Rotorcraft Airloads Measurements: Extraordinary Costs, Extraordinary Benefits
The 31st Alexander Nikolsky Honorary Lecture

William G. Bousman*
U.S. Army Aeroflightdynamics Directorate (Retired)
Moffett Field, CA

The first airloads measurements were made in the 1950s at NACA Langley on a 15.3-ft-diameter model rotor, stimulated by the invention of miniaturized pressure transducers. The inability to predict higher harmonic loads in those early years led the U.S. Army to fund airloads measurements on the CH-34 and the UH-1A aircraft. Nine additional comprehensive airloads tests have been done since that early work, including the recent test of an instrumented UH-60A rotor in the 40- × 80-ft Wind Tunnel at NASA Ames. This historical narrative discusses the 12 airloads tests and how the results were integrated with analytical efforts. The recent history of the UH-60A Airloads Workshops is presented, and it is shown that new developments in analytical methods have transformed our capability to predict airloads that are critical for design.

Notation

a	speed of sound, ft/s
b	number of blades
C_M	section pitching moment
C_N	section normal force
$C_T/\sigma = T/\pi\sigma\rho\Omega^2R^4$	rotor thrust coefficient
$C_W/\sigma = GW/\pi\sigma\rho\Omega^2R^4$	gross weight coefficient
c	blade chord, ft
GW	aircraft gross weight, lb
M	Mach number
M_t	section moment, inch-lb/inch
$M^2C_M = 2M_t/\rho a^2c^2$	section pitching moment
$M^2C_N = 2N_t/\rho a^2c^2$	section pitching normal force
m	slope, linear regression
N	section normal force, lb/inch
N_R	rotor speed, rpm
n_z	load factor, g
R	blade radius, ft
r	radial coordinate, ft
r^2	coefficient of determination
T	rotor thrust, lb
V	flight speed, ft/s
v	section velocity, ft/s
α_s	angle of attack, deg
θ_0	collective pitch, deg
μ	advance ratio, $V/\Omega R$
ρ	air density, slug/ft^2
σ	rotor solidity, $bc\pi/R$

*Corresponding author; email: barlowi@earthlink.net.
Presented at the American Helicopter Society 66th Annual Forum, Virginia Beach, VA, May 3–5, 2011. Manuscript received March 2014; accepted June 2014.

Preface

It is traditional for the Nikolsky Lecturer to draw some connection between the lecturer and Professor Nikolsky, something that becomes more difficult to do with each passing year. I have no such connection, but I do have a link to the start of the honorary lectureship and that will have to suffice.

In 1978, Dewey Hodges and I wrote a paper on the correlation of theory and experiment for helicopter rotor aeromechanical stability (Ref. 1). I had the opportunity to present the paper at the Fourth European Rotorcraft Forum in Stresa, Italy, in September of that year. The plenary session was a presentation of "Early Development of the Helicopter at Sikorsky." Sergei Sikorsky gave the presentation based on his and Bill Paul's delving into the Sikorsky archives (Fig. 1). Most of the lecture focused on Igor Sikorsky's notebooks. It was a marvelous talk and very stimulating for a young engineer. Unfortunately, there was no written version.

That winter, I think in January, Bart Kelley presented a talk to the American Helicopter Society's San Francisco Bay Area Chapter on Art Young, Larry Bell, and the early history of the Bell two-bladed rotor (Fig. 2). I found this talk amazing as well, and wondered why we could not have some of this fascinating history written down.

In the summer of 1979, I became the President of the San Francisco Bay Area Chapter. In quiet moments in the test area behind our offices at Ames Research Center, I started thinking whether there might be a way to create a history-oriented lecture and ensure that it was written down. I had a vague notion of the AIAA lecture series, so I called the AIAA

DOI: 10.4050/JAHS.59.031001

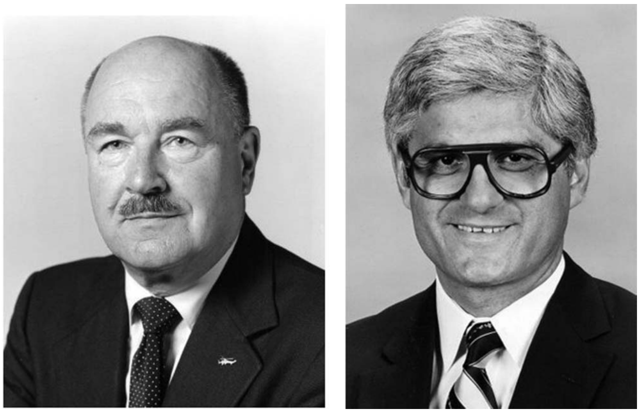

Fig. 1. Sergei Sikorsky (left) and Bill Paul (courtesy of Sikorsky Aircraft).

Fig. 2. Bart Kelley (AHS International Archive).

office and asked how they had structured their Dryden Lectureship in Research. The AIAA staffer I spoke with was very kind and sent me considerable information on the award. I then called the AHS and asked Kim Smith how we could go about proposing a new honorary award. She explained the process of making a formal proposal and then presenting it to the Board.

The chapter and I put together a proposal for an honorary lectureship that would include both a lecture and a subsequent written manuscript to be published in the *AHS Journal*. Bob Wood was the AHS Western Region Vice President at the time, and he agreed to take the proposal to the next AHS Board Meeting. The Board approved our proposal and named it in honor of Professor Alexander A. Nikolsky. The first recipient of the Alexander A. Nikolsky Honorary Lectureship was Steppy Stepniewski of Boeing Vertol. He presented this inaugural lecture at the 37th Annual Forum in New Orleans in 1981. Subsequently, a biography of Professor Nikolsky and that first lecture were published in the Journal (Refs. 2, 3).

Introduction

Airloads are the aerodynamic forces on the rotor blade and can be measured by installing pressure transducers at the blade surface. Figure 3 shows the planforms of the 12 instrumented rotor blades that have been used in the airloads tests that are the focus of this narrative. These tests

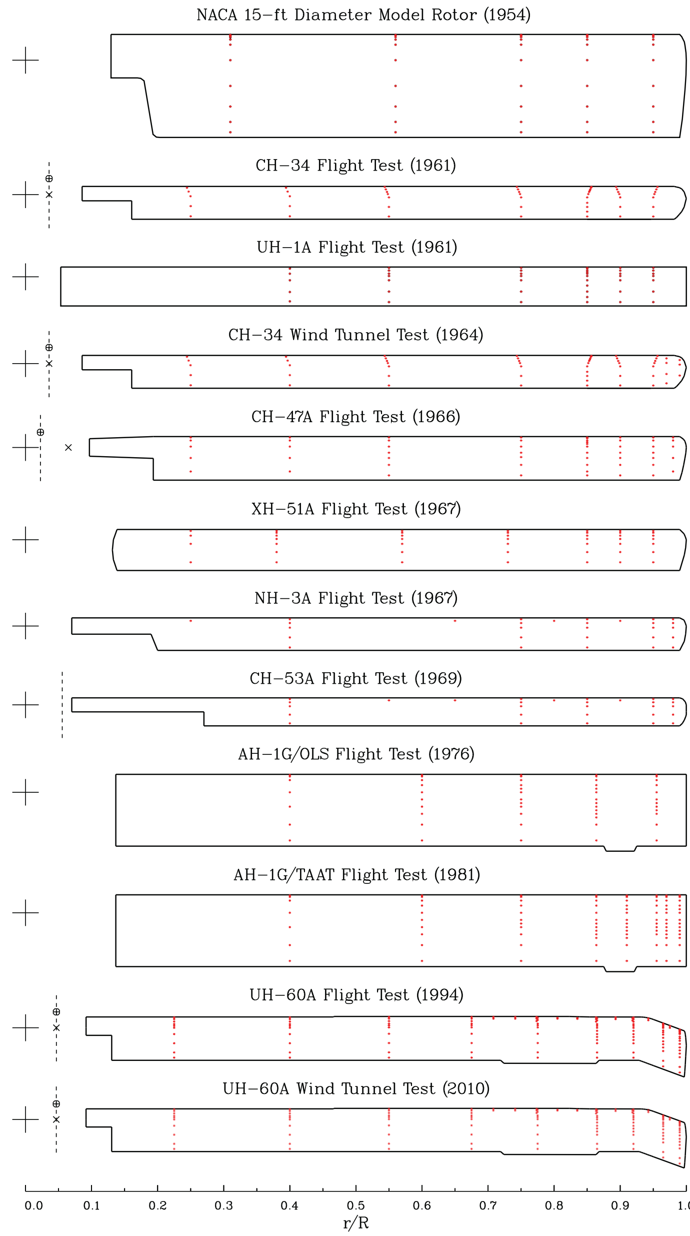

Fig. 3. Blade planforms for 12 airloads tests showing locations of upper surface pressure transducers.

have used at least five radial stations for the measured airloads, and the average number of transducers at any station has ranged from 5 to about 12. After the individual pressures have been measured and recorded, they are integrated along the blade chord to provide normal force and pitching moment (and in some cases chord force). The normal forces at the radial stations may then be integrated to provide the blade thrust.

The airloads on the rotor are important for performance, flight control, fatigue loading, vibration, and acoustics. The steady or zeroth harmonic forces determine the helicopter's lift and propulsive force. First harmonic airloads are essential for control. The oscillatory airloads, usually the first to third harmonics, determine the fatigue loading on the blade and controls. Higher harmonics of airloading that are not canceled at the rotor hub are important for vibration. Still higher harmonics of the airloads are important for radiated acoustic noise.

I will begin my narrative by addressing the extraordinary costs of these airloads tests, in part, by describing how they fit into the concept of

Table 1. Big Science programs

Project	Cost
International Space Station (ISS)	$35–100 billion
International Thermonuclear Experimental Reactor (ITER)	$13 billion
Superconducting Super Collider (SSC)	$8–11 billion
Large Hadron Collider (LHC)	$8 billion
James Webb Space Telescope	$6.8 billion

"Big Science." I will then discuss what these experiments must achieve to bring about benefits that are comparable to their costs.

The primary theme of this narrative is a history of airloads testing, from the first experiment by Jack Rabbott and Gary Churchill around 1954 (Ref. 4) to the wind tunnel test of the UH-60A blades in 2010 (Ref. 5). To understand these experiments, it is also essential to understand the development of airloads theory over the same time period. I am an engineer not a philosopher, but I am attracted to the oriental concept of yin yang that suggests that conflicting forces are interconnected and must achieve balance. I see experimentation as yin and theoretical developments as yang. But these are both just two sides of one problem. In the past decade, the UH-60A Airloads Workshops have been successful in bringing these two sides together and a discussion of those workshops and the transformation in our predictive capabilities is an important part of my narrative.

In addition, the influence of technology is felt throughout this period, both on the experimental and the theoretical sides. Here there is also conflict, this time between new technological capabilities that offer sometimes too much or sometimes too little. Both the experimentalist and the theoretician need to balance their needs with the new possibilities. So, the subtheme of technology development will weave in and out of my narrative.

Finally, I will conclude my story with five challenges. These are areas where I think we need to focus if we are to complete the promise of our new methods, tools, and understanding from the past decade.

By restricting myself to the 12 airloads tests that are the core of my narrative, I have excluded many excellent test programs based on pressure transducer measurements. These include full-scale flight tests with measurements at a limited number of radial stations and numerous model rotor tests. Many of these tests deserve their own history.

Extraordinary Costs, Extraordinary Benefits

A useful perspective of the costs of major research programs is that of "Big Science." In the world of national and international science, projects that fit the moniker of Big Science are those that are too large to fund from conventional national research budgets. Each of these projects requires long and painstaking negotiations to develop the mission and funding. The promise that is made in all of these projects is that when overruns occur, the project will not eat everyone else's resources.

Table 1 lists a sampling of Big Science programs. A typical mix, some of these are currently operating (the space station and the LHC), one has been canceled (the SSC), and two are in development (ITER and the new space telescope). For the Webb Space Telescope, an independent panel reported a $1.7 billion overrun in November 2010, bringing the cost to $6.8 billion. "The overrun is $700 million more than NASA now spends each year on all astronomy projects" (Ref. 6). There is currently an effort in Congress to terminate the project (Ref. 7). Most of these projects are multinational; the expenses are simply too great for any one country to afford.

Table 2. Big Science programs in the helicopter world

Project	Cost
Integrated Technology/Flight Research Rotor (ITR/FRR)	$60 million
Tiltrotor Research Aircraft (XV-15)	$46 million
Rotor Systems Research Aircraft (RSRA)	$42 million
UH-60A Airloads Program	$6 million

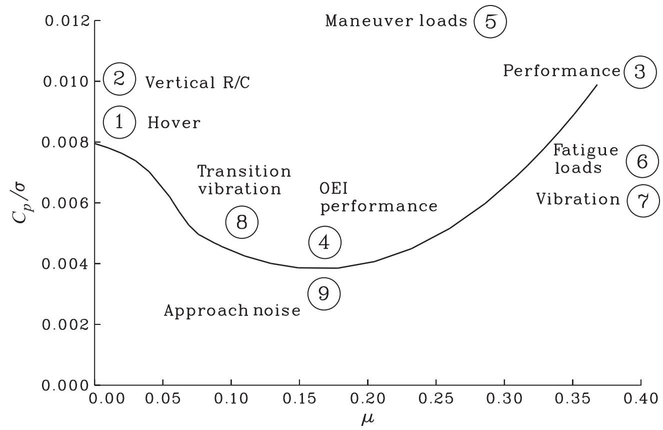

Fig. 4. Knowledge requirements for rotorcraft designer for new aircraft designs.

In our own world of helicopter development, the numbers associated with Big Science are in the millions, not the billions, as shown in Table 2. The ITR/FFR project in the mid-1980s was for the development and test of two prototype rotors that would employ the most recent technology developments, updating our industrial capabilities since the development of the UTTAS (Utility Tactical Transport Aircraft System) and AAH (Advanced Attack Helicopter) programs. But after a few preliminary technology studies, the program was canceled.

The XV-15 and RSRA developments occurred in the 1970s, as described recently by Ward (Ref. 8). The XV-15, a tiltrotor technology demonstrator, was a notable success and led to the eventual development of the V-22 Osprey. The RSRA, a "flying wind tunnel," was brought to flight status, but never achieved its intentioned purpose (Ref. 9).

The UH-60A Airloads Program (Ref. 10), by comparison, was less costly than these others, but had the same characteristics of many Big Science projects in its ability to overrun costs. As with so many of these types of programs, it was also canceled and that cancellation, followed by subsequent success, is part of my narrative.

The extraordinary costs of airloads test programs must be matched by extraordinary benefits. It is not sufficient to simply collect data and publish a few test reports. Rather, it is essential that the data be useful for the rotorcraft designer and be able to affect future aircraft designs.

Larry Jenkins, Director of Research and Technology at Bell Helicopter Textron, briefed the National Research Council in 1995 about the essential knowledge that was required by the rotorcraft designer for improved helicopter designs in the disciplines of aeromechanics. I show Larry's requirements of essential knowledge in Fig. 4, overlaid on the power required curve of a typical helicopter as a function of advance ratio.

In the discipline of aeromechanics, the helicopter designer must consider performance, critical design and fatigue loads, vibration, and acoustics—all in a balanced approach. In hover, the designer must be able to accurately compute hover performance (1), the most unique attribute for a helicopter. For military aircraft, there is also the need to predict the vertical climb capability of a helicopter (2), a required increment in installed power to give helicopters additional maneuver capability at

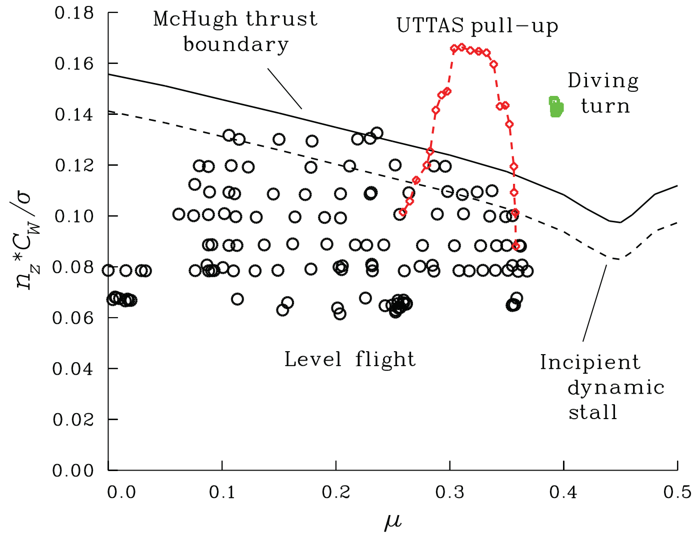

Fig. 5. Nondimensional weight coefficient over solidity (including effect of load factor) as a function of advance ratio for UH-60A Airloads Program. Level flight data, a UTTAS pull-up maneuver, and a diving turn are compared with McHugh's thrust boundary and an incipient dynamic stall boundary.

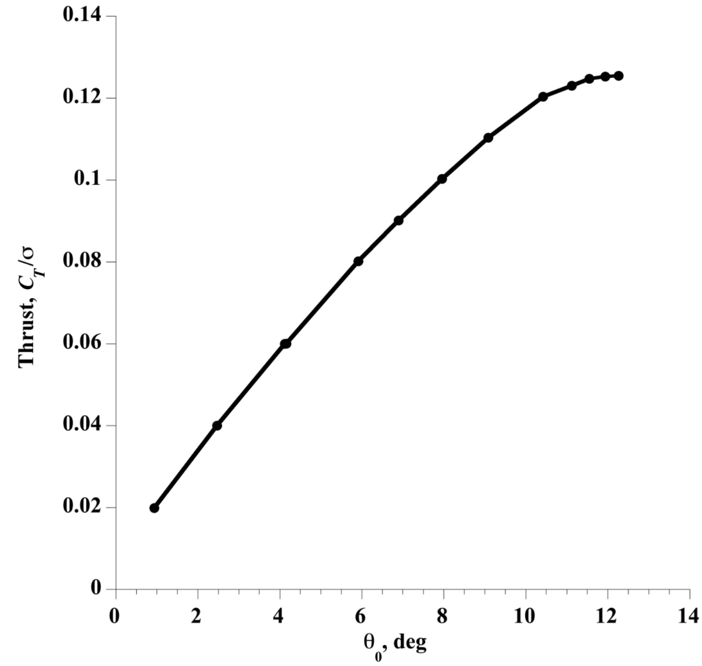

Fig. 6. Nondimensional thrust coefficient over solidity as a function of collective pitch for the UH-60A in the 40- × 80-ft Wind Tunnel; $\mu = 0.30$, $\alpha_s = 0$ (Ref. 5). Figure courtesy of Tom Norman.

their hover ceiling. Similarly, at cruise or maximum level flight speed, the designer must be able to accurately calculate the power required (3). For multiengine aircraft, it also necessary to compute the one engine inoperative (OEI) performance (4). This is important for civilian designs where the OEI performance is critical for engine failure while leaving a landing platform and for military designs in defining the rotorcraft's service ceiling.

Critical design loads occur in maneuvers (5); these may occur infrequently, but are the most severe loads encountered by a rotorcraft in flight. Fatigue loads (6), normally the first three harmonics, influence component safe lives or on-condition replacement. These loads cannot be allowed to occur in normal operation, lest excessive fatigue damage and early part replacement result.

Vibration typically occurs at high speed (7) and at the transition speed (8), about $\mu = 0.1$. For a four-bladed rotor, vibration is caused mostly by the third-to-fifth harmonics of rotor loads. Excessive vibration reduces mission capability and degrades crew and passenger comfort. Where the designer cannot reduce these vibratory loads in the design, he must accommodate them with some form of vibration reduction equipment during development.

Finally, the designer must account for radiated acoustic noise (9), whether at approach, as illustrated here, or for other conditions, such as at high speed.

Improvements in designer capability are the objective of all of the airloads testing of the past half century. To provide the extraordinary benefits in the title of my narrative, a significant improvement in designer capability must be shown.

History of Airloads Testing

Flight envelope limits

It is essential that airloads testing include flight conditions throughout the flight envelope, but there is a special benefit for testing at the envelope boundaries. The thrust limits are for the most part caused by dynamic stall, and the propulsive limits are caused both by dynamic stall on the retreating side of the rotor and supersonic flows on the advancing side.

Figure 5 shows the flight envelope of the UH-60A as it was tested in 1993–1994. The ordinate is nondimensional weight coefficient, C_W/σ, times the aircraft load factor (acceleration), n_z. Typically in flight-testing, rotor thrust, C_T, is not accurately measured, whereas the weight is. For most purposes, the two coefficients are roughly the same. By including the product of load factor, it is possible to include both level flight cases ($n_z = 1.0$) and maneuvers.

McHugh's thrust boundary (Refs. 11, 12) is used to define the flight envelope thrust limit for a helicopter rotor. That experiment used a 5.92-ft-diameter, three-bladed model rotor that had been designed and built such that rotor aerodynamic limits were encountered before the structural limits. Hence, at each trim condition in the wind tunnel, the rotor collective was increased until the rotor balance showed a thrust reversal, that is, the rotor thrust boundary. This test has uniquely defined the rotor thrust boundary in level flight and hence the lifting flight envelope. In maneuvers, however, it is possible to exceed the thrust boundary, at least for short periods of time. As shown in Fig. 5, this occurs in both transient maneuvers such as the UTTAS pull-up and in steady diving turns.

The thrust boundary shown in Fig. 5 has been examined recently in the test of the UH-60A pressure-instrumented rotor in the NASA Ames 40- × 80-ft Wind Tunnel (Ref. 5). Figure 6 shows the measured rotor thrust as a function of collective pitch angle at $\mu = 0.30$. As the collective is increased, the incremental increase in rotor thrust with a collective pitch angle decreases until it approaches zero at the thrust boundary. There is fairly good agreement of the measured thrust boundary in Fig. 6 with McHugh (Ref. 11). The UH-60A data show a boundary at C_T/σ of 0.126 and McHugh's measurements show about 0.124. But McHugh's thrust boundary was determined for a constant propulsive force, whereas the UH-60A boundary was for a zero shaft angle.

The thrust boundary (flight envelope limit) is caused by dynamic stall. Figure 7 shows the measured section pitching moments at $r/R = 0.92$ as a function of eight collective pitch values for the UH-60A rotor in the wind tunnel test. At the thrust boundary, the pitching moment shows

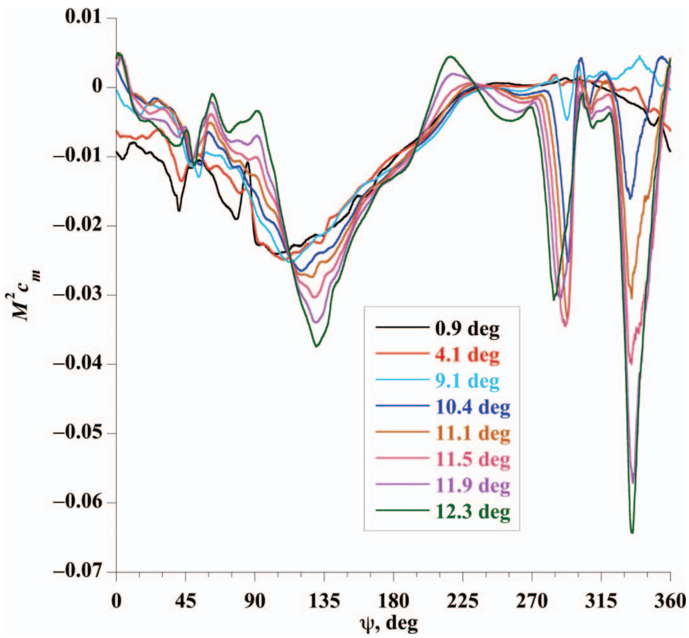

Fig. 7. Nondimensional pitching moment as a function of azimuth angle for the UH-60A in the 40- × 80-ft Wind Tunnel for eight collective pitch angles; $\mu = 0.30$, $\alpha_s = 0$, $r/R = 0.92$ (Ref. 5). Figure courtesy of Tom Norman.

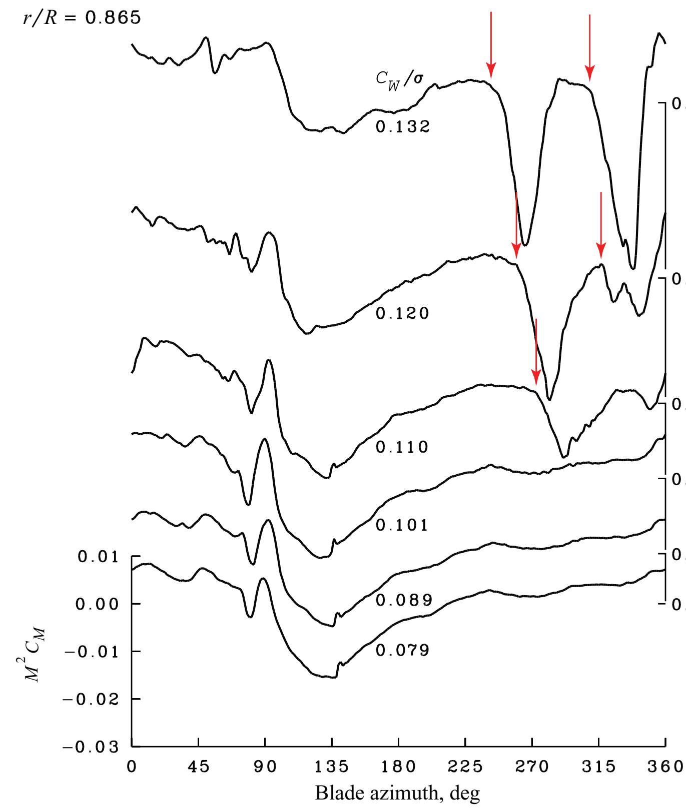

Fig. 8. Nondimensional pitching moment as a function of azimuth angle for the UH-60A at the propulsive force limit in level flight; $r/R = 0.865$, 0–120 harmonics. Red arrows show the dynamic stall cycles.

two cycles of deep stall in the fourth quadrant and the rotor has run out of lift. But at lower collective pitch angles, the stall is less severe. The lowest pitch angle where there is evidence of dynamic stall is about 9.1°. At this angle, there is a single cycle of incipient dynamic stall. The thrust at this point of incipient stall is about 12% below the thrust boundary. In the flight envelopes, I show in this narrative, I use this incipient dynamic stall line as a way of showing how dynamic stall becomes progressively more severe as the thrust boundary is approached (see Fig. 5).

The propulsive force limits for the helicopter may depend upon the thrust boundary or transonic loading. The level flight data shown in Fig. 5 were obtained for six airspeed sweeps at constant C_W/σ, roughly from 0.08 to 0.13 in increments of $C_W/\sigma = 0.01$. The pitching moments on the blade at $r/R = 0.865$ are shown in Fig. 8 for the six limiting conditions. In all six sweeps, the UH-60A is power limited at these propulsive limits (some helicopters may be structurally limited at these loading conditions). At the highest thrust conditions, both the lift and propulsive force are limited by dynamic stall. Although Fig. 8 shows section pitching moment and not power, the extent of the dynamic stall cycles are a good indicator of the loss of lift and the significant increase in drag that occur in severe dynamic stall.

At lower thrust conditions, the aircraft is power limited not because of dynamic stall (there is none), but because of the supercritical flows on the advancing side of the rotor. As the blade starts into the first quadrant, there is a rapid increase in Mach number whereas at the same time the blade pitch angle is being reduced. At the limit conditions shown in Fig. 8, supersonic flow forms on the forward section of the upper surface of the airfoil and is followed by a shock. As the blade pitch angle becomes negative, supersonic flow and its associated shock form on the lower surface. The relative motions of the supersonic flows on the upper and lower surfaces cause rapid variations in the section pitching moments (as shown on the advancing side in Fig. 8) and are a good indicator of the high drag occurring near the tip of the blade for these conditions.

The high-speed capability of a helicopter is thus limited by either dynamic stall on the retreating side or supersonic flow on the advancing side. If rotor speed is reduced, this reduces the supersonic drag, but makes dynamic stall worse. If the rotor speed is increased, the effects of dynamic stall may be eliminated, but the supersonic drag increases. As in the Merle Travis song "16 Tons," made popular by Tennessee Ernie Ford in the 1950s,

> One fist of iron, the other of steel
> If the right one don't a—get you
> Then the left one will

No matter, at the propulsive force limit, either dynamic stall or supersonic drag and the associated loads will get you.

The McHugh thrust boundary limit is to some extent idealized. Both McHugh's model-scale measurements and the 40- × 80-ft Wind Tunnel test data show that the thrust boundary is reduced by trim changes, such as an increase in propulsive force or an increase in shaft angle. But these shifts are small and do not diminish the value of the thrust boundary.

Early NACA research into rotor loads

Fred Gustafson reported on early performance tests of a Sikorsky YR-4B in forward flight (Ref. 13) and in hover with Al Gessow (Ref. 14). Figure 9 shows a photograph of that aircraft at Langley Field. The primary purpose of these tests was to obtain performance data, but Gustafson also looked at rotor speed variation as a means of identifying the stall boundaries. In this sense, these experiments and subsequent analysis of the data (Refs. 15, 16) represent one of the earliest formal studies of rotor loading.

In the initial tests, Gustafson obtained steady level flight data, as shown in Fig. 10, with a maximum speed of $\mu = 0.24$. From the maximum

Fig. 9. Sikorsky YR-4B tested at the NACA in the mid1940s (Fig. 2 of Ref. 13, NASA photograph, courtesy of Teresa Hornbuckle).

Fig. 11. Sikorsky H-19A tested at the NACA in the late 1950s (Fig. 1 of Ref. 17; NASA photograph, courtesy of Teresa Hornbuckle).

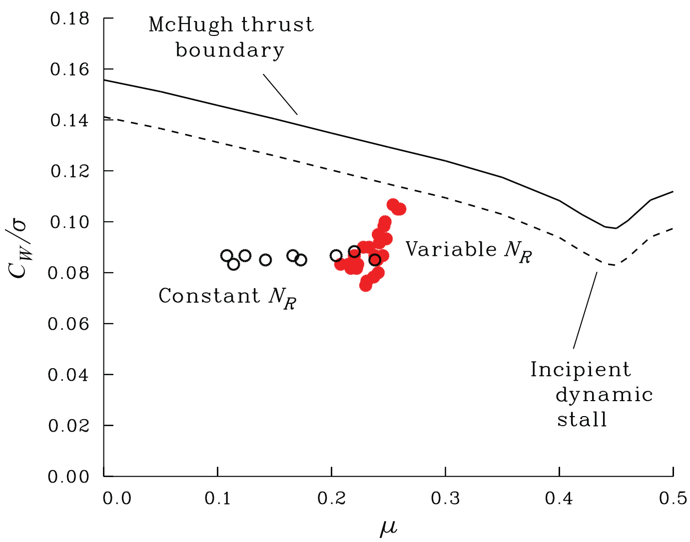

Fig. 10. YR-4B performance test points compared to typical helicopter flight envelope. Steady level flight data at constant rotor speed as open circles (Flt 5) and reduced rotor speed cases as solid circles (Flt 9) in Ref. 13.

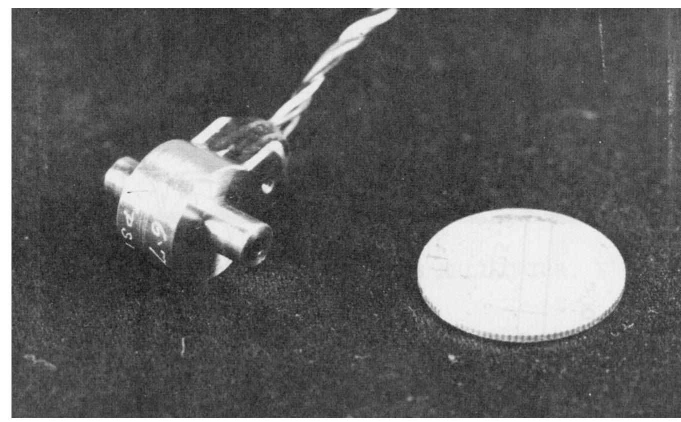

Fig. 12. Patterson's miniaturized differential pressure transducer, a dime is shown on the right (photograph from Ref. 21).

speed condition, the engine speed "was carried to the lowest rotational speed at which the pilot could control the aircraft." The decrease in rotor speed, N_R, provided for an increase in advance ratio, but also increased the thrust coefficient by the square of the rotor speed. Although no individual blade measurements were obtained, it appears that this test approach did allow the test aircraft to encounter dynamic stall.

Gustafson and his co-workers were under no illusions that a helicopter in forward flight was limited only by dynamic stall. Gustafson and Myers (Ref. 15) wrote, "Tip stall and compressibility thus ultimately limit the high speed of the helicopter."

In the late 1950s, LeRoy Ludi published a series of reports on flight tests of a U.S. Army Sikorsky H-19A bailed to the NACA at Langley Field (Refs. 17–20). Figure 11 is a photograph of the H-19A (Sikorsky Aircraft S-55). One blade of the H-19A was instrumented with strain gauges. Flap and chord bending and torsion moments were measured at $0.14R$, and flap bending moments were also obtained at $0.40R$.

Flight data were obtained for relatively benign conditions as well as for severe loading cases including dynamic stall in maneuvers and level flight, vertical descents in the vortex ring state, and landing approaches. To examine dynamic stall, Ludi used the same approach that Gustafson had used with the YR-4B, that is, reducing the rotor speed to increase both μ and C_W/σ. The test aircraft achieved advance ratios as high as 0.36 and values of C_W/σ as great as 0.148. Plots of the torsion moments show substantial increases in the moments under dynamic stall conditions (Ref. 18).

By looking at many different flight conditions for the H-19A, Ludi was able to identify those that had the greatest impact on blade loads. These publications were helpful in providing the industry a better focus on critical flight conditions as well as for the test planning needed for the first airloads flight tests in the following years.

The 12 airloads tests

Twelve rotorcraft airloads tests were accomplished, starting in 1953 and extending to 2010, a span of 57 years. The stimulus for these tests began with the work of John Patterson at the iconic NACA Instrumentation Research Division at Langley Aeronautical Laboratory in the early 1950s (Ref. 21). Patterson developed a miniaturized differential pressure transducer with high bandwidth and minimum sensitivity to g forces (see Fig. 12).

Patterson's objective was to devise a miniature transducer that would fit within the wings of high-speed aircraft wind tunnel models, would have high-frequency response suitable for measurements of wing buffet, and would be insensitive to g forces, either vibratory or centrifugal. Wind tunnel and propeller tests were the primary "customers" for the new transducer, but rotorcraft researchers immediately saw the potential for the new device. By 1953 Jack Rabbott had a two-bladed teetering rotor constructed and 50 of Patterson's transducers were installed in the blade at five radial stations (Ref. 23).

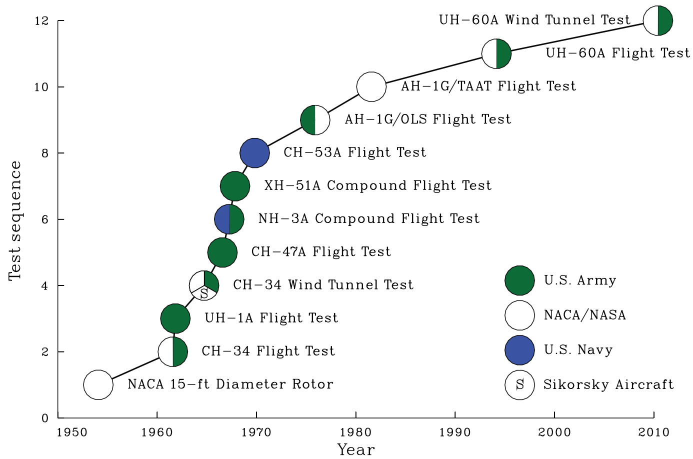

Fig. 13. Sequence of 12 airloads tests.

From the starting point of the NACA differential pressure transducers of the early 1950s on the two-bladed teetering rotor tested in the 30- × 60-ft Wind Tunnel (Ref. 4), there have been 11 additional airloads tests. The sequence of these tests by year is shown in Fig. 13. The date is based on the final test date (if recorded) or an appropriate estimate based on contract or report dates. Descriptive parameters for the test rotors and their instrumentation are shown in Table 3. A detailed description of each test is provided in Appendix 1 of Ref. 46.

The sponsors of the airloads tests are shown in Fig. 13, although the actual cost sharing is unknown where there was more than one sponsor. Unlike the other test programs, the CH-34 wind tunnel test included some funding from Sikorsky Aircraft. All the other tests were funded by U.S. Government agencies, one indicator of the extraordinary costs of these programs.

Seven of the 12 airloads rotors were tested in the 1960s. This concentration of testing was probably a result of the enabling technology of the new pressure transducers, but may have been affected by other factors. The U.S. Army obtained the responsibility for their own aircraft development programs in that decade rather than relying on the Navy or Air Force for these projects. Two of the airloads tests were compound helicopters, the Sikorsky NH-3A and Lockheed XH-51A, and these tests were a part of a larger effort to look at this technology on four different flight vehicles (Ref. 47). After the initial test activity in the 1960s, there were only four additional tests in the next 40 years, two of the Bell AH-1G Cobra and two of the Sikorsky UH-60A Black Hawk.

Table 3 provides details about the 12 airloads tests. The first several rows give information about the rotor or aircraft, whereas the remaining rows show information about the instrumentation. The number of radial stations refers to those stations where there were at least five pressure transducers along the blade chord (with the exception of the two tip stations on the CH-34 rotor tested in the 40- × 80-ft Wind Tunnel at Ames). In a few tests, additional pressure transducers were used at other radial stations. Single pressure transducers were added at 0.09c at four radial stations on both the NH-3A and the CH-53A flight-test programs. The UH-60A rotor had additional absolute pressure transducers added near the leading edge on both surfaces at eight radial stations to better quantify blade–vortex interactions.

The number of pressure transducers per station ("X'ducers/station") in Table 3 is an average of the number of installed transducers over all radial stations. For the tests that used differential pressure transducers (or absolutes wired as differentials), the average is just the number of pressure transducers divided by the number of stations. For the last four tests, which used absolute pressure transducers, there were sometimes

Table 3. Description of airloads rotor tests

Test	1	2	3	4	5	6	7	8	9	10	11	12
Aircraft	Model rotor	CH-34	UH-1A	CH-34	CH-47A	NH-3A	XH-51A	CH-53A	AH-1G	AH-1G	UH-60A	UH-60A
Type	Wind tunnel	Flight	Flight	Wind tunnel	Flight	Flight, compound	Flight, compound	Flight	Flight	Flight	Flight	Wind tunnel
Sponsor	NACA	NASA Army	Army	NASA, Army, Sikorsky	Army	Navy, Army	Army	Navy	Army, NASA	NASA	NASA, Army	NASA, Army
Manufacturer	NACA	Sikorsky	Bell	Sikorsky	Boeing	Sikorsky	Lockheed	Sikorsky	Bell	Bell	Sikorsky	Sikorsky
Number of blades	2	4	2	4	3 (×2)	5	4	6	2	2	4	4
Airfoil	0012	0012	0015	0012	mod 0012	0012	mod 0012	mod 0011	mod 0009	mod 0009	SC1095, SC1094 R8	SC1095, SC1094 R8
Twist, deg	0.0	−8.0	−15.0	−8.0	−9.0	−4.0	−4.0	−6.0	−10.0	−10.0	−16.0	−16.0
Solidity	0.0974	0.0622	0.0369	0.0622	0.0619	0.0781	0.0788	0.1150	0.0690	0.0690	0.0826	0.0826
Diameter, ft	15.3	56.0	43.8	56.0	51.9	62.0	35.0	72.0	44.0	44.0	53.7	53.7
Tip speed, ft/s	481	650	716	650	712	660	651	709	746	746	719	719
Radial stations	5	7	6 (5)	9	8	5	7	5	5	8	9	9
X'ducers/station	10.0	7.0	7.3 (7.4)	6.2	6.8	5.0	6.6	5.0	11.0	11.8	12.3	12.3
Rotating sensors	57	67	78 (49)	70	166	90	85	109	285	363	354	322
Test points	6	129	17 (4)	10	121	74	49	56	238	312	962	2,755
Bandwidth, harmonics	24	12	6 (12)	36	8	36	10	36	9, 37, 78	9, 37, 78	120	1028
Rotating samples	15,936	205,110	20,015	48,480	316,052	479,520	60,760	439,438	2,527,798	4,220,674	64,198,493	1,444,243,200
Test hours	–	<10.0	6.4	–	–	16.4	–	10.8	28.0	35.0	57.0	83.0
Completion date	1954	1961	1961	1964	1966	1967	1967	1969	1976	1981	1994	2010
References	Refs. 4, 23, 24	Refs. 25, 26	Ref. 22	Refs. 27, 28	Refs. 29–33	Refs. 34, 35	Refs. 36–38	Refs. 39, 40	Ref. 41	Refs. 42, 43	Refs. 44, 45	Ref. 5

more transducers installed on the upper surface than the lower. The average for these tests is half the number of transducers divided by the number of stations. Thus, there is equivalency between the two types of transducers.

Rotating sensors are those whose signal was transferred from the rotating system to the fixed system, usually by a set of slip rings. These sensors include the pressure transducers, strain gauge bridges on the blade, accelerometers, pitch-link loads, and a number of other measurements (Ref. 46).

The bandwidth is defined in Table 3 as the number of harmonics. The number of azimuthal samples per revolution is twice the bandwidth. The azimuthal step size is 360° divided by the number of azimuthal samples.

The number of rotating samples is the sum of the number of samples for each sensor for one revolution times the number of test points. In a number of these tests, more than one revolution of data were recorded, but the "Rotating samples" in Table 3 are for a single revolution for each test point.

For the UH-1A test, four test points were obtained with the bandwidth increased to 12 harmonics instead of 6. To obtain this increased bandwidth, it was necessary to reduce the number of sensors that were recorded. These changes are shown in Table 3 in parentheses. The purpose of the increased bandwidth is discussed below.

Both rotors on the CH-47A were instrumented for that test and hence there were many more rotating sensor measurements than in prior tests and more rotating samples as well.

The two AH-1G Cobra tests used multiplex frequency modulation (FM) analog tape recording. The bandwidth, therefore, depended on which FM band the instrumentation was assigned to. There were three bandwidths: roughly nine harmonics for structural parameters, 37 harmonics for inboard pressure transducers, and 78 harmonics for outboard pressure transducers.

Technology and airloads testing

Improvements in technology have had a significant impact on airloads testing over the half century covered in my narrative. In many cases, the technology improvements have enabled major advances in the amount of data that could be obtained in these tests. But there has been a downside as well. Sometimes we simply were not able to handle some of the new technologies and we lost control of the data.

I characterize the test measurements that were made in the 12 tests into two groups in Figs. 14 and 15, respectively. Figure 14 shows the number of instrumented radial stations, the number of chordwise pressure transducers, and the total number of rotating sensors over time. Figure 15 shows the natural logarithm of the number of test points, the harmonic bandwidth, and the number of rotating samples over time.

As shown in Fig. 14, the number of radial stations has varied from five to nine over the past half century. Reducing the number of radial stations has the advantage of a consequent reduction for modern tests of 20–30 pressure transducers, but too few instrumented radial stations means that there will be unexamined aerodynamic events on the rotor.

The first test installed 10 differential pressure transducers at each radial station. Subsequent tests dropped this number, soon reaching a basement level of only five transducers. This number has climbed for the most recent tests, and the average number is about 12 (for absolute pressure transducer measurements, that means 24 transducers at each radial station). The impetus to install more pressure transducers at each radial station is largely a result of attempting to better understand transonic flow over the rotor airfoil as well as the progression of the dynamic stall vortices, both nonlinear phenomena.

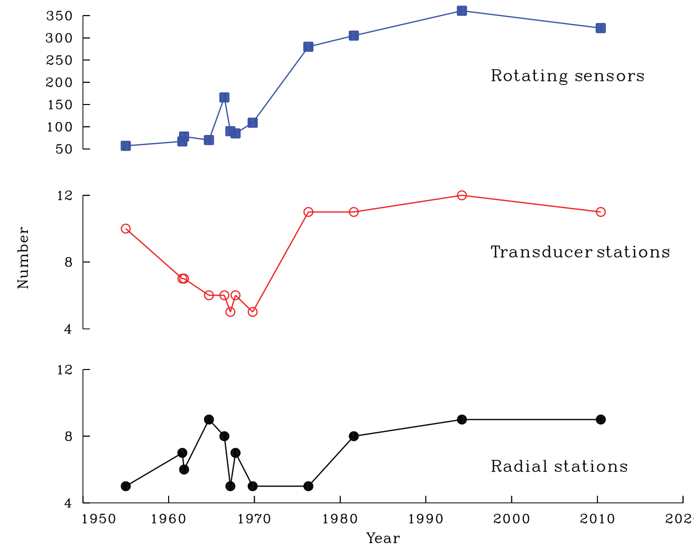

Fig. 14. Number of instrumented radial stations, chordwise pressure transducers, and the total count of rotating sensors for 12 airloads tests as a function of years.

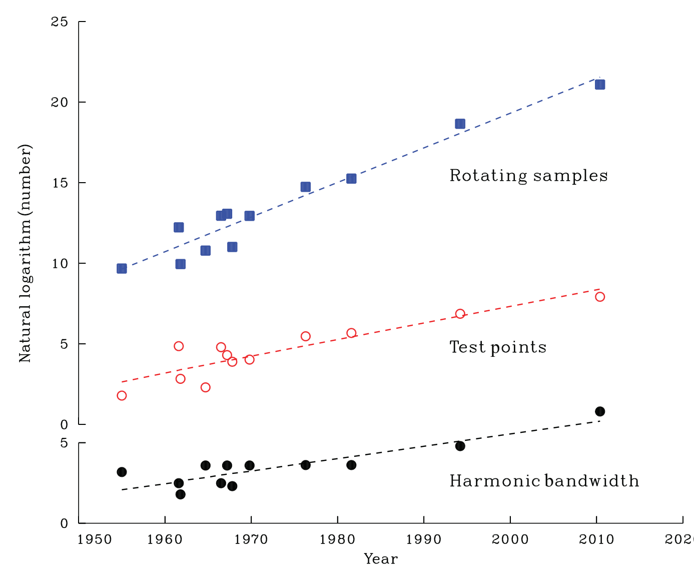

Fig. 15. Natural logarithm of number of recorded harmonics, test points, and rotating samples per rev for 12 airloads tests as a function of years.

Once the number of radial stations and chordwise pressure transducers has been selected, the total number of rotating sensors is roughly determined. Figure 14 shows that the average number of pressure transducers at each station closely matches the total number of sensors. The one exception is for the CH-47A flight test where both rotors were instrumented.

In Fig. 15, I show the natural logarithm of the number of harmonics, test points, and the total rotating samples. Each of these parameters has shown exponential growth over the past half century, albeit at different rates. Much of this increase has been enabled by improvements in the technologies that deal with acquiring, recording, and storing the measured data.

The first experiment was based on Patterson's development work at the NACA Langley Aeronautical Laboratory (Ref. 21). As shown in Fig. 16, the early airloads tests all used differential pressure transducers.

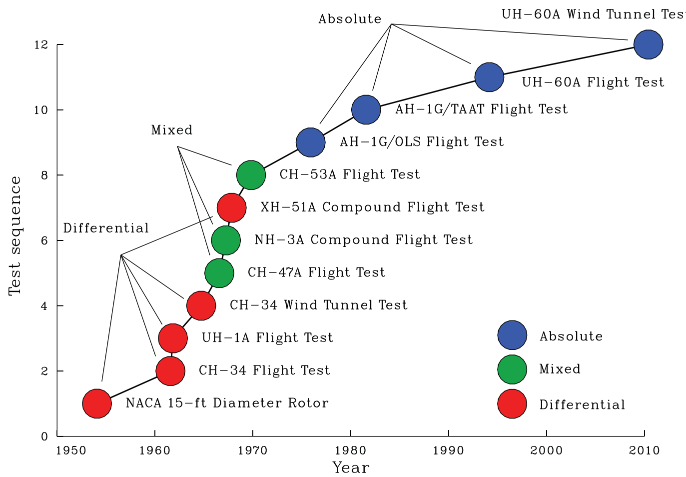

Fig. 16. Pressure transducer developments over the past half century.

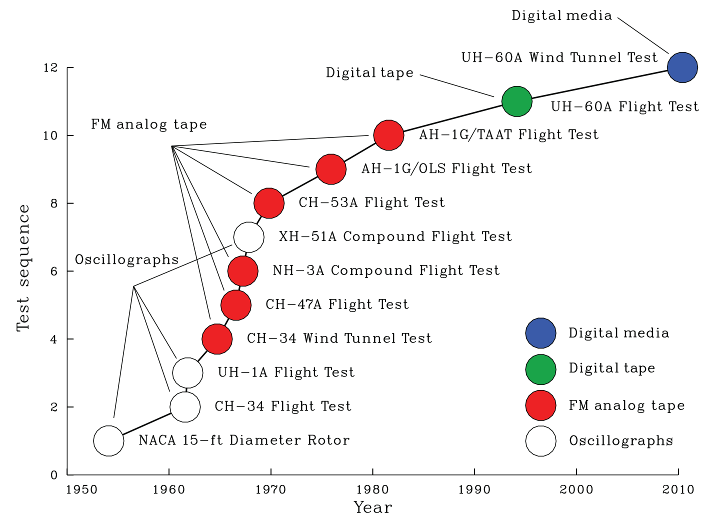

Fig. 17. Data recording developments over the past half century.

These miniaturized transducers were suitable for installation in full-scale rotor blades, but the major drawback was that drilling holes in the blade spar significantly reduced the blade's fatigue life.

There is no discussion of the fatigue design and testing for the CH-34 rotor (Refs. 26, 27), but John Ward (personal communication, November 24, 2010) recalls that the responsibility for this testing was his first job after joining the VTOL Branch at NASA Langley. They tested a single specimen of the blade with holes drilled in the spar, and analysis indicated that the blades were good for a 10-h lifetime (Ward, personal communication, November 24, 2010). The blades were flown successfully and were later used in the wind tunnel test.

Engineers at Bell Helicopter Textron (UH-1A) and Lockheed California Company (XH-51A) also fatigue tested blade specimens and calculated appropriate safe lifetimes (Refs. 22, 36).

By the 1960s, a number of commercial businesses had begun to design and manufacture miniaturized absolute pressure transducers. For the helicopter manufacturers involved with airloads measurements, the new absolute pressure transducers solved the fatigue-damage problem with the differential pressure transducers, since these new transducers could be surface-mounted on the blade and did not affect its structural integrity.

The three tests in the 1960s that used absolute pressure transducers on the blade structural spars treated the upper and lower surface pressure measurements as though they represented a differential pressure measurement. They either wired the transducers such that the output was a differential measurement, or they recorded the absolute pressures separately and computed the differential pressure during data reduction.

The first test to use absolute pressure transducers at all spanwise and chordwise locations was the AH-1G/OLS test (Ref. 41). Under U.S. Army sponsorship in 1965, Bell started a series of technology demonstration programs that defined the necessary instrumentation and data processing that would provide an improved understanding of aerodynamic and structural loads in normal flight. From our present perspective, the most important test was the instrumentation of one radial station of a UH-1H blade that was then tested in the NASA Ames 40- × 80-ft Wind Tunnel (Ref. 48). This test demonstrated that differential pressure transducers did not adequately characterize the aerodynamics over the rotor blade, and absolute pressure transducers were required. All subsequent airloads tests have used absolute pressure transducers to measure the rotor blade pressures.

The technology of recording the pressure measurements has also changed over the past half century (Fig. 17). In Ref. 49, Lunn and Knopp provided a history of the changes that occurred over the decades of the 1960s and 1970s when most of the 12 airloads tests were run:

> The evolution to our present data system in this 20 yr period has progressed from oscillograph recording, frequency modulated analog tape recording to programmable pulse code modulation (PCM) digital recording and telemetry from the aircraft, complemented by data-handling techniques which have progressed from colored pencils and hand analysis to large scale, real time computer analysis.

As shown in Fig. 17, the early tests, the NACA model rotor, the CH-34 in flight, and the UH-1A, plus the later XH-51A compound flight test, all recorded data on one or more oscillograph recorders. The oscillograph rolls were then "processed" using an optical device with a set of crosshairs that would transfer the signal amplitude and time to punched cards each time the operator clicked a digitization button.

The introduction of multiplex FM analog tape simplified the recording of pressure data and increased the accuracy. The technology capability in the new multiplex FM analog systems also encouraged flight-test organizations to record greater amounts of data.

In some cases, the signal conditioning was done on the rotor hub, in other cases, in the aircraft. The early tests multiplexed the signals in the aircraft and then recorded them on analog tape, but the AH-1G tests did the multiplexing in a hub-mounted bucket ("muxbucket").

The analog-to-digital (A/D) conversion of the multiplexed FM tapes was done in a ground station for all of the tests using analog tapes. Considerable effort was taken to keep the slip rings clean since contamination could lead to dropouts or spikes in the pressure data. As Lunn and Knopp noted (Ref. 49), pulse code modulation (PCM) became an option and A/D was then done in the rotating system and the PCM stream could be sent down through the slip rings and there were far fewer problems with the pressure data. In the most recent rotor test in the NFAC, the PCM streams are brought into the fixed system with a noncontacting capacitive data coupler.

The technology for data storage has changed significantly over the past 50 or so years (Fig. 18). Data storage for the NACA model rotor was simply the data points plotted on the graphs in the report, roughly a total of 16 kB. Today, these data are stored in large computers. The data from the UH-60A wind tunnel test occupy roughly 5 TB. The PIV and blade deflection images probably occupy another 10 TB (Tom Norman, personal communication, September 5, 2012).

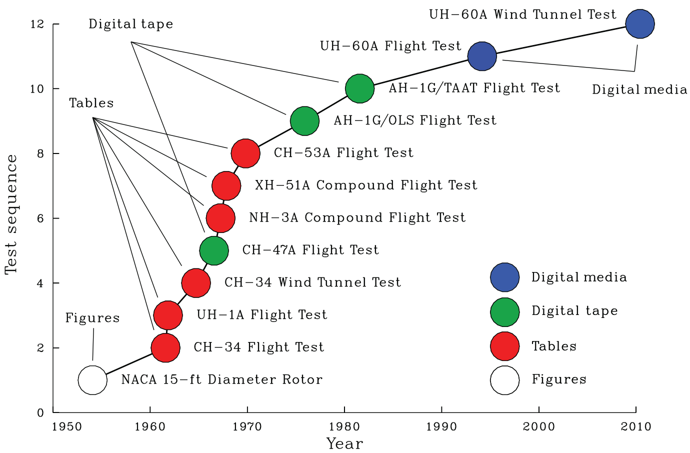

Fig. 18. Data storage developments over the past half century.

The early tests that used multiplexed FM analog tape data, for the most part, did not attempt to create a permanent database of digital data following the A/D conversion in their ground-based computers. Rather, they processed the data in one or more passes and wrote the results to tables, most made with the IBM chain printers of the time. Unfortunately, some of the tabulated data are barely legible because of too much or too little ink and the setup of the printers (Refs. 35, 40).

The next big step was to write the data to digital tape for permanent storage. This was apparently done with the CH-47A airloads data, although the details are obscure. For the AH-1G/OLS test, the analog data were processed and then recorded on about 173 nine-track digital tapes. For the AH-1G/TAAT test, there were a total of 350 tapes (from the original 23 FM analog tapes). The low data density of the nine-track digital tapes of the era created data-handling problems. For the OLS data, it was initially left to the user to access the digital data using the complex Data Definition statements and this was quite awkward (Don Merkley, personal communication, February 24, 2012). The Army contracted with Bell to provide a user interface program called DATAMAP (Refs. 50, 51). Access to the database was much improved with the use of DATAMAP (Merkley, personal communication, February 24, 2012).

Eventually, the large tape machines that could access the OLS and TAAT digital tapes became obsolete. Once this happened, the digital tapes could no longer be read and they were discarded.

A decade later, when the UH-60A flight test was conducted, there had been a number of advances in the technology. The A/D was done in a bucket mounted in the rotating system, the Rotating Data Acquisition System (RDAS). The digital data were then a PCM stream that was passed through the slip rings and recorded on digital tape. The data from individual flights were processed in a ground station, very much like the prior tests that used FM analog tapes. After processing, the digital data were written to a magnetic disk. There were roughly 16 times more data for the UH-60A flight program than for the AH-1G/TAAT test. Even with advances in the intervening years, the storage of the data was costly. Eventually, the 30 GB of data were written to optical disks stacked in a "juke box."

The UH-60A wind tunnel test also did the A/D in the rotating system, but it was transferred to the fixed system using a capacitive data coupler. Once in the main computer, all the processing and storage was on that computer. At last, the storage technology had caught up with the recording technology.

But digital data storage is ephemeral. Technical obsolescence, as with the two AH-1G tests, can make data disappear almost overnight, regardless of the original expense incurred in acquiring the data. Management changes can have the same effect. As Wayne Johnson has said (Ref. 52),

> We have had paper for a couple of thousand years, printing presses for a couple of hundred, computers have been with us for maybe a couple of decades. . . . I think actually putting things down on paper and saving them has a lot to be recommended.

Table 4. Airloads tests, first publication date, and number of citations

Test	Date	Citations
NACA Model Rotor Test	1956	29
CH-34 Flight Test	1963	149
UH-1A Flight Test	1962	46
CH-34 Wind Tunnel Test	1966	68
CH-47A Flight Test	1967	26
NH-3A Flight Test	1970	27
XH-51A Flight Test	1968	29
CH-53A Flight Test	1970	42
AH-1G/OLS Flight Test	1977	97
AH-1G/TAAT Flight Test	1988	70
UH-60A Flight Test	1994	226
UH-60A Wind Tunnel Test	2011	42

Benefits Obtained from Airloads Testing

In the Introduction, I discussed how the benefits from airloads testing, to be of value, must provide the engineering understanding that is the basis for improved design tools that can be used in the development of new rotorcraft. It is desirable, therefore, to examine the history of these programs to understand both quantitatively and qualitatively the impact these measurements have made on our technology.

In using various technology metrics to understand our progress, it is useful to recognize that not all of our industry's advances are documented in the open literature. From the government's perspective, the funding for any of these research programs may be justified if it provides the industrial designers significant knowledge that will improve new rotorcraft. But in this narrative, I will only address those results that are in the public domain.

Citations as a measure of benefits

One of the simplest ways to look at how the 12 airloads test data have been used is to count the number of citations in the literature. In my preparation for this lecture, I have collected as many citations as I could for each of the test programs. Table 4 shows the 12 tests (ordered by test date), the date of first publication, and the number of citations. The greatest number of citations are for the UH-60A and CH-34 flight tests, flown about 30 years apart. Although citation indices are popular means to assess progress in the sciences, they are too superficial to provide historical insight and, particularly, the judgment of the benefits of these programs.

But insight into the uses of these data can be obtained by focusing more closely on the distribution of these citations over time. I show such distributions in Figs. 19 and 20, where I plot the cumulative number of citations per year for each test, starting from the test date. I have divided the tests into two groups. In Fig. 19, I show (mostly) the earlier tests, whereas I show the later tests in Fig. 20. I also use different ordinate scales for the two figures.

Figure 19 shows the cumulative citations for seven tests. In most of these tests, the cumulative number of citations is fewer than 40. There

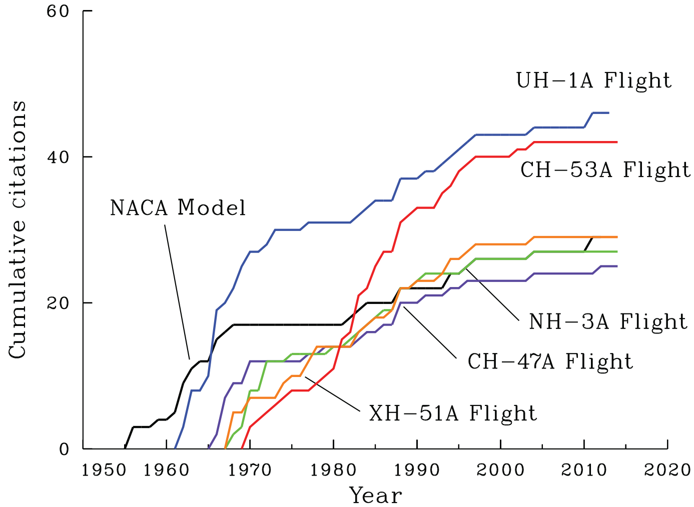

Fig. 19. Cumulative citations as a function of time (mostly for earlier tests).

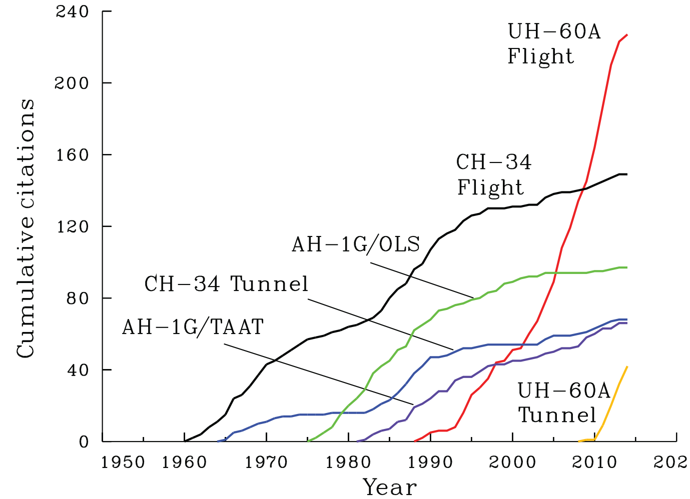

Fig. 20. Cumulative citations as a function of time (mostly for later tests).

is a similarity in the distributions for many of these tests, that is, there is a rise in the number of cumulative citations analogous to the first-order time rise of an exponential function. The initial rise in the early citations has a number of causes. Many of these tests were contracted by the U.S. Government, and some of the publications represent contract requirements. In some cases, there has been an immediate need for the data and the government has encouraged the rapid dissemination and use of that data.

Following the first-order-like rise in cumulative citations, subsequent citations tend to occur at a relatively slow rate. In some cases, these later citations are from survey papers, rather than a direct use of the data. For example, the last paper using the CH-47A airloads data was published in 1968 and the flight-test data were soon lost. The remaining citations refer to a few specific results published in the earlier literature or are citations of the test program.

The CH-53A flight-test data are an exception to the pattern of cumulative citations in Fig. 19. Both the airloads and structural data were used for many years after the initial publications (almost exclusively by Sikorsky Aircraft authors).

The cumulative citation patterns for the later tests (and the early CH-34 flight and wind tunnel tests) in Fig. 20 show more variation. The CH-34 flight-test data were used even before the original publication of the data reports because of the intense interest in the higher harmonic loading that could not be predicted at that time. The CH-34 wind tunnel test, on the other hand, focused on high-speed airloads and was not used very much after initial publication. This changed following the publication of Euan Hooper's masterly comparative paper looking at vibratory airloads (Ref. 53). His use of analysis and data visualization stimulated new interest in the CH-34 rotor measurements, and both airloads data sets were used by investigators well into the 1990s.

The data from the AH-1G/OLS flight test were used in two phases. In the first phase, Bell Helicopter Textron was funded to reduce the airloads as well as ground-acoustic data that were recorded simultaneously. These data were then provided to various investigators (Refs. 54, 55) to compare radiated acoustic pressures based on the airloads with the microphone measurements. The second phase was an examination of vibration and structural loads data as a part of the Design Analysis Methods for Vibrations (DAMVIBS) program. This included tabulated structural load and vibration data (Ref. 56) that were used extensively by the DAMVIBS collaborators (Ref. 57). These data were also used in a series of papers by Yeo and Chopra (Refs. 58, 59). Those structural and vibration data remain, but the airloads data are gone.

Citations of the follow-on AH-1G/TAAT test occurred at a lower rate than for the AH-1G/OLS. But the publication of airloads data for a limited number of cases (Ref. 43) has allowed analytical comparisons with these data to continue to the present.

The use of the UH-60A flight-test data is quite different from the other tests in that the number of citations has increased in subsequent years rather than following the typical pattern and decreasing with the passage of time. The reason for the increasing use of the UH-60A flight-test data in the past decade is a result of a number of factors and will be the focus of much of the rest of my narrative.

The UH-60A wind tunnel test was completed in 2010. Although it is too soon to predict the long-term trend of this test, it appears very much like the flight-test cumulative citation distribution with its rapid initial rise.

Understanding airloads

Our understanding of helicopter airloads developed as new and improved theoretical methods were developed, often using the airloads test data discussed in this paper. The development of theoretical methods, as viewed through the prism of airloads measurements, provides a better way of assessing their importance than a list of citations or their cumulative distribution. The milestones in the development of airloads theory were described by Wayne Johnson in the 30th Nikolsky Lecture (Ref. 60), and I cannot improve on that historical perspective. What I will do here is take advantage of our perspective from the past decade and show how airloads measurements have contributed to the development of our improved analyses.

Datta and his colleagues reviewed the progress that had been made with recent advances in coupled computational fluid dynamics (CFD) and computational structural dynamics (CSD) analyses at the midpoint of the 2000s, mostly using the UH-60A flight-test data (Ref. 61). Figure 21 is a copy of their Fig. 2 where I have added numbers for the three problems that they emphasized: (1) blade vortex loading at low speed and its effects on vibration, (2) dynamic stall at moderate speed or in maneuvers, and (3) vibratory loads at high speed. I will look at the use of flight measurements and the development of analytical methods for

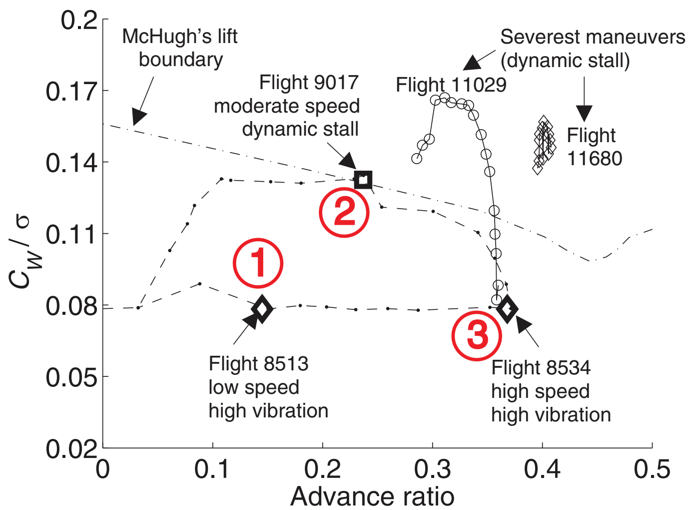

Fig. 21. The three airloads problems used to measure progress in rotorcraft airloads theory (Ref. 61).

each of these three problems in turn. Each will provide us a window into the past.

First Problem: Vortex wake loading at low speed. Throughout the late 1940s and the 1950s, helicopter developers encountered large-amplitude harmonic loads in flight that could not be predicted by the analytical methods of the day. In a series of flight experiments at the NACA at Langley Field using a bailed Sikorsky H-19A, Ludi reported on flight conditions that caused high loads (Refs. 18, 19). The H-19A had only limited strain-gauge instrumentation on a blade, but this was sufficient to show that large-amplitude blade flap bending moments occurred in low-speed flight.

Each of the helicopter companies had analysts working on these problems, but this was before the era of contract support for the companies for analytical developments. At that time, the U.S. Army TRECOM (now AATD) tended to use the Cornell Aeronautical Laboratory (CAL) to develop new methods (Ray Piziali, personal communication, February 7, 2011) and the U.S. Navy supported academic institutions such as the Massachusetts Institute of Technology (MIT).

The airloads measurements made on the NACA model rotor at Langley Field in 1954 (Ref. 4) showed higher harmonic loading at low speeds in the tunnel. Rabbott and Churchill, referring to this loading distribution, wrote "the magnitude of the loading varies by a factor of 3 to 4, with sharp gradients in the regions of 90° and 270° of azimuth." These sharp gradients, caused by vortex wake loading, would soon be understood with the analytical developments based on digital computers in the 1960s.

Concerning the prediction of these high loads, Professor Rene Miller later commented (Ref. 62), "Attempts to obtain a closed form solution to this problem, or one based on tabulated integrals, were not successful and it was evident that extensive computer facilities would be required."

John McHugh at TRECOM (and, later, John Yeates) saw the need for airloads measurements in flight and instituted two test programs. The first was a Sikorsky CH-34 that was modified by Sikorsky and bailed to NASA (Refs. 25, 26). The flight-testing at Langley Field started in October 1960 and was completed in July 1961. The second program was a Bell Helicopter UH-1A modified and flown at Bell Helicopter (Ref. 22). That testing was started in July 1961 and was completed in September.

At the same time, McHugh talked with Frank DuWaldt at CAL about the need to develop calculation methods using the new digital computers and a program was established in 1960 (Ray Piziali, personal communication, February 7, 2011). At about the same time, a similar effort started at MIT with Professor Miller under Navy sponsorship.

Truly useful data are rarely supplied in time to those that need it and that has been true of all of the airloads tests. There were many complaints about the delays in publishing the CH-34 flight-test data (Ref. 63). But there were significant efforts at NASA to informally provide early test results. Burpo and Lynn (Ref. 22), Piziali and DuWaldt (Ref. 64), and Wood and Hilzinger (Ref. 65) all refer to a letter from F. L. Thompson, dated May 24, 1961, with initial results from the CH-34 flight test. Floyd L. Thompson was the Langley Research Center Director from May 23, 1960, to May 1, 1968, and it is undoubtedly the case that this was a service to the funding agency TRECOM (John Ward, personal communication, November 24, 2010). Ray Piziali (personal communication, February 7, 2011) recalls that the data that they used for correlation with their new prescribed wake model were supplied by TRECOM, but he does not remember seeing the Thompson letter. Similarly, Mike Scully (personal communication, November 18, 2013), a student working under Professor Miller in 1963, remembers using tabulated CH-34 loads data that had been provided to MIT, but he does not remember the Thompson letter. It is likely that the results in the Thompson letter were the same data that were later published by Scheiman and Ludi (Ref. 25).

The UH-1A flight-test program lagged the CH-34 flight test by a few months. Bell Helicopter had designed their test to sample the data every 30° to provide six harmonics. But TRECOM asked them to fly some cases with a sample every 15° to provide better resolution (the same sample rate used for the CH-34 test). The reason for the change was so that CAL could use the data in the validation of their new prescribed wake model (Ref. 22).

Professor Miller compared his prescribed wake with data from the NACA model test and the CH-34 flight test (Refs. 62, 66). Ray Piziali and his colleagues also compared their prescribed wake model with data from the NACA model test, the CH-34 flight test, and the UH-1A flight test (Refs. 64, 67–69). Ray credited CAL's Walt Targoff for the "form in which the problem was cast and the method of solution" in the foreword to Ref. 63.

Figure 22 is a comparison of the Piziali model with CH-34 flight-test data at seven radial stations. Qualitatively, the agreement is good and far superior to prior models that did not properly represent the vortex wake. This sort of agreement was typical for all three data sets for both the MIT and CAL models. The industry quickly made use of the benefits of a prescribed wake model (see, e.g., Ref. 65).

The flight-test data, the early digital computers, and the careful work of Miller and Piziali were all essential for the significant progress that occurred over just a few years in the early 1960s for the First Problem. Since then, there have been many improvements in prescribed wake approaches. The free wake took a bit longer, but by the early 1970s, successful efforts were coming in that development as well. This work has continued to the present and modern CFD methods using various wake capture methods have been successful.

Second Problem: Dynamic stall. It was clear to the early investigators that stall and compressibility were both factors that limited helicopter performance in forward flight (Ref. 15). Ludi's flight experiments at the NACA with the Sikorsky H-19A showed that the torsion loads increased significantly in maneuvering flight (Ref. 18). But the mechanism of the stall on a rotor and whether it was analogous to fixed-wing stall was not clear at the start of the 1960s.

Both of the Army-sponsored flight tests in the early 1960s included maneuvers and the UH-1A flight test also included high-altitude test points to increase the blade loading. From what we now know about flight limitations on helicopter rotors, both of these test aircraft

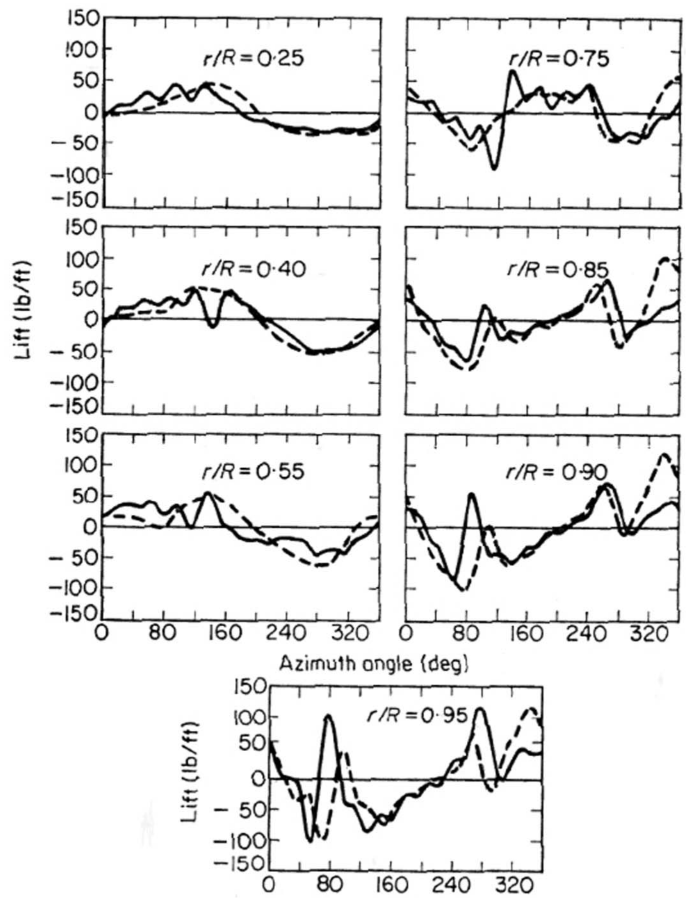

Fig. 22. Prescribed wake model (dashed line) compared with CH-34 flight data (solid line); $\mu = 0.18$ (Ref. 69).

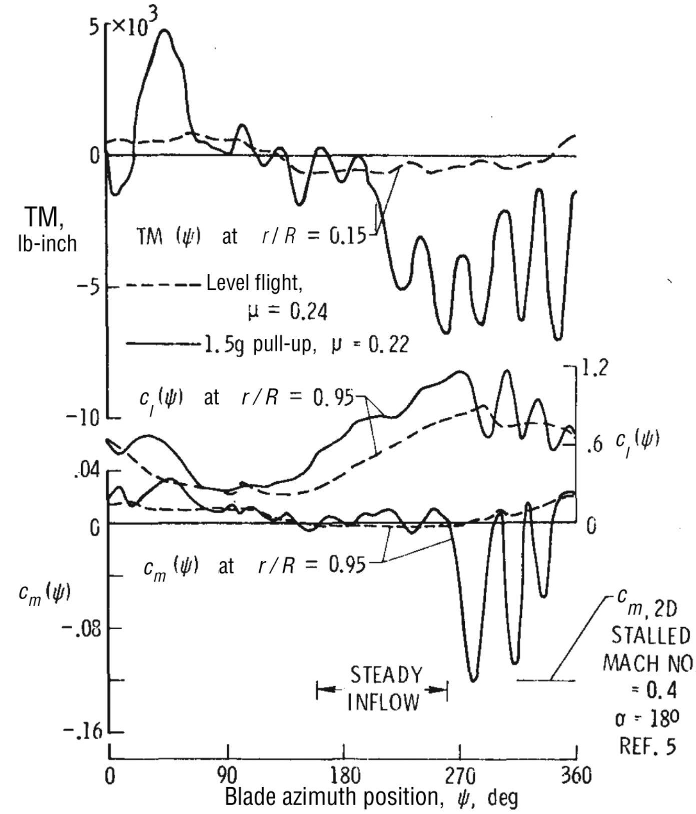

Fig. 23. Redigitization of CH-34 flight-test data in level flight and maneuver (Ref. 74).

encountered dynamic stall during their testing. Yet the 15° and 30° azimuth sample rates used on these tests probably lacked the resolution to allow a characterization of the dynamic stall behavior.

Norm Ham and his students at MIT provided significant insights into the dynamic stall phenomenon in a series of experiments in the 1960s (Refs. 70–72). They examined pressure measurements from both a hover rotor test and a two-dimensional (2D) airfoil undergoing a ramp increase in angle of attack in the wind tunnel to characterize dynamic stall. They concluded that under dynamic stall conditions an intense vortex was formed near the leading edge of the airfoil and passed aft along the upper surface. This vortex passage was the source of both moment and lift stall on the airfoil.

In complementary work, Harris and Pruyn used both pressure measurements from the CH-47A airloads test and model rotor data to show the effects of dynamic stall on rotor loading (Ref. 73).

John Ward at NASA Langley took a second look at the CH-34 flight-test data obtained in the early 1960s. In the late 1960s, the original oscillograph rolls were still stored at the center. He redigitized a limited number of flight cases to obtain better frequency resolution (Ref. 74). He selected five cases, including both maneuvers and level flight. Rather than use a fixed sample rate for the redigitization, he used a variable rate based on his inspection of the time histories. When rapid variation occurred, he sampled every 2°, when there was less variation, he reduced the sample rate. He did this for all of the pressure measurements. He then integrated the blade pressures to provide both normal force and pitching moments (the first time that anyone had ever computed the moments for this data set).

An example of this effort is shown in Fig. 23, a reproduction of Fig. 8 from Ward's paper. The figure compares two cases, both from Flight 89, a combined collective and cyclic pull-up maneuver (Ref. 26). The first case is the level flight entry to the maneuver at $\mu = 0.24$ and $C_W/\sigma = 0.088$, and the second case is the revolution at the peak load factor of $1.5g$ at $\mu = 0.22$ ($C_W/\sigma = 0.127$). In level flight, the normal force and pitching moment show largely 1/rev behavior at this radial station. But in the maneuver, three dynamic stall cycles are seen in the fourth quadrant with severe changes in the pitching moment near the blade tip and the concomitant changes in the torsion loads near the blade root. Ward postulated that the source of the torsional response was primarily caused by the vortex wake spacing, which was aggravated by dynamic stall. Based on analysis of the UH-60A airloads flight test (Ref. 75), it is now apparent that dynamic stall is the dominant source of the loading, not the rotor wake.

Ward's paper was an important step in understanding the source of the dynamic stall problem from flight-test measurements. McCroskey and Fisher (Ref. 76) were able to increase our understanding by looking at the problem with a model rotor that included extensive aerodynamic measurements. They tested a model with absolute pressure transducers at the $0.75R$ radial station on one blade and skin-friction gauges on a second blade. The angle of attack was estimated from differential pressure measurements on the lower surface of the airfoil near the leading edge (based on calibration of the blade from 2D airfoil tests). This angle-of-attack measurement was accurate at blade azimuths where the blade was not stalled. Over the range where the blade was stalled, they estimated the angle from "the blade cyclic input, elastic twist. . ., and theoretical flapping."

The resulting angle of attack is shown as a function of the blade azimuth in Fig. 24 to illustrate the dynamic stall events. The test case

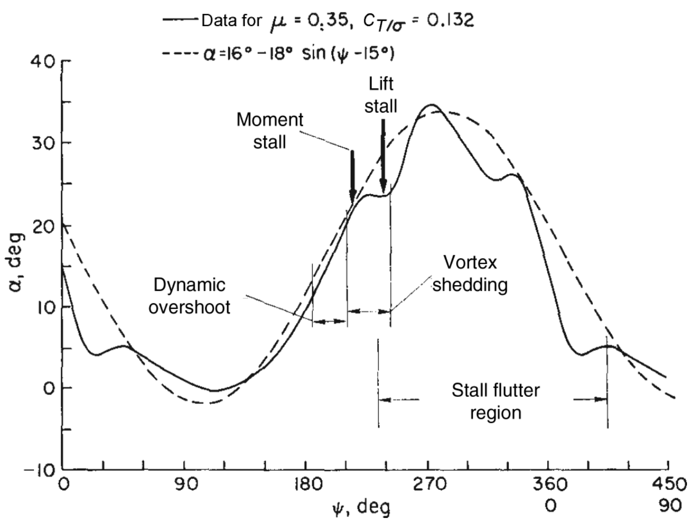

Fig. 24. Angle of attack as a function of blade azimuth at 0.75*R* (Ref. 76).

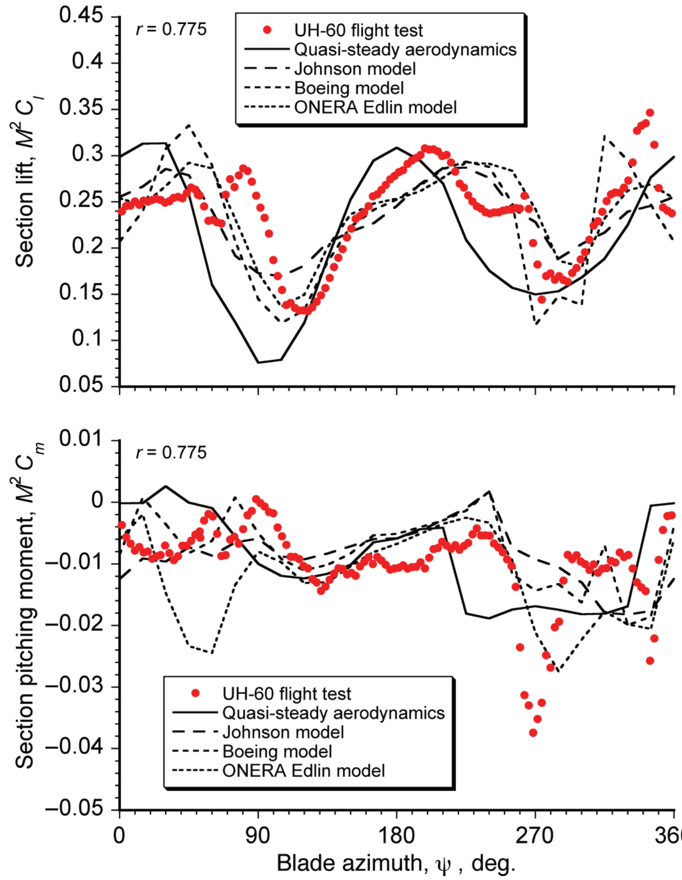

Fig. 25. Calculations using five dynamic stall models in CAMRAD II compared to UH-60A airloads data for a condition with severe dynamic stall, Counter 9017 (from Ref. 84 as replotted by Leishman in Ref. 83).

was for $\mu = 0.35$ and $C_T/\sigma = 0.132$, conditions beyond McHugh's thrust limit boundary. The dynamic stall starts in the third quadrant and is characterized by the shedding of a leading edge vortex. As it passes back along the upper surface of the airfoil the pitching moment drops rapidly ("moment stall"), then as the vortex leaves the trailing edge the lift collapses ("lift stall"). Within the "stall flutter region," there are repeated stall cycles as the flow separates and reattaches while the blade undergoes elastic deformation in torsion.

The work of Ward (Ref. 74) and McCroskey and Fisher (Ref. 76) extended the insights of previous investigators to provide a basic understanding of the dynamic stall phenomenon and its importance to helicopter design. The following decades were fruitful in providing many 2D and three-dimensional (3D) tests of airfoil motions related to dynamic stall. Some of these tests provided new understanding of the dynamic stall phenomena through detailed and comparative measurements (Ref. 77). Some provided data for semiempirical models of dynamic stall, which were then incorporated into analytical methods (Refs. 78–82). Other tests focused on airfoil designs that would provide improved dynamic stall characteristics, improved performance, and reduced loads.

Dynamic stall data from the UH-60A airloads flight-test program became available in the late 1990s, and it was possible to test some of the various semiempirical dynamic stall models. Leishman (Ref. 83) replotted the calculations made by Nguyen and Johnson (Ref. 84) as shown in Fig. 25 (I have used color to show the flight data better). The flight-test point in this case is the representative dynamic stall condition identified by Datta et al. (Ref. 61) (see Fig. 21). None of the various semiempirical models captures the lift or moment time histories with any accuracy. To some degree, the quasi-steady aerodynamic calculation (no dynamic stall model) does as well as any.

The semiempirical dynamic stall models developed from the early 1970s to the 1990s have been a disappointment. Whereas the result of the experimental measurements for the First Problem (vortex wake loading at low speed) was translated almost immediately into practical computational models, this did not happen for the Second Problem.

Third Problem: High-speed structural loads. From the beginning of helicopter development, the problem of increased drag on the advancing blade and the consequent performance limitations have been understood, at least to some degree. We have understood that the airfoil drag will increase in a nonlinear manner beyond a certain Mach number ("drag divergence"), just as will the pitching moments ("Mach tuck"). We have been able to make adequate performance predictions based on the steady 2D airfoil characteristics using a table lookup approach in our comprehensive analyses. But we have not begun to understand the unsteady transonic airloads at high speed until quite recently (Ref. 61).

I consider this Third Problem to be "cryptic" because so many of the fundamentals were hidden from us until we developed better measurements, better experiments, and a realization that these high-speed loads were a separate problem from dynamic stall.

The first step in understanding that high-speed loads were not related to dynamic stall came from the experiments of McHugh and his colleagues at the Boeing Vertol Company (Refs. 11, 12). The importance of the McHugh test data is best understood by jumping back and forth in time over the decades from the 1960s to the 1990s (but without losing our perspective of the time lines of these events).

In the late 1980s, inspired by Hooper's comparative study of airload measurements (Ref. 53), I made a similar comparison of structural measurements for eight rotor tests (Ref. 85). Figure 26 shows the range of level flight cases that I examined and compares these to the McHugh thrust boundary (Ref. 11). What is new in this figure is the addition of the incipient stall boundary based on the UH-60A wind tunnel tests completed in 2010 (Ref. 5). The incipient stall boundary marks the first evidence of stall on the rotor as thrust is increased.

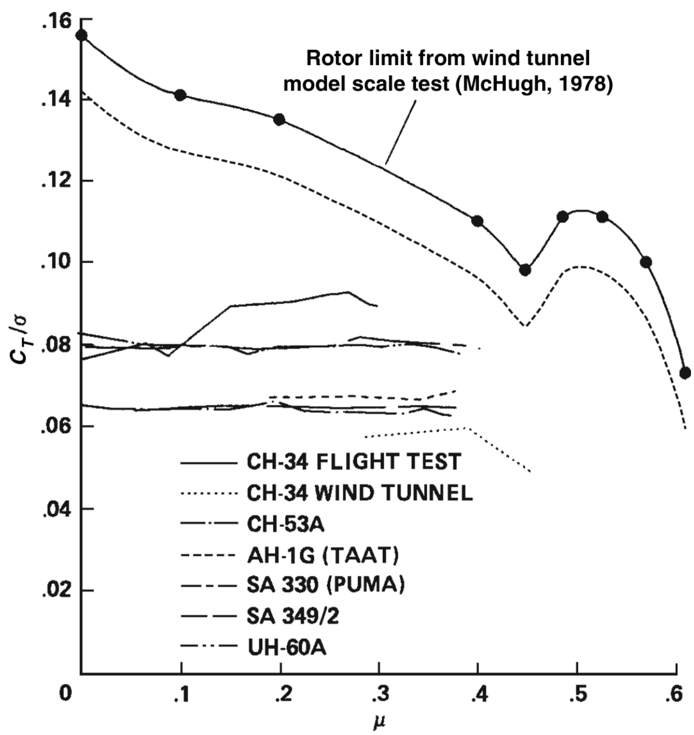

Fig. 26. Flight and wind tunnel structural loads tests, nondimensional thrust as a function of advance ratio (Ref. 85). The rotor thrust limit is based on Ref. 11 and the incipient dynamic stall (dashed line) on Ref. 5.

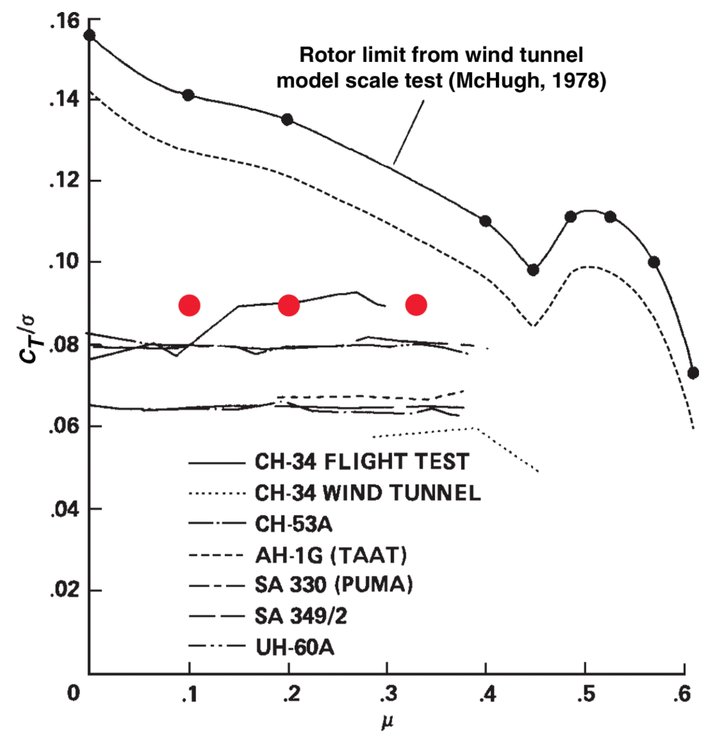

Fig. 28. Calculation points (solid red circles) for a hypothetical rotor (Ref. 86) overlaid on Fig. 26.

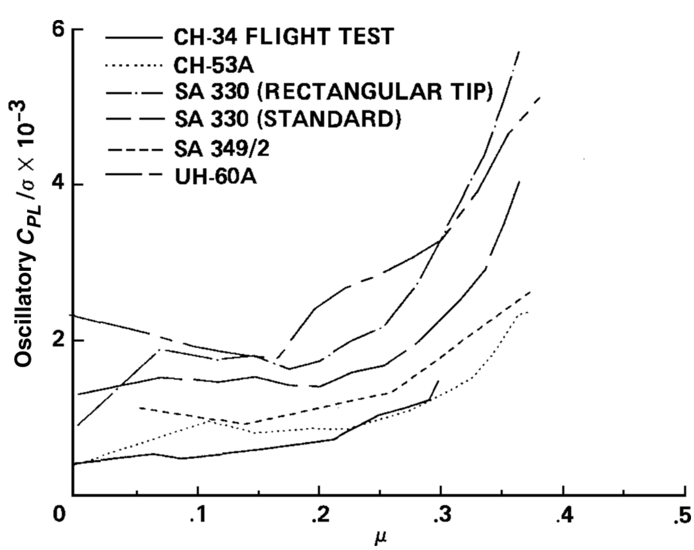

Fig. 27. Nondimensional pitch-link loads as a function of advance ratio (Ref. 85).

What we now know is that none of these rotor tests encountered dynamic stall for these level flight conditions. Their level flight performance was limited by power or unsteady loads, but not by dynamic stall. The structural loads were rapidly increasing for each of these tests as shown for the pitch-link loads in Fig. 27. For most of these rotors, the loads increase becomes progressively greater as advance ratio increases. We now understand that this load increase is a result of the transonic unsteady airloads on the rotor, but in the 1970s the common opinion was that these increased loads at high speed were a consequence of dynamic stall.

Bob Ormiston devised a comparative calculation test in 1973 for a hypothetical rotor (Ref. 86). His purpose was to see what could be learned about the new comprehensive analyses by comparing calculations from as many companies and institutions as was possible. The purpose of selecting a hypothetical rotor was to provide a level playing field for all of the analyses. In consultation with the contributing analysts, Bob selected three cases: (1) a low-speed case, $\mu \sim 0.1$, that would test the modeling of the low-speed vortex wake loading, (2) a moderate-speed case, $\mu \sim 0.2$, well removed from airfoil nonlinear behavior, and (3) a high-speed case, $\mu \sim 0.33$, that would result in dynamic stall. I overlay these three cases in Fig. 28, using Fig. 26 as a reference. It is apparent that the high-speed case is well short of incipient dynamic stall (but at that time there were no data to document rotor thrust limitations).

I show the calculations of the elastic torsional deflection at the blade tip that were made with six computational models in Fig. 29. These differ widely from each other, and many show significant oscillations in the fourth quadrant, as though dynamic stall was occurring. The results of these comparisons were first shown in a specialists' meeting held at NASA Ames Research Center in February 1974, jointly sponsored by the American Helicopter Society and NASA (Rotorcraft Dynamics, NASA SP-352).

One of the unusual features of the AHS/NASA conference was that the panel discussions, questions, and answers were taped, transcribed, and included in the NASA SP. It is particularly illuminating that in the transcribed comments there was no mention of the possibility that unsteady transonic loading was a cause of the loads at high speeds—it was not on our collective radar at the time.

In the next decade, Hooper (Ref. 53) specifically addressed the problem of vibratory airloads in his remarkable paper that compared measured airloads from seven airloads tests using novel visualization techniques.

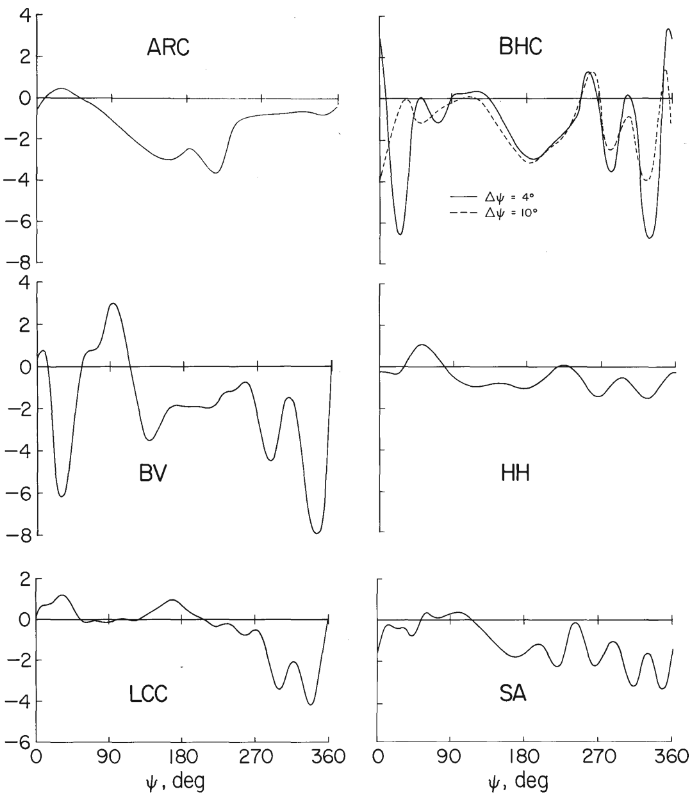

Fig. 29. **Comparison of calculated tip elastic torsional deflection (deg) for a hypothetical rotor, $C_T/\sigma = 0.0897$, $\mu = 0.33$ (Ref. 86). Methods used: Ames Research Center (ARC), Bell Helicopter C81 (BHC), Boeing Vertol C60 (BV), Hughes Helicopters SADSAM (HH), Lockheed California 3110 (LCC), and Sikorsky Aircraft Normal Modes (SA).**

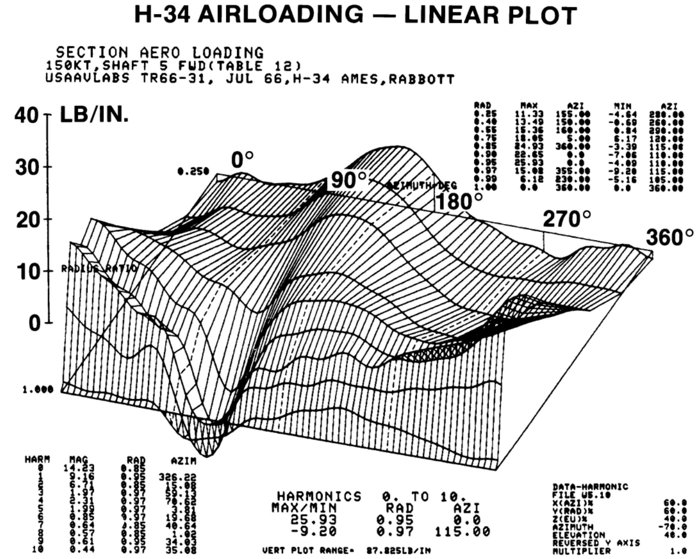

Fig. 30. CH-34 section normal forces in wind tunnel test, $\mu = 0.39$, $\alpha_s = -5°$ (courtesy of Euan Hooper).

Figure 30 shows the normal forces as a function of both radius and blade azimuth for one of these rotors, the CH-34 in the Ames 40- × 80-ft Wind Tunnel (Ref. 27). The use of a Cartesian grid provides a way of understanding both the azimuthal and radial loading. He made similar plots for six other rotor tests at both high and low speeds and concluded that the fundamental vibratory load behavior was similar for nearly all of these rotorcraft, particularly at low speed.

Hooper's comparative study was a significant accomplishment in many respects. His demonstration of the similarities in vibratory loading at low speed for different helicopter rotors in many ways provided a book end for the First Problem. The early airloads data that had defined low-speed vortex wake loading and were instrumental in developing the prescribed wake models (and the later free wake models) were shown to be universal. But the high-speed vibratory loading was a different problem; there was no obvious phenomenological explanation. Cowan et al. (Ref. 87) later remarked that Hooper's work showed that "the understanding of what causes these vibratory airloads was totally inadequate."

The lack of understanding to which Cowan et al. referred we now understand was related in part to limitations of the airloads data sets that Hooper had studied. First, six of the seven data sets used differential pressure measurements (only the AH-1G/OLS test relied on absolute pressure transducers). Although differential pressure measurements can provide accurate integrated normal forces and approximate pitching moments, they mask the behavior of the actual pressure distributions on the upper and lower surfaces. This is unimportant for subcritical flows, but the development of transonic or supersonic regions in high-speed flight will create unsteady loads that are difficult to understand without absolute pressure measurements.

Another difficulty in understanding the high-speed loads was the lack of pitching moment calculations for the airloads data sets that Hooper studied. Only one of those seven data sets, the XH-51A, included the calculation of the pitching moments (and with only five chordwise stations those moments may not have been trustworthy). Without knowing the measured pitching moments, the aeroelastic behavior of these rotors was hidden from us.

In the early 1980s, at about the same time that Hooper was looking at the early airloads data, the Royal Aircraft Establishment (RAE) in Britain and the Office National d'Études et de Recherches Aérospatiale (ONERA) and Aerospatiale in France embarked on a flight-test program with a research Puma with absolute pressure transducers installed on a modified blade tip. The program was done in two phases. The first used a mixed-bladed rotor with a swept tip opposite a rectangular "paddle" rotor and two standard blades (Ref. 88). The second phase tested a rotor with four swept tip blades (Ref. 89). A photograph of the aircraft used in the second test is shown in Fig. 31. Between 12 and 21 absolute pressure transducers were installed at outboard radial stations at $0.92R$, $0.95R$, and $0.978R$.

An international collaboration was formed in 1987 to compare the data from these tests with the most recent full-potential CFD codes. Investigators from the United States and Australia joined with researchers at the RAE, ONERA, and Aerospatiale. In this initial effort, the focus was primarily on comparison of measurements with CFD analyses, including a coupled CFD/CSD method based on Tung et al. (Ref. 90). A workshop was held in Farnborough in May 1988 and reported the next year in Amsterdam (Refs. 91, 92).

A follow-on effort focused on additional comprehensive analysis calculations as well as coupled CFD/CSD approaches that included improvements to the coupling method developed by Tung et al. The new calculations were examined in a workshop at NASA Ames Research Center in May 1990 (Ref. 93).

An examination of the section normal forces on the research Puma at high speed shows that the advancing side dip pointed out by Hooper (Ref. 53) is also seen on this aircraft (see Fig. 32). The pressure distributions in this case (Ref. 93) show an area of transonic flow on the upper surface in the first quadrant as the local Mach number increases

Fig. 31. Research Puma with swept-tip blades at RAE Bedford.

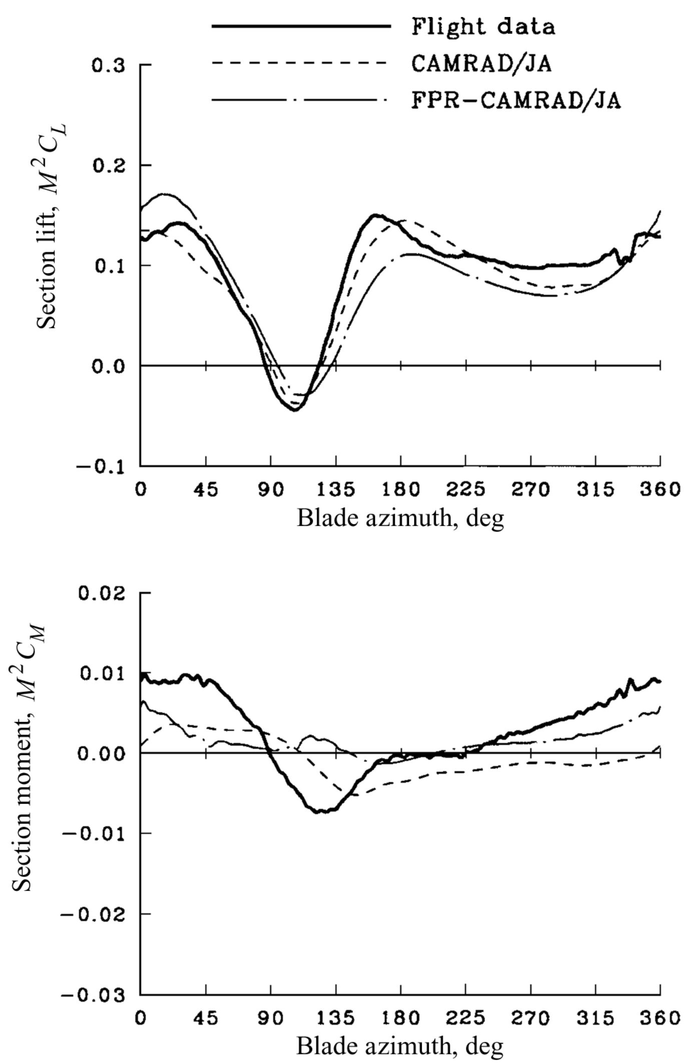

Fig. 32. Comprehensive and CFD/CSD models compared to measured normal force and pitching moment on the research Puma with a swept tip at $r/R = 0.95$, $C_w/\sigma = 0.070$, $\mu = 0.40$ (Ref. 93).

even as the lift is reduced. As the lift goes through zero near 90°, there is transonic flow on both surfaces. Over the region of negative lift for the next 45°, there is significant transonic flow on the lower surface. Then as the angle of attack becomes positive again, there is an increasing supercritical flow on the upper surface until the reduction of the local Mach number allows the flow to become subcritical around the retreating side of the disk.

The unsteady nature of the supercritical flows on both the upper and lower surfaces has a profound effect on the airfoil section forces and moments. As shown in Fig. 32, both the comprehensive method (CSD) and the coupled calculation (CFD/CSD) are more or less able to capture the section normal forces (although the comprehensive analysis CAMRAD/JA is as good or better than the coupled analysis), but the pitching moment predictions for both methods are poor. The comprehensive method can deal with viscosity through its 2D table lookup approach at inboard locations, but not near the blade tip. The coupled CFD/CSD method used did not include viscosity, but was able to model 3D effects at the blade tip. From the two collaborations, we learned that both approaches were inadequate.

By the 1990s, our measurements were perhaps sufficient to understand some parts of the Third Problem. But to obtain accurate calculations, we had to solve the aeroelastic problem, that is, we had to be able to accurately calculate the large pitching moments on the outer blade, calculate the torsional response, and obtain the correct elastic deformation (and tip angle of attack). The advent of the UH-60A flight-test data, the series of workshops that followed that flight-test program, and the new Navier–Stokes CFD models changed everything.

UH-60A Airloads Program and Workshops

Flight-testing accomplished in the UH-60A Airloads Program was envisioned as an integral part of a much larger effort sponsored by NASA and the U.S. Army called the Modern Technology Rotors (MTR) Program (Ref. 94). In their paper, Watts and Cross described a program of extensive testing of two modern rotors, the Boeing Vertol Model 360 and the Sikorsky Aircraft UH-60A. The testing would include multiple phases including flight tests, full-scale wind tunnel tests, model rotor wind tunnel tests, and ground vibration tests. They proposed that these systematic tests would be followed by testing of other new rotors from Bell Helicopter Textron and McDonnell Douglas.

A key part of the MTR program was that flight, wind tunnel, and model rotor tests would all include extensive pressure instrumentation on the rotor blades. Looking back at the vision in their paper today, one can only be awed by their optimism considering the problems that followed. For the Model 360, wind tunnel testing of a pressure-instrumented rotor was accomplished (Refs. 87, 95), but a full-scale pressure-instrumented blade was never built. A pressure-instrumented blade for the UH-60A was fabricated, but the flight-test program was canceled before any data were obtained. How that program finally succeeded is a part of my narrative.

UH-60A Airloads Program

Under the MTR program, two instrumented blades were designed and built by Sikorsky Aircraft and they were delivered to Ames Research Center in late 1988. One blade was instrumented with strain gauges and accelerometers, and the other had 242 absolute pressure transducers. Two hundred and twenty-one of these transducers were installed at nine radial stations; the others were used to characterize blade–vortex interactions at the blade leading edge.

The critical design path for the data processing system was to digitize the data in the rotating system and then split the pulse code modulated (PCM) data into 10 streams and pass it through slip rings to a

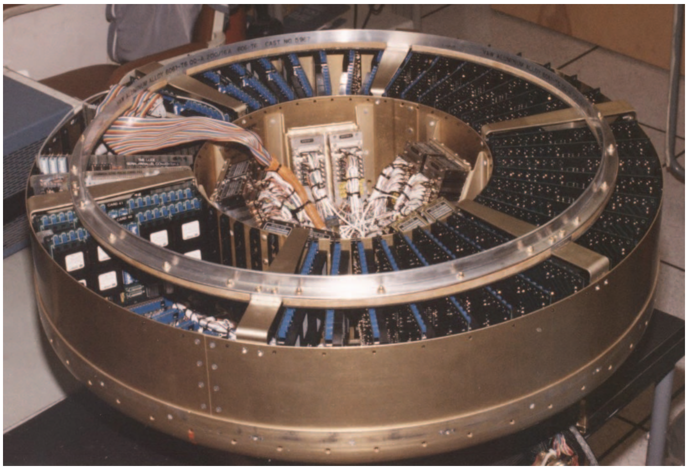

Fig. 33. RDAS in the laboratory (NASA Ames Research Center).

multiplexer that combined the streams and recorded it on tape in the aircraft cabin (Ref. 96). That data-processing system, referred to as the RDAS, was designed and developed at Ames Research Center (see Fig. 33). The required data rates were about six times greater than the capability available at the time. The final data rate was about 7.5 MB/s and was a major technological hurdle that caused no end of developmental problems. (Twenty years later, the data rate for streaming video to your smartphone is 1–2 MB/s; technology moves fast.)

Initial work on the RDAS was started in April 1985, 3 years before the instrumented blades would be delivered. This work attempted to make use of already qualified hub-mounted hardware, the "mux bucket" used in the previous AH-1G/OLS and AH-1G/TAAT tests (albeit with a completely different data processing scheme). This was referred to as the RDAS I (Ref. 96). The mux bucket was modified to provide more room for components beneath the original envelope. By the time, it was recognized that there was still not sufficient room in the mux bucket for the 10 PCM streams nearly 54 months had elapsed. (The discarded RDAS I mux bucket was modified in the following years for use on the JUH-60A RASCAL aircraft, which is still doing flight control research in 2014.)

RDAS IIa (and all of the subsequent versions) used the same hub-mounted container as shown in Fig. 33. There was sufficient room for the 10 PCM streams, but stream synchronization could not be obtained. Attempts to fix this problem were not successful, and it was recognized after about 25 months that a redesign was required. NASA put together a committee of "wise old men" from the instrumentation side of the house under the chairmanship of Rod Bogue of NASA Dryden. They quickly put together a list of necessary changes. All of these were valuable; the most important was the implementation of a master clock that cured the synchronization problem.

RDAS IIb was the redesigned system as recommended in the Bogue Report. A new problem of excessive high-frequency noise cropped up. This was less serious than the previous problems and was fixed by installing new shielding, but another 17 months had passed by.

The final configuration, RDAS III (or just RDAS) was installed on the aircraft for airworthiness testing during April 1993. The aircraft was flown through a series of critical maneuvers, but no maneuver limitations caused by the RDAS were observed and the aircraft was cleared for the flight-test program at the end of the month.

Two weeks later, the flight-test program was canceled. All funding was eliminated as of September 30th, the end of the fiscal year. The cancellation was partly because of Administrator Golden's insistence that all NASA flight-testing be done at Dryden, but also because of the long series of development problems on the RDAS.

Optimistically, the best we could do by the end of September was to make eight flights. So the new test plan was a description of those eight flights on a single sheet of paper. We circulated it to the companies and the universities and set our priorities. That summer we managed five flights, but only the last two had everything working properly.

NASA Ames's Director of Aeronautics, Tom Snyder, made a deal. If we could demonstrate we had solved our data acquisition problems and had good data by the end of September, he would transfer funds from the other divisions and branches in his directorate and let us fly until the end of the year. Bob Kufeld and I made a 3-hour presentation at the end of the month to a panel of Tom's division and branch chiefs. The presentation went well, and Tom let us go ahead. We flew a collaborative ground acoustics program with NASA Langley in November. After a rainy December when we could not fly, Tom granted us two more months. We completed our 31st flight in late February 1994. By the summer, all of the data were stored and accessible and the branch was dissolved. Tom had broken the primary promise of all "big science" projects, he had taken the funds needed to finish the project from the rest of his organization. Most of the UH-60A flight-test data still being used today were obtained because of Tom's decision.

UH-60A Airloads Workshops

We had 30 GB of airloads data stored on an optical jukebox at NASA, but for what purpose? Bob Kufeld and I examined what we felt were the most important parts of the data set (Refs. 97, 98) and in the process developed confidence in the validity of the data. But we wanted to find a way to involve industry.

In 1995, we created what we called the Airloads Working Group. We found a small amount of money to provide minimal support for Bell Helicopter Textron, Boeing Helicopters, McDonnell Douglas Helicopters, and Sikorsky Aircraft. Each company selected two cases and used visualization tools as a better way of understanding the data obtained. NASA and the U.S. Army at Ames Research Center did the same, and all the efforts were exchanged. Discussions of a follow-on program did not lead to a continuation of this effort.

About 1999, Bob Ormiston developed a detailed plan for a series of airloads workshops that would be sponsored by the National Rotorcraft Technology Center (NRTC). This was a well-planned, top–down approach that would use funds from both the NRTC and its industrial partner, the Rotorcraft Industry Technology Association (RITA). The need to assign funding based on a detailed plan caused political problems and the approach failed.

In 2001, Yung Yu, as part of his responsibilities at the NRTC, proposed a new format for the Airloads Workshop. He persuaded both the industry and academia to propose projects for the NRTC/RITA consortium that would take advantage of the UH-60A data. The Airloads Workshops would then be held twice a year in conjunction with the NRTC/RITA review and planning meetings. This ad hoc, bottom-up approach worked, and 26 workshops have been held from 2001 to early 2014.

In the initial years, the meetings were organized by Yung Yu. After his retirement, Mike Rutkowski took over. From the beginning, the workshops were a mixture of researchers from industry, government labs, and the universities. Rules were developed slowly on an ad hoc basis, and none were written down. Each workshop tended to start out with outrageous goals, few of which were ever met. But enough was accomplished in the 12 years to maintain the interest of the participants.

The workshops have been enormously successful as I will describe in the next section. I do not know why this mix of people and ideas worked so

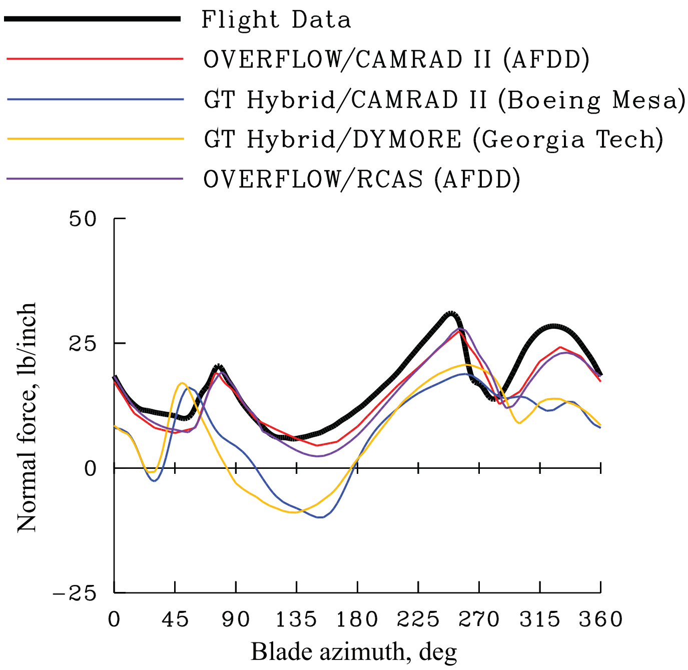

Fig. 34. Comparison of measured normal force at 0.92R for the UH-60A with four coupled CFD/CSD methods for the First Problem, $\mu = 0.15$, $C_W/\sigma = 0.079$.

well over such a long period, but a key ingredient has been the individual leadership of participants from industry, government, and academia.

Airloads Workshops and the new calculations

From the beginning, the workshops focused on the three problems that Datta and his colleagues (Ref. 61) would later summarize, that is, the low-speed vortex wake loading, dynamic stall in level flight and maneuver, and unsteady transonic flow on the advancing blade tip at high speed. At first, the Third Problem, that of unsteady transonic flow drew the most attention.

Calculations with a number of comprehensive analyses showed no improvement over past efforts. Although some of the predictions of normal force were fairly good, the pitching moments were unsatisfactory. The workshops focused on breaking the problem down into separate pieces by using the measured airloads to calculate the appropriate elastic response (Ref. 99, e.g.) and then use those elastic responses as inputs to the new Navier–Stokes CFD models. This work progressed quickly to the next stage, and soon a number of investigators were showing results using coupled CFD/CSD methods (Ref. 100).

How well did the new calculations based on coupled CFD/CSD do? In a series of figures, I show the workshop calculations for each of the three problems that I have used as a theme of this narrative. These figures are based on calculations made by workshop participants from early 2007 to the summer of 2009: Hyeonsoo Yeo, Bruce Charles, Nischint Rajmohan, Mahendra Bhagwat, Marilyn Smith, and their collaborators.

First Problem. This problem deals with the airloads caused by the low-speed vortex wake. The early airloads tests first stimulated the analytical developments of prescribed wake models, then eventually free-wake models. Present day methods are capable of reasonably accurate calculations, although there are still a few problems in terms of the accuracy of the advancing and retreating side peak loads in both amplitude and phase.

Figure 34 compares four CFD/CSD calculations for the normal force at 0.92R with the UH-60A flight-test measurements for this problem. The four calculations are combinations of two CFD models (OVERFLOW and GT Hybrid) and three comprehensive methods (CAMRAD II, RCAS, and DYMORE).

The calculations in Fig. 34 show that the major difference between the methods is in the CFD model and no significant difference is observed in the comprehensive part. The two coupled calculations that use OVERFLOW show good agreement with the measurements, particularly in matching the peak disk vortex loading on the advancing and retreating sides. OVERFLOW includes the wake tip vortices within its solution grids and provides a good representation of the vortex wake loading. GT Hybrid, on the other hand, saves considerable computer time and cost by modeling the vortex wake in much the same manner as the comprehensive analyses and this has caused differences in azimuths of the calculated and measured vortex-loading spikes.

I show accuracy maps for the four sets of calculations at all nine radial stations in Fig. 35. The accuracy maps are based on linear regression of each analysis compared to the test data. Roughly, accuracy is measured by the slope m and scatter by the coefficient of determination r^2. (Details on this approach can be found in Refs. 46 and 101.) The maps show that the CFD model in this case is responsible for significant differences in the results, with more scatter seen for the GT Hybrid-based calculation than for the OVERFLOW-based calculation. The accuracy of GT Hybrid is much the same whether DYMORE or CAMRAD II is the CSD partner.

The coupled calculations using OVERFLOW provide slightly better results than have been obtained from a comprehensive analysis by itself, whereas the calculations using GT Hybrid are not as good.

What is more striking about the First Problem calculations is how well the methods agree with each other. That is, the OVERFLOW calculations are very similar whether the structural model is from CAMRAD II or RCAS. The same is seen for the GT Hybrid-coupled calculation whether the comprehensive model is CAMRAD II or DYMORE. We have come a long way from the days of the hypothetical rotor comparison in 1974 (Ref. 86) when few calculations matched each other.

Second Problem. The Second Problem deals with the effects of dynamic stall on the airloads. Through much experimentation, we have learned a great deal about the phenomenon of dynamic stall but we have not been able to translate that knowledge into accurate calculations.

Figure 36 compares five CFD/CSD calculations for the normal force at 0.92R with the UH-60A flight-test measurements. For this problem, there are five combinations for the coupled calculations. OVERFLOW is coupled with CAMRAD II, DYMORE, and RCAS, whereas GT Hybrid is coupled with CAMRAD II and DYMORE.

The calculations in Fig. 36 show that all of the methods provide similar results and roughly match the data. Each shows reduced loading on the advancing side, and most show a loss of lift caused by the first dynamic stall cycle at about 280°. But each calculation shows its own peculiarities, sometimes in amplitude and sometimes in phase shift, and few show satisfactory agreement in the phase of the second stall cycle at 350°.

I show the accuracy maps for the five sets of calculations at all nine radial stations in Fig. 37. The ellipses in this figure indicate scatter in the results. The results with OVERFLOW are better than GT/Hybrid, but the OVERFLOW results are not as good as were seen for the First Problem.

For the First Problem, it was striking how the accuracy of the results was independent of which comprehensive analysis was coupled to the CFD calculations. In terms of the accuracies shown in Fig. 37, that is also the case for this problem. But if the fine detail is examined in this figure, differences are seen between the coupled calculations depending upon which of the three comprehensive analyses is used.

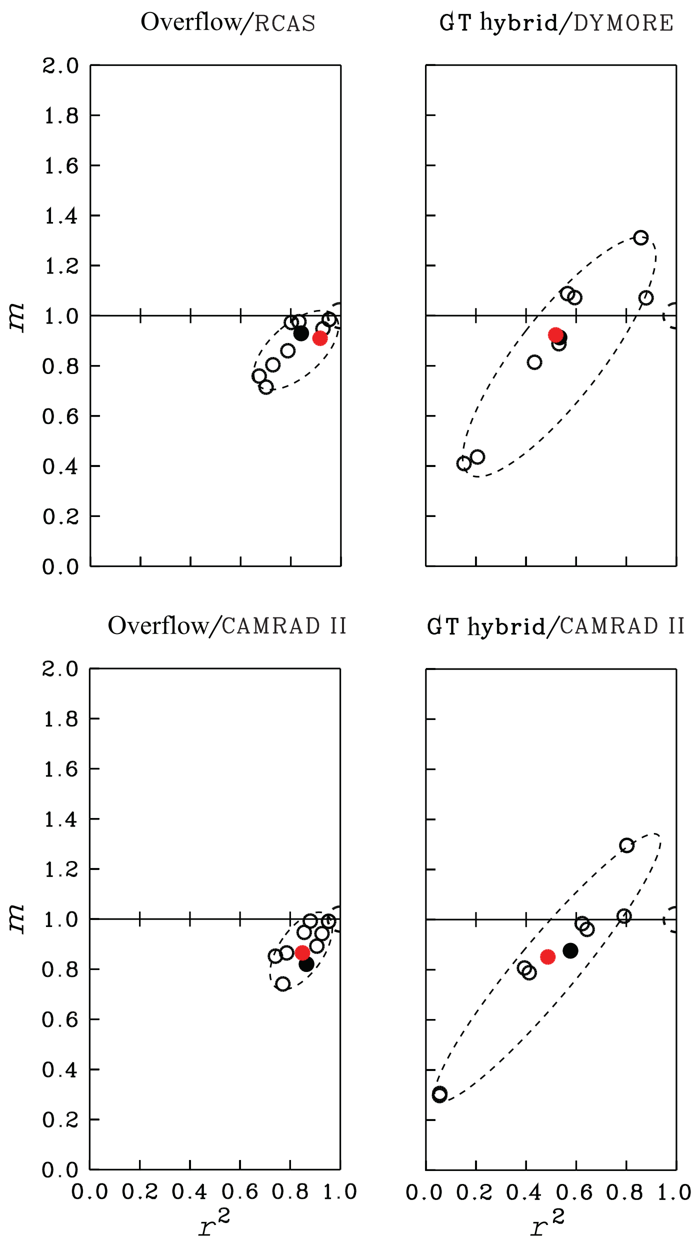

Fig. 35. Accuracy maps of measured normal forces at nine radial stations (open circles) for the UH-60A with four coupled CFD/CSD methods for the First Problem, μ = 0.15, C_W/σ = 0.079. Solid black circles are for 0.92*R*, and solid red circles show the combined accuracies.

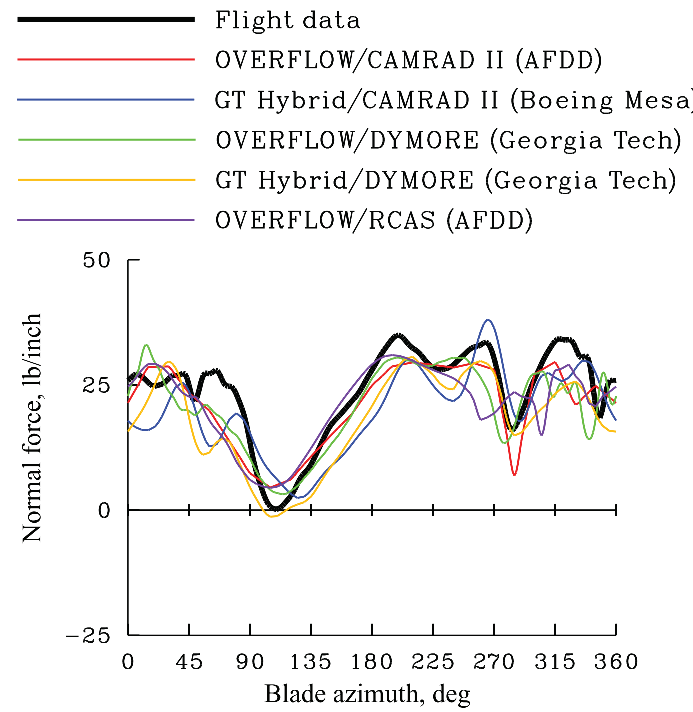

Fig. 36. Comparison of measured normal force at 0.92*R* for the UH-60A with five coupled CFD/CSD methods for the Second Problem, μ = 0.24, C_W/σ = 0.133.

The accuracy maps for the calculations at all nine radial stations are shown in Fig. 39. In most cases, the scatter ellipse is quite tight. The combined accuracy for the five coupled methods lies on an accuracy circle that ranges from 7% to 14%.

Third Problem. The Third Problem deals with the high-speed vibratory loads caused by supercritical flows near the blade tip, a problem poorly understood over the past 40 years.

Figure 38 compares five CFD/CSD calculations for the normal force at 0.92*R* with the UH-60A flight-test measurements. For this figure, there are five combinations for the coupled calculations. OVERFLOW is coupled with CAMRAD II, DYMORE, and RCAS, whereas GT Hybrid is coupled with CAMRAD II and DYMORE. All of the calculations in Fig. 38 show good predictions of the measured normal force and are in good agreement with each other. This is remarkable considering the great difficulty that there has been with this problem over the past 40 years.

The Airloads Workshops transformation

The transformative event that has characterized the Airloads Workshops and the success of the new coupled calculations was the result of putting together many bits and parts that eventually led to these improved analyses. There is an old saying that "success has a thousand fathers, but failure is an orphan." The success of the workshops has depended upon many organizations and many people.

I show a schematic in Fig. 40 of the various parts that came together to allow the success that we have obtained. I have divided these contributions into seven categories. Starting on the left side, the first of these categories are the contributions the UH-60A Airloads Program data, of which quite enough has already been said in my narrative.

The second of the contributions was from the Rotorcraft Centers of Excellence (RCOEs). Norm Augustine recommended the creation of academic centers for rotorcraft research in 1981 (Ref. 102). The purpose of the RCOEs was to develop long-term rotorcraft technology programs based on academic research at a few selected institutions. A competition to select the new centers was held in 1982 under the direction of the Army Research Office. The winners of the first competition were the University of Maryland, Georgia Tech, and Rensselaer Polytechnic Institute (RPI).

Program oversight changed when the NRTC took over the program in the mid-1990s. At that time, Penn State replaced RPI in the triumvirate of rotorcraft centers. In 2006, the program was restructured and named the Vertical Lift Research Centers of Excellence. Only Georgia Tech and Penn State remained as centers. A new competition in 2013 returned the University of Maryland to the former triumvirate.

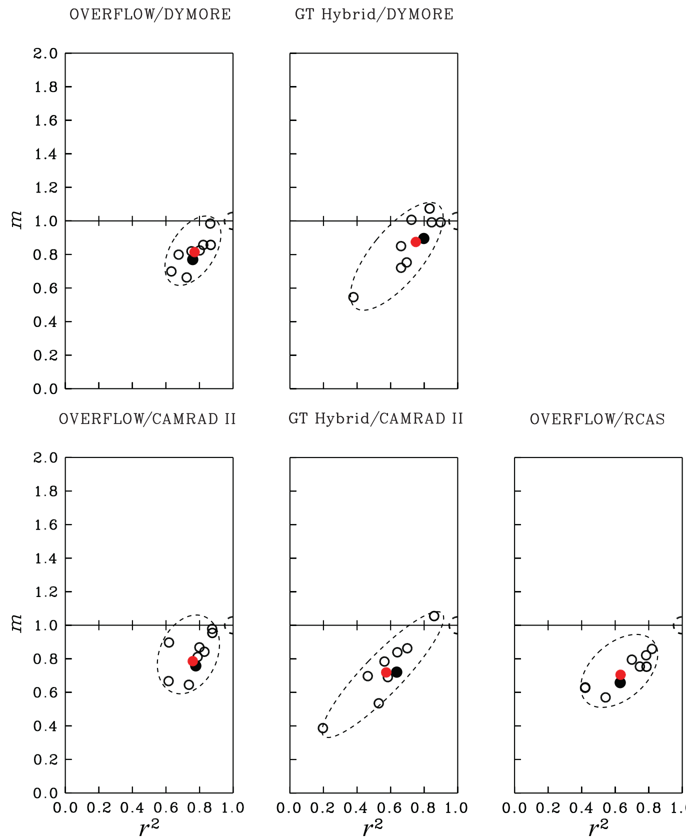

Fig. 37. Accuracy maps of measured normal forces at nine radial stations (open circles) for the UH-60A with five coupled CFD/CSD methods for the Second Problem, $\mu = 0.24$, $C_W/\sigma = 0.133$. Solid black circles are for 0.92R, and solid red circles show the combined accuracies.

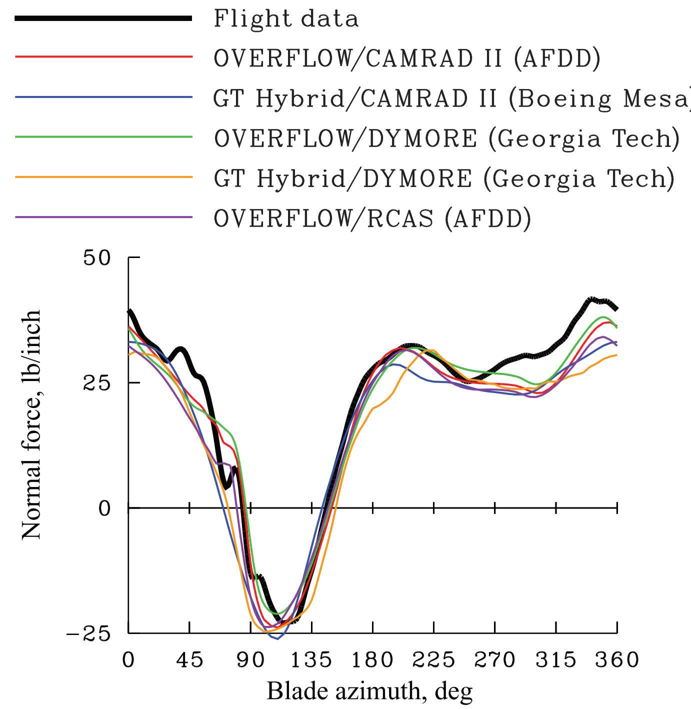

Fig. 38. Comparison of measured normal force at 0.92R for the UH-60A with five coupled CFD/CSD methods for the Third Problem, $\mu = 0.37$, $C_W/\sigma = 0.078$.

The RCOEs were a success for two reasons, both well understood when the centers were recommended in 1981. First, the centers provided academic capabilities with a long-term view of needed improvements in rotorcraft technology. Second, many graduates of the RCOEs have moved into industry and government positions where they have made significant contributions.

The third of the major contributors to the workshop transformations were the NRTC and RITA. In the early 1990s, both the U.S. Army and NASA were pursuing separate initiatives to increase the relevance of government R&D efforts. The two initiatives were fused, and with the participation of the U.S. Navy and the Federal Aviation Administration, NRTC was formed in 1995. At the same time, the U.S. industry put together RITA to share resources for research into precompetitive technologies. Money was the glue that held these two organizations together. It was under the NRTC and RITA that the Airloads Workshops were sponsored. The continuity provided by NRTC and RITA was an important element in developing trust between researchers in industry, the government, and academia.

The fourth contributor to the workshop success was the addition of the Defense Advanced Research Projects Agency (DARPA) as a participant. In early 2004, DARPA started the Helicopter Quieting Program (HQP), working through NASA Ames Research Center. Prior to the program start, Dr. Lisa Porter, the DARPA Program Manager, attended our fall 2003 Airloads Workshop in Atlanta. She explained the objectives of the HQP, and at the same time learned about the UH-60A data set. That data set became one of the HQP test cases, and the additional funding broadened the efforts of the workshop (Ref. 103).

But DARPA's contribution extended beyond the additional funding. Jay Dryer, working for DARPA, dove into the UH-60A data base on TRENDS and uncovered a phase error that I had made in extracting the data from TRENDS for use by the workshop participants (Ref. 104). All of us working with that data were grateful for the error that Jay uncovered.

The final three contributions to the workshop success deal with three aspects of rotorcraft modeling technology: comprehensive analyses (sometimes referred to as CSD), CFD, and the coupling of CFD and CSD. Wayne Johnson's 30th Alexander Nikolsky Honorary Lecture (Ref. 60) provides a detailed and insightful summary of each of those technology aspects. Here, I will limit myself to a few brief comments on the three computational categories.

Digital computers were a main enabler of new helicopter analyses starting in the early 1960s. Bell Helicopter Textron developed a comprehensive analysis that became the C81 program, an early attempt to provide a balanced analysis that could model multiple configurations (Ref. 60). The U.S. Army adopted C81 as its primary analysis program in 1973.

In February 1974, NASA Ames Research Center and the American Helicopter Society sponsored a meeting on rotorcraft dynamics. As discussed earlier, this conference included a comparison of a number of the early industry comprehensive analyses in the calculation for a "hypothetical" rotor (Ref. 86). These calculations in many cases were divergent, which stimulated much discussion as to whether a standard analysis should be developed for helicopters. Dick MacNeal, the developer of NASTRAN, said "No." When asked why, he elaborated (Ref. 105):

> I think that there is great virtue in diversity, particularly when there is a great deal of doubt as to the physics of the problem, the methods of analysis, etc. If we settle on one particular approach, we will all use it and we will all go over the cliff together like lemmings going into the sea.

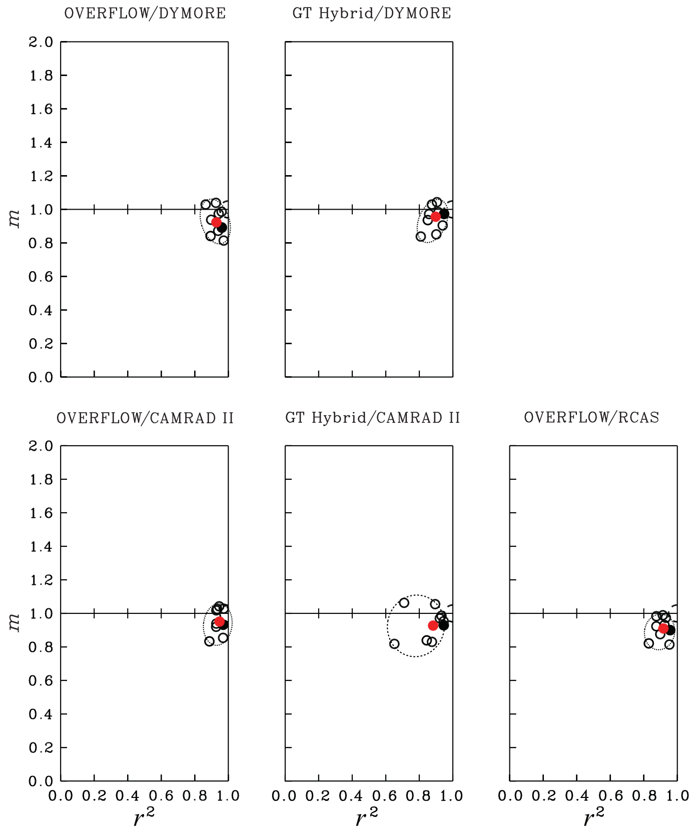

Fig. 39. Accuracy maps of measured normal force at nine radial stations (open circles) for the UH-60A with five coupled CFD/CSD methods for the Third Problem, $\mu = 0.37$, $C_W/\sigma = 0.078$. Solid black circles are for $0.92R$, and solid red circles show the combined accuracies.

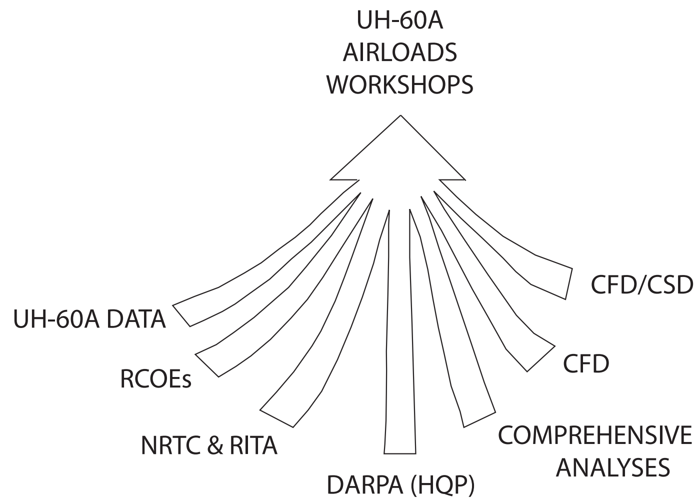

Fig. 40. Factors contributing to the success of the UH-60A Airloads Workshops.

The Army pursued the notion that C81 should be a standard analysis over the next few years. They funded Bell Helicopter Textron, Boeing Vertol, and Sikorsky Aircraft to apply C81 to their own aircraft types and judge the utility of the analysis. Johnson (Ref. 60) has written that the “results were disappointing” and “the position against universal adoption of C81 was clear.”

Despite the problems with developing a standard analysis, much had been learned by the late 1970s. In 1977, the Army embarked on the development of 2GCHAS, the Second Generation Comprehensive Helicopter Analysis System, a new comprehensive analysis that they believed would become the new standard. 2GCHAS, or “2-G-Charlie” as it quickly became known, never obtained that success. Instead, a number of other new comprehensive analyses were developed. These included CAMRAD and its successors from Johnson Aeronautics starting about 1980, UMARC from the University of Maryland beginning about 1988, DYMORE from Georgia Tech about 1996, and finally RCAS, the reincarnation of 2GCHAS, beginning about 1997. Each of these methods was different, but unlike the situation in 1974 where analytical predictions differed widely, these modern analyses provided much the same results and we all were able to avoid the rush into the sea of MacNeal’s lemmings.

CFD became a major contributor to the success of the Airloads Workshops, particularly as more powerful