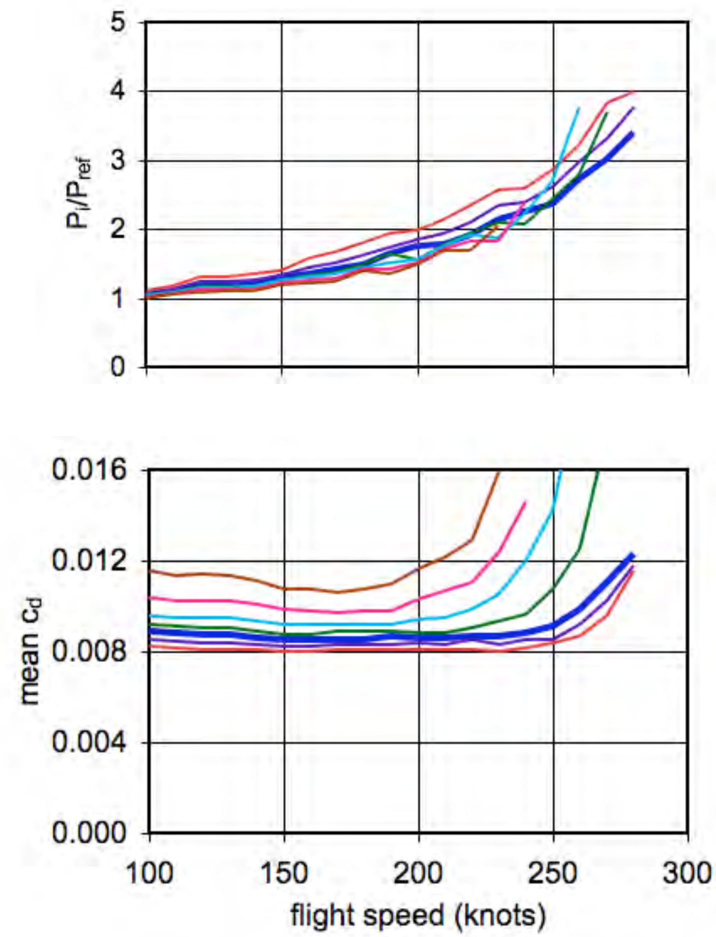
• **Advanced airfoils: RAH-66 technology, high M_{dd}, no penalty for thick sections at root**

Rotor and Aircraft Performance



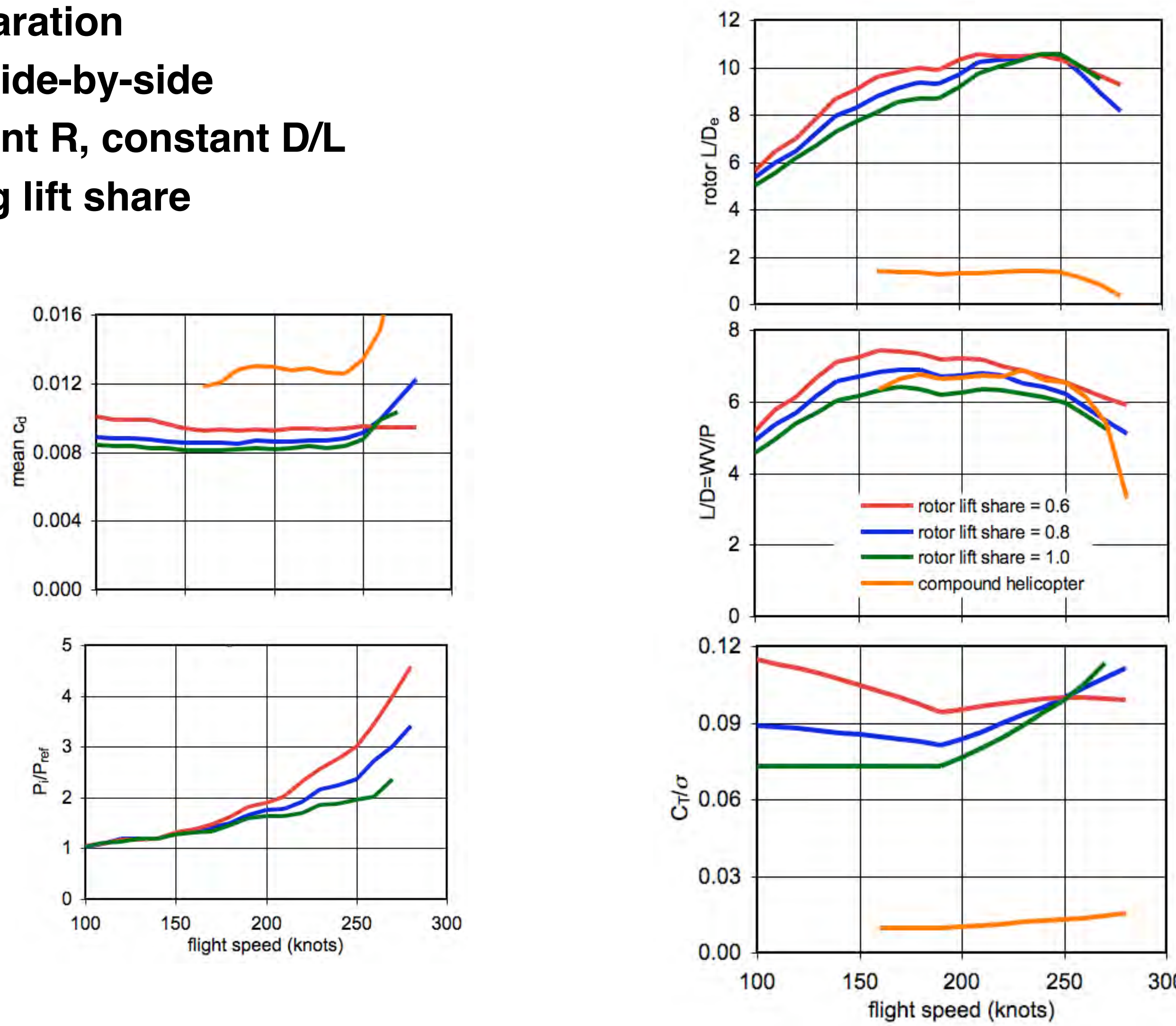
Rotor and Aircraft Performance





Aircraft Configuration

- Rotor separation
- Tandem, side-by-side
    - constant R, constant D/L
- Rotor/wing lift share



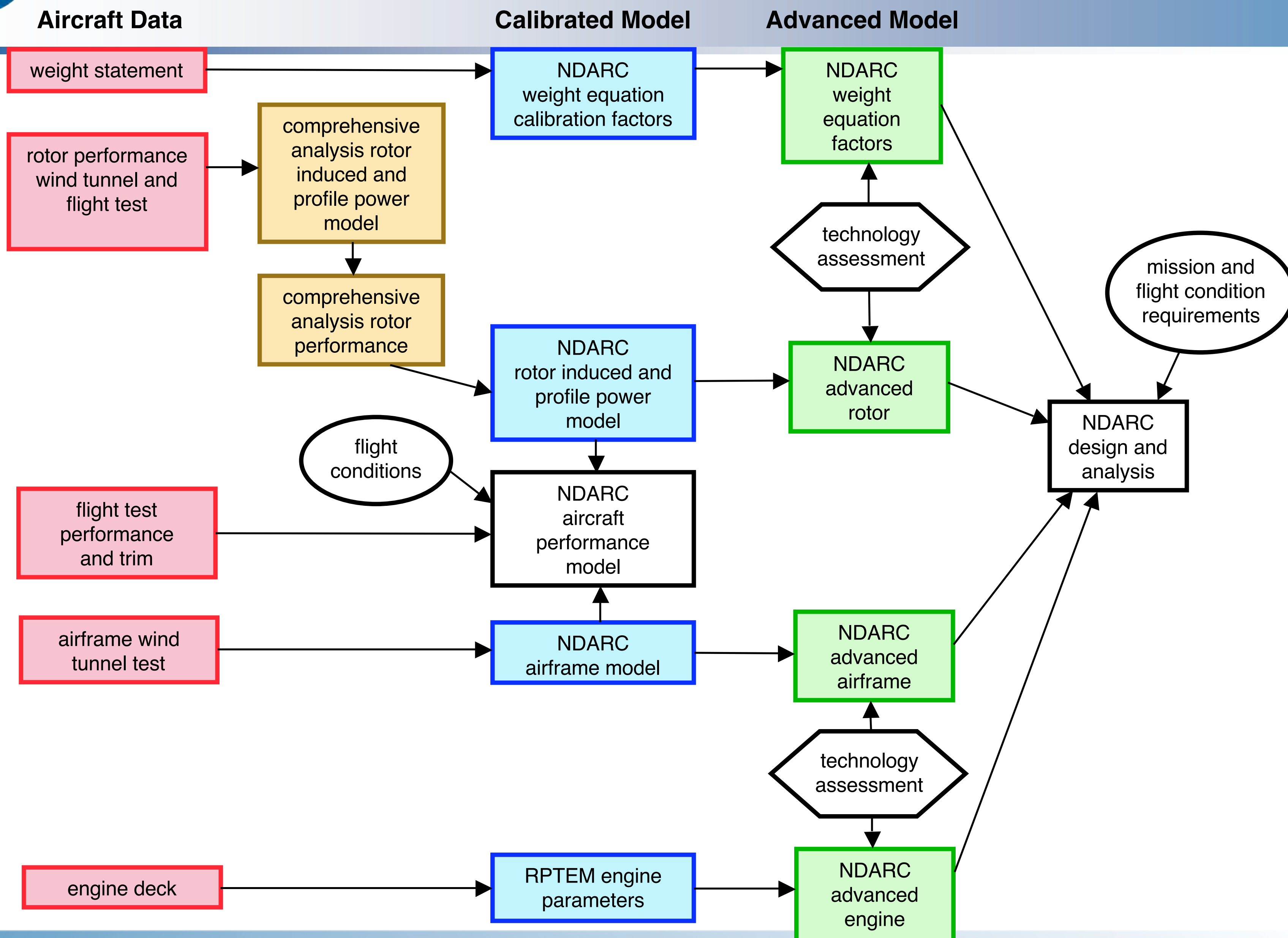
NDARC
NASA Design and Analysis of Rotorcraft

- NASA TP 2009-215402, December 2009
- American Helicopter Society Aeromechanics Specialists' Conference, San Francisco, January 2010

- Cover coaxial and compound configurations, and lift offset rotor

- Development test cases
  - UH-60A (single main-rotor and tail-rotor helicopter)
  - CH-47D (tandem helicopter)
  - XH-59A (coaxial lift-offset helicopter)
  - XV-15 (tiltrotor)

Validation Process



Rotor Power

- Power required: induced + profile + parasite

$$P = P_i + P_o + P_p$$

- Parasite power = propulsive force x flight speed ($P_p = -XV$)

- Induced power factor κ and mean drag coefficient $c_{d\,\text{mean}}$

$$P_i = \kappa P_{\text{ideal}} = \kappa T v_{\text{ideal}}$$

$$P_o = \rho A(\Omega R)^3 C_{Po} = \rho A(\Omega R)^3 (\sigma/8) c_{d\,\text{mean}} F_P(\mu, \mu_z)$$

- Models account for influence of
  - Speed
  - Thrust
  - Compressibility
  - Stall
  - Lift offset
  - Induced interference between twin rotors

- Calibration of model reflects level of technology

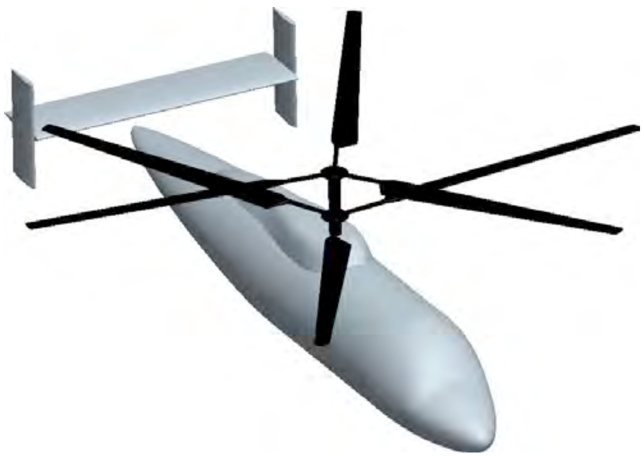
Component Weight Calibration Factors

	UH-60A	CH-47D	XH-59A	XV-15
structure				
wing group, basic structure				0.98 *
rotor group, blade assembly	1.02	0.94	1.00 **	0.93
hub & hinge	0.98	1.03	1.00 **	0.88
fairing/spinner		0.97		
empennage group, tail rotor	1.18			
horizontal tail	0.94		1.03	1.42
vertical tail	2.47		1.65	0.60
fuselage group, basic	1.03	1.03	1.06	1.03
alighting gear group, basic	0.74	1.00	0.98	0.96
engine section or nacelle group				
engine support + air induction group	1.27	0.89	1.71	0.85
engine cowling	0.91	0.93	0.99	0.56
propulsion group				
engine system, accessories	0.71	0.74	1.44	0.62
fuel system	0.83	1.04	0.97	2.25
drive system, gear boxes + rotor shaft	0.91	0.90	1.06	1.35
transmission drive	0.85	0.79		0.62
systems and equipment				
fixed wing flight controls	1.15		0.57	0.72
rotary wing flight controls, non-boosted	1.17	0.99	1.08	0.94
boost mechanisms + hydraulic	1.17	1.59	1.13	1.08
boosted	1.06	0.77	2.29	1.02

*model calibrated for XV-15 wing; **model calibrated for XH-59A rotor

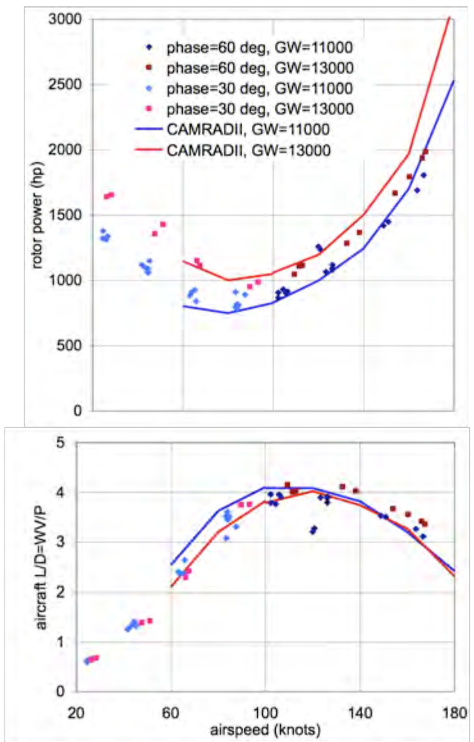
XH-59A Coaxial

	helicopter configuration
Disk loading (lb/ft^2)	8.84
power loading (hp/ft^2)	5.21
Rotor	
C_W/σ at design gross weight	0.069
radius (ft)	18
solidity (thrust-weighted)	0.0636
number of blades	3
tip speed (ft/sec)	650
Engines	PT6T-3
number of engines	1
takeoff power (hp)	IRP = 1726
MCP SLS sfc (lb/hp-hr)	0.599
weight/power (lb/hp)	0.39
drive system limit (hp)	1500
Design gross weight	9,000
structural design gross weight	9,000
maximum takeoff weight	9,000
weight empty	8,051
Cruise drag D/q (ft^2)	14.78
$(D/q) / (W/1000)^{2/3}$	3.42
Download DL/T	0.025

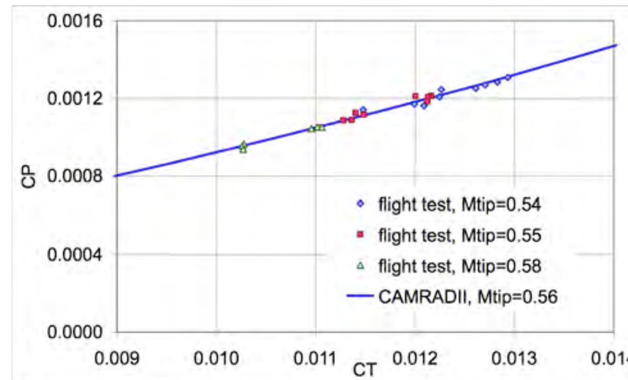


XH-59A Performance Correlation

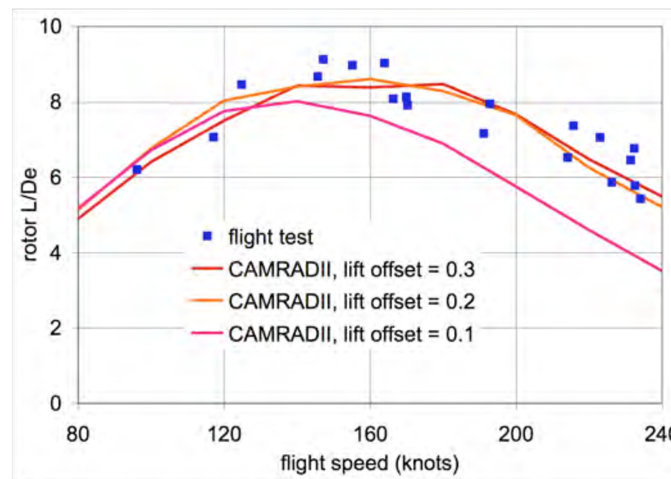
helicopter



hover



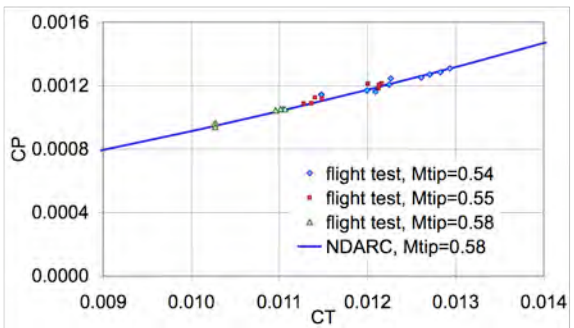
aux propulsion

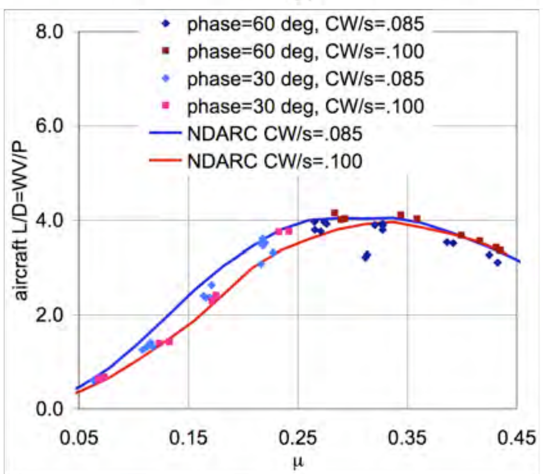


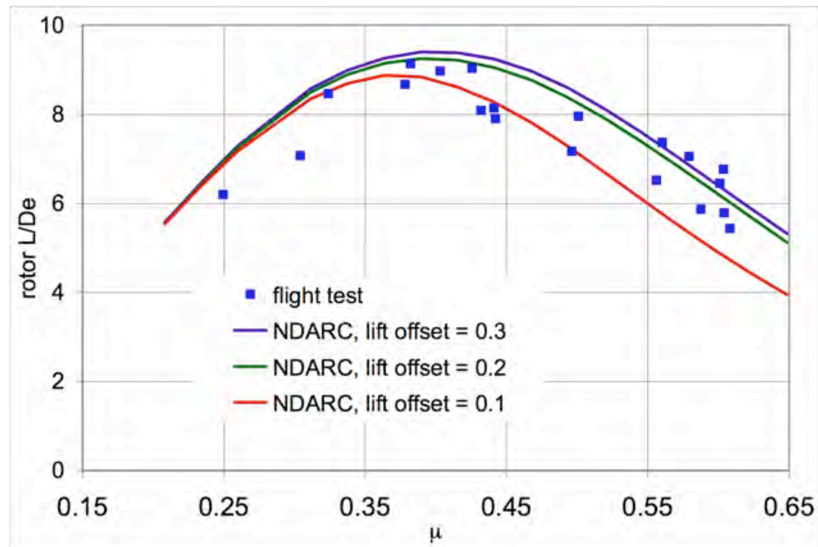
CAMRAD II calculations

NDARC Calibration for XH-59A

- NDARC induced and profile power model fitted to CAMRAD II calculations
  - Hover: C_T/σ = 0.02-0.18
  - Forward flight: μ = 0.15-0.45, C_T/σ = 0.06-0.12, M_{at} to .92
  - Forward flight, aux prop: μ = 0.15-0.65, lift offset = 0-0.3







X2TD Design and Flight Test

- Bagai, A. "Aerodynamic Design of the X2 Technology Demonstrator." American Helicopter Society 64th Annual Forum, Montreal, Canada, April 2008.
- Bagai, A. "Aerodynamic Design of the X2 Technology Demonstrator Main Rotor Blade." American Helicopter Society Southwest Region Technical Specialists' Meeting on Next Generation Vertical Lift Technologies, Dallas, TX, October 2008.
- Blackwell, R., and Millott, T.A. "Dynamics Design Characteristics of the Sikorsky X2 Technology Demonstrator Aircraft." American Helicopter Society 64th Annual Forum, Montreal, Canada, April 2008.
- Wake, B.E.; Hagen, E.; Ochs, S.; Matalanis, C.G.; and Scott, M.W. "Assessment of Helicopter Hub Drag Prediction with an Unstructured Flow Solver." American Helicopter Society 65th Annual Forum, Grapevine, TX, May 2009.
- Walsh, D.; Weiner, S.; Arifian, K.; Bagai, A.; Lawrence, T.; and Blackwell, R. "Development Testing of the Sikorsky X2 Technology Demonstrator." American Helicopter Society 65th Annual Forum, Grapevine, TX, May 2009.
- Lawrence, T., and Jenney, D. "The Fastest Helicopter on Earth. Sikorsky Aimes to Break the Helicopter Speed Record." IEEE Spectrum (September 2010).

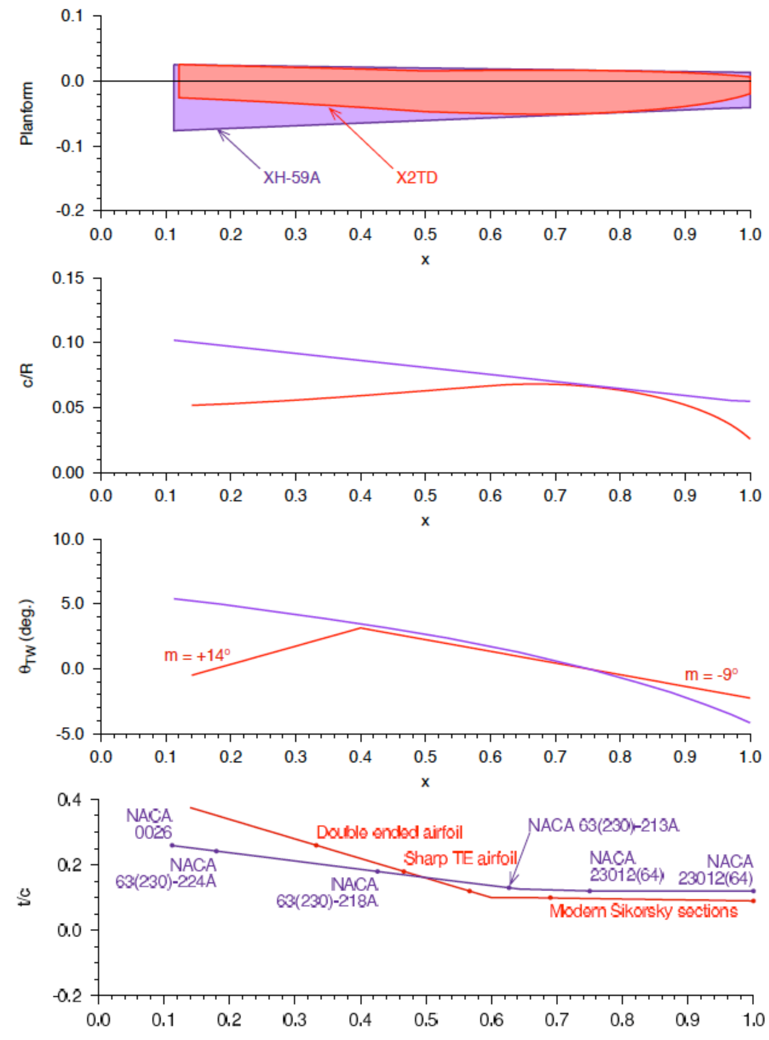
X2TD Description

- Rotor
  - Radius = 13.2 ft
  - 2x4 blades
  - Solidity = 0.1441
  - Max M_{at} = 0.9
  - Upper CCW, lower CW
  - Blades cross over tail
  - Separation 18 in, z/D = 0.0568
  - Twist 14° (r=0-0.4) / -9° (r=0.4-1.0)
- Horizontal tail
  - 9x3+7 = 34 ft^2
  - 5° incidence relative rotor shaft axes
  - Volume = 0.06, effective AR = 3.5
- Vertical tail
  - 15.4 ft^2
  - Volume = 0.03, effective AR = 1.2

X2TD Description

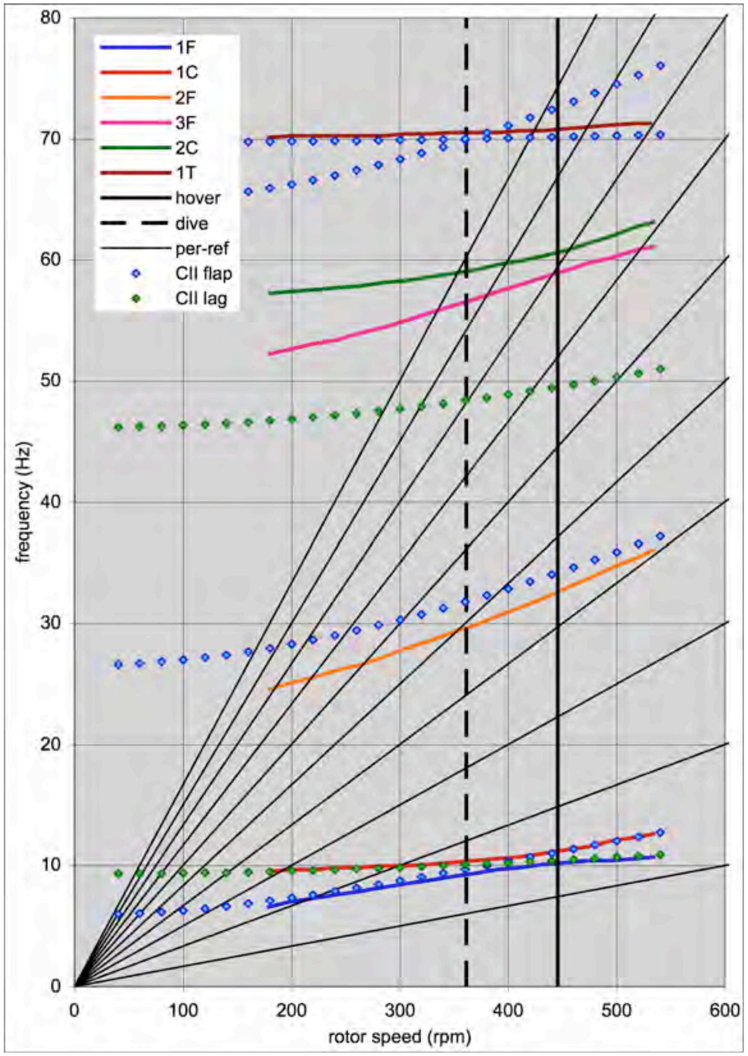
- **Chord, airfoils: from Bagai AHS Forum 2008**

r/R	t/c	
0.142	0.376	
0.331	0.263	double-ended
0.468	0.182	sharp TE
0.568	0.120	
0.600	0.101	modern Sikorsky sections
0.690	0.101	
1.000	0.091	



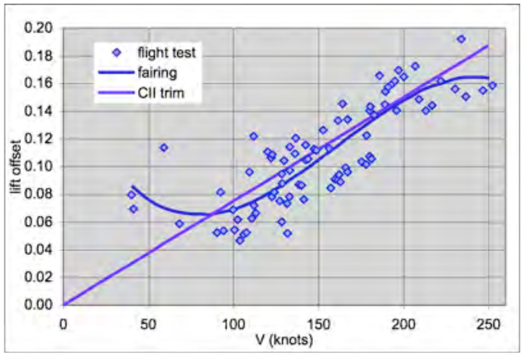
X2TD Description

- **Fan plot: from Blackwell and Millott, AHS Forum 2008**
- **CAMRAD II structural dynamics model: scaled XH-59A**



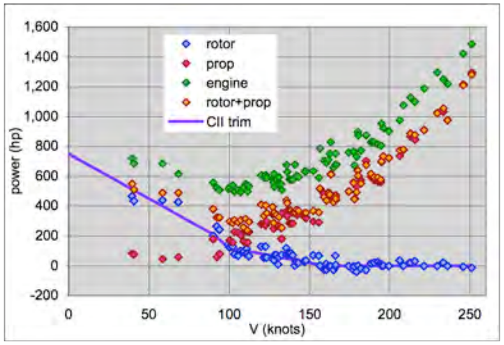
X2TD Performance Calculation

- Lift offset: assumptions about data —
  - Measure blade root flap bending moment
  - Convert 1/rev to hub roll moment
  - Lift offset = M/(R*.5*GW)



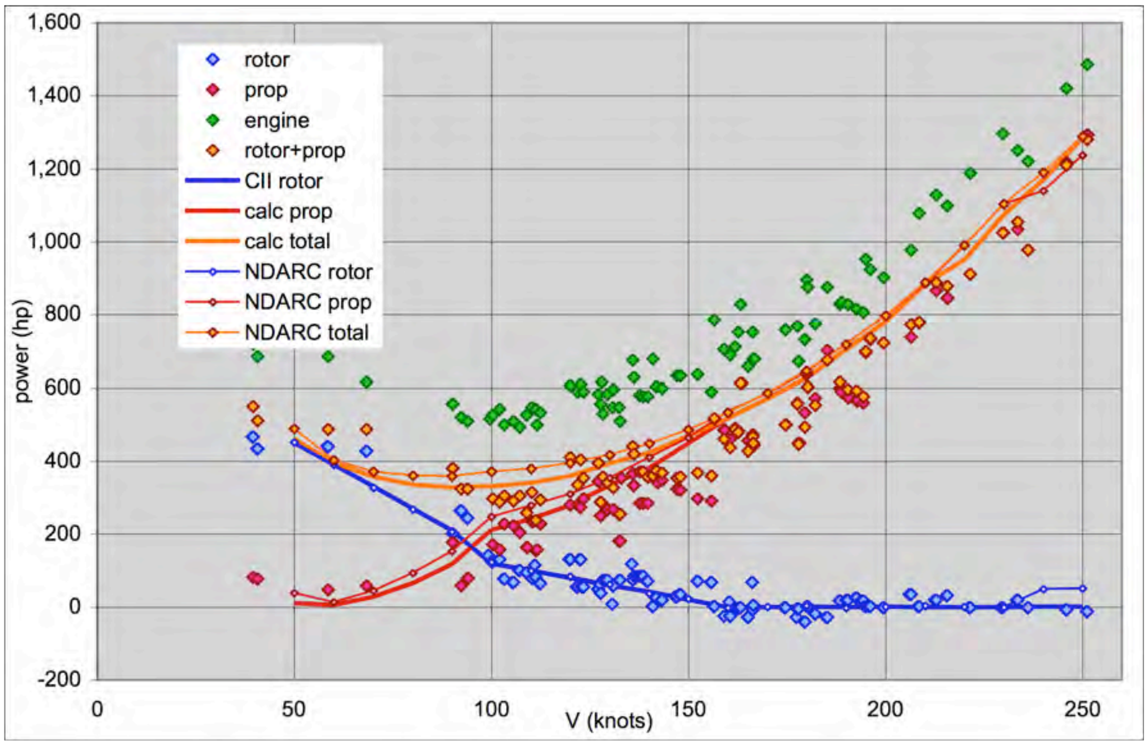
- Rotor power: approximated by faired curve

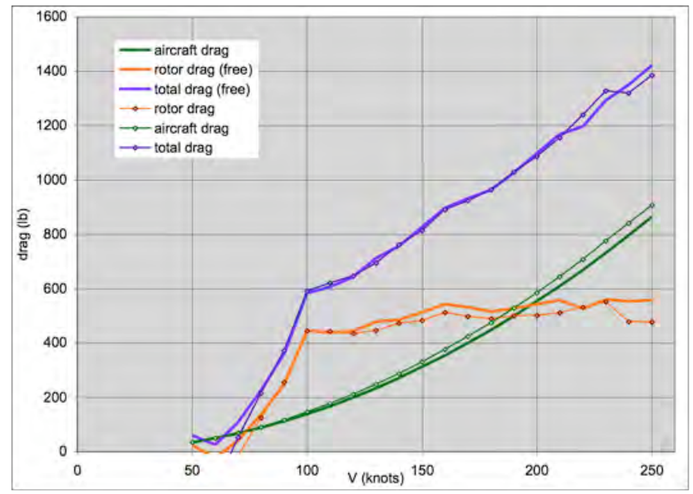
- Trim for calculated performance:
  - F_z(rotor+tail) = GW, M_z=0
  - Rotor roll moment = offset*R*.5*GW ft-lb, pitch moment=0
  - Pitch angle so rotor power = measured
  - Significant lift from tail

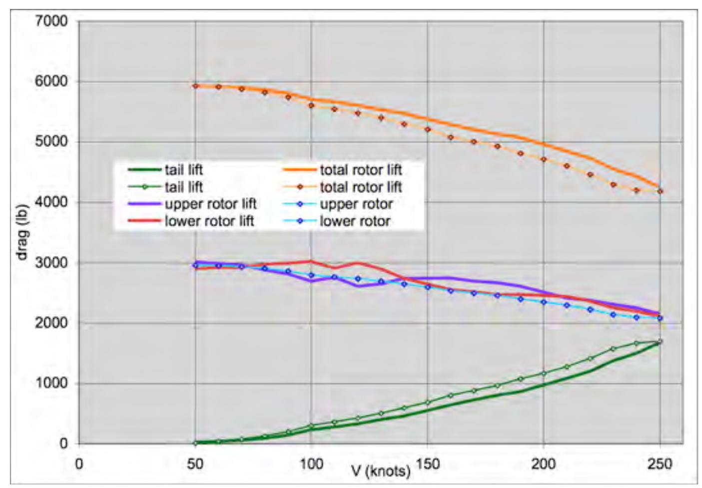


- Propeller power = $D_{total}V/\eta$
  - η = 0.85
  - $D_{total} = D_{rotor}$ (calculated) + $q*D/q_{airframe}$
  - $D/q_{airframe} = 1.4(GW/1000)^{2/3} = 4.6$ ft^2

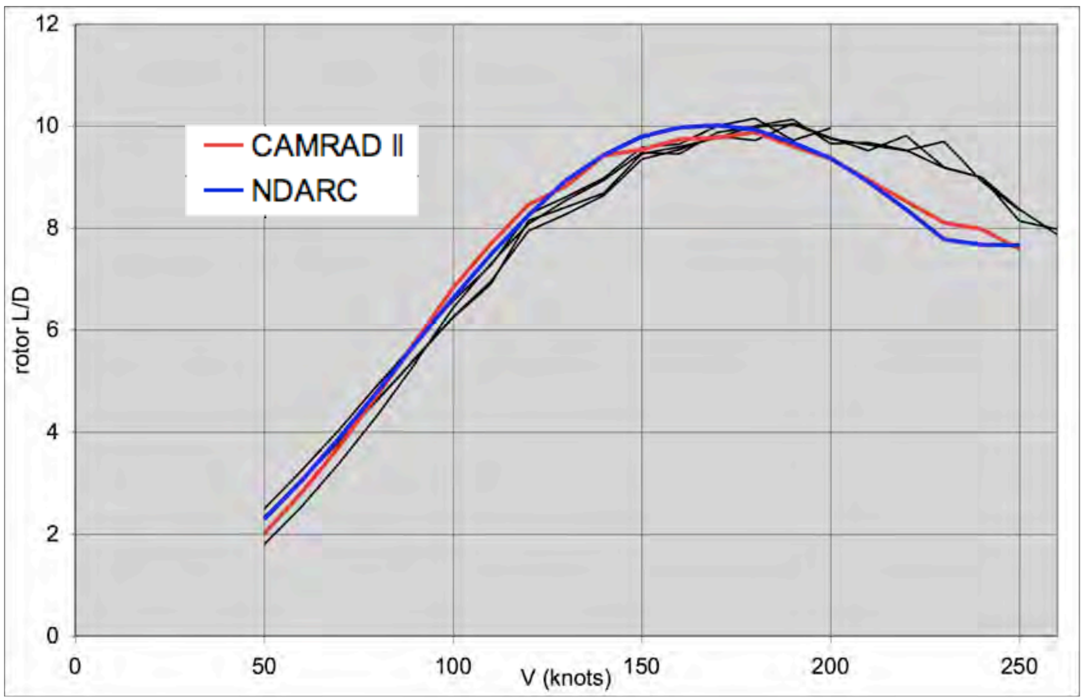
X2 Performance Calculation and Calibration

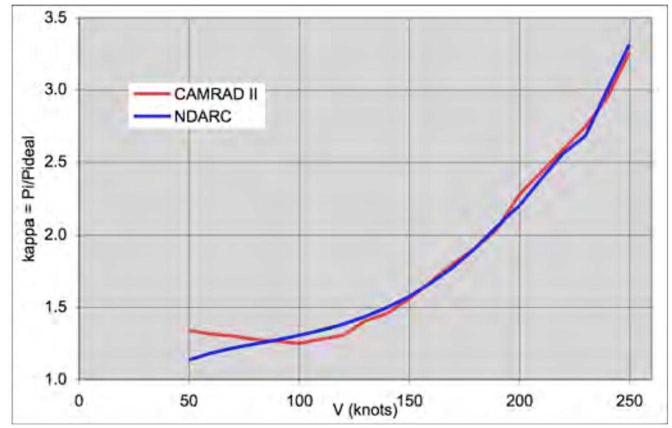


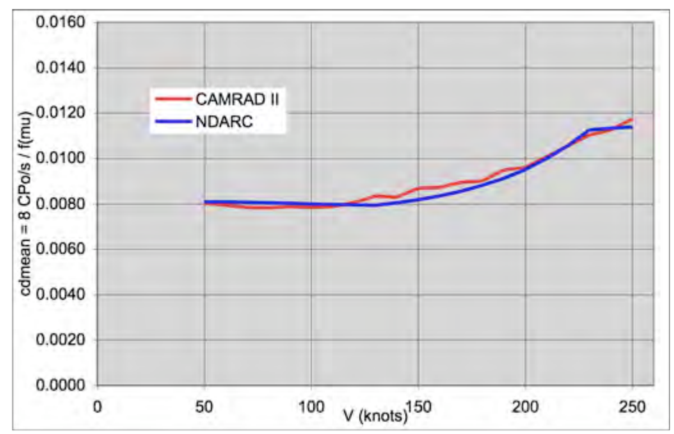




X2 Performance Calculation and Calibration







Lift Offset Compound for JMR

- Starting point
    - AFDD Compound JMR-C-MEA1-02
    - X2TD rotor models (small rotor power)
    - AATE engine model
    - RC/NDARC rotor weight model with generous tech factor

- Trim:
    - Hover and low speed
        - 6 F/M with collective, cyclic, pedal, pitch and roll
        - lift offset = 0, differential pitch moment = 0
    - Cruise
        - 6 F/M with collective, lateral cyclic, pedal, elevator, prop coll, roll
        - rotor roll moment = offset (.25), rotor pitch moment = 0
        - pitch = 5° (small rotor power)

- Optimized
    - Disk loading
    - Cruise altitude = 14k

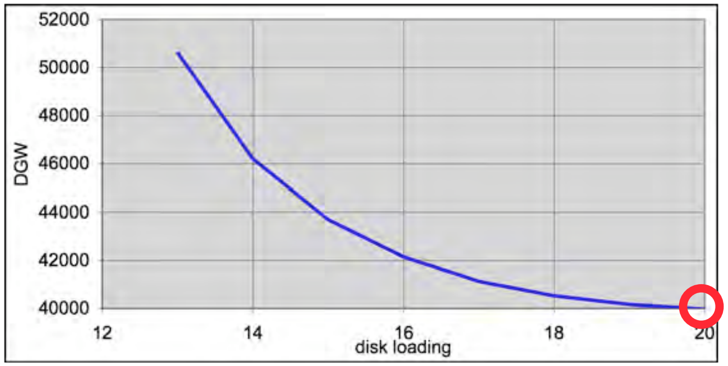
Lift-Offset Rotor Weight Model

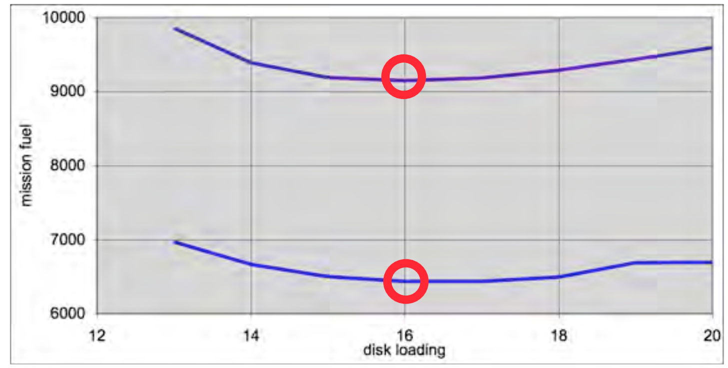
- AFDD ASRO (1983) model for RC code, incorporated in NDARC
  - Calibrated to XH-59A

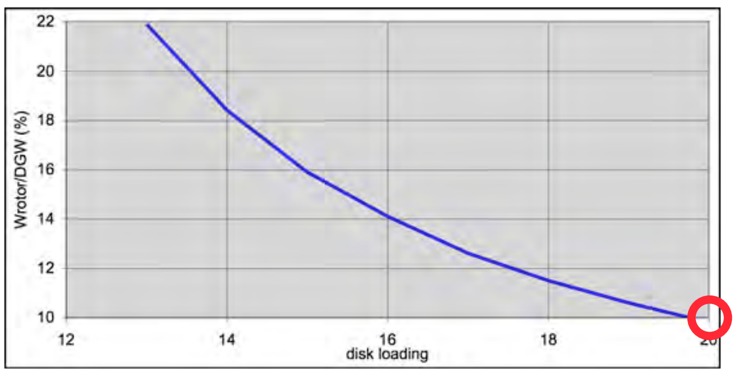
- Blade weight: beam maintain tip separation with moment GW*R
  - $W \sim W_{SD} n_z R \ (R/t_{0.2R})^2/(h/D)$
- Hub weight: plates maintain strength with CF and blade bending moment
  - $W \sim W_{blade} (V_{tip})^2 (t_{0.2R}/R)$ and $W_{SD} n_z R N_{blade}$
- Inter-rotor shaft weight: beam maintain strength with moment offset*GW*R
  - $W \sim W_{SD} n_z RL \ (R/t_{0.2R})(h/D)$

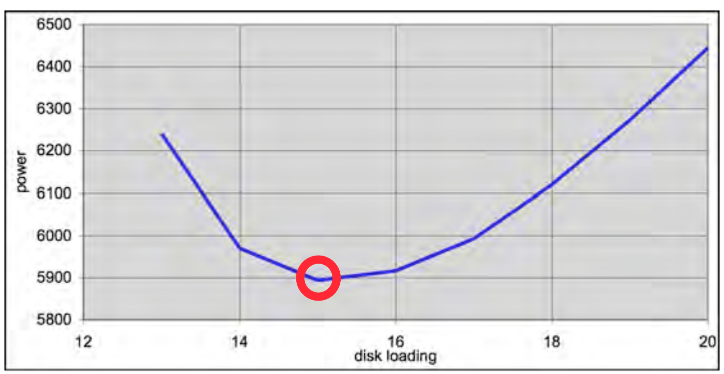
- Tech factors
  - Load criterion (n_z): 4/5.25 ?
  - Advanced materials: 0.8 blade, 0.6 hub ?
  - Advanced design: 0.5 ?

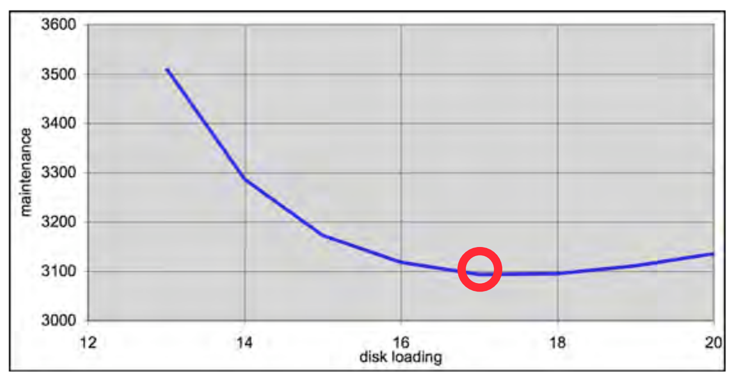
Disk Loading











Choice:

16 lb/ft^2

JMR-X-ME1A-00 Design

- **PRELIMINARY**
  - **Not reviewed by design team**
  - **Baseline for rotor weight sensitivity (TF=.4 blade, .3 hub -> 14%DGW)**

Configuration	Helicopter	Compound	Tiltrotor	Lift Offset
Designation	JMR-H-ME1A-02	JMR-C-ME1A-02	JMR-T-ME1A-02	JMR-X-ME1A-00
Design Gross Weight (DGW), lb	36,493	41,434	44,538	42142
Struct. Design Gross Weight, lb	35,354 (97%)	39,771 (96%)	43,714 (98%)	39979 (95%)
Max. TO Weight, lb (%DGW)	45,951 (126%)	51,961 (125%)	55,913 (126%)	52503 (125%)
Op. Wt, Empty, lb (%DGW)	24,450 (67%)	30,668 (74%)	33,922 (76%)	30256 (72%)
Weight Empty, lb (%DGW)	22,583 (62%)	28,166 (68%)	31,481 (71%)	27906 (66%)
Mission Fuel, lb (%DGW)	5,880 (16%)	5,468 (13%)	5,233 (12%)	6433 (15%)
Fuel Capacity, lb (%DGW)	8,075 (22%)	8,235 (20%)	6,854 (15%)	9148 (22%)
Design Payload, lb (%DGW)	6,600 (18%)	6,600 (16%)	6,600 (15%)	6600 (16%)
Wing Loading (DGW), lb/sqft	n/a	85	100	n/a
Disk Loading (DGW), lb/sqft	10	12	15	16
Rotor Diameter, ft	69	66	43	58
Hover Tip Speed, ft/s	725	725	750	725
Cruise Tip Speed [†], ft/s	725	475	626	650
Aircraft Figure of Merit	0.62	0.61	0.66	0.70
Cruise: Altitude, ft	12,000 (ISA)	24,000 (ISA)	18,000 (ISA)	14000 (ISA)
Speed, kt	153	229	254	178
L/De (WV/P)	4.4	6.6	7.0	4.55
SFC, lbfuel/hp-hr	0.386	0.343	0.343	0.353
6k/95F Speed (≤90%MCP), kt	184	235	280	202
95F HOGE Ceiling (DGW), ft	7,632	7,475	7,673	8127
Inst. Power (MRP/SLS), hp/eng.	4,723	6,048	6,737	5916
Drive System Limit, hp	7,083	9,069	10,103	9123
Op. Length / Width / Height, ft	86.7 / 69.1 / 24.0	81.2 / 66.3 / 21.9	53.5 / 98.0 / 20.3	64x58x23

Plans — JMR Design IPT

- Rotor optimization for hover and cruise conditions
  - Planform, twist
  - Airfoils?
  - Rotor shaft angle in cruise for best system performance

- Performance for range of conditions
  - Calibrate NDARC rotor models

- Design JMR-X-ME1A-02
  - Optimized (disk loading, etc.)
  - Off-design performance
  - Exploration of design criteria (max speed, etc.)

- Sensitivities
  - Rotor and hub weight

AHS SF 2012 Paper

- Design and Performance of Lift-Offset Rotorcraft for Short-Haul Missions
    - Wayne Johnson, Alex Moodie, Hyeonsoo Yeo
    - AHS Future Vertical Lift Aircraft Design Conference, San Francisco, January 2012

- Designs of lift-offset compound helicopters for civilian and military short-haul, medium-lift missions
    - Aircraft sized for 20 passengers, with a range of about 300 nm
- Rotor performance for a nominal lift-offset rotor configuration calculated using CAMRAD II, results used to develop rotor performance model for NDARC
- Size lift-offset compound helicopters (NDARC), varying mission requirements such as range and speed, and varying design parameters such as disk loading
    - Preliminary selection of designs based on appropriate metrics
- Optimize rotor blades for these designs (CAMRAD II), update NDARC rotor model
- Size lift-offset rotors (NDARC), based on optimized rotor performance
- Influence of technology
    - Rotor hub and blade weight
    - Airframe and hub drag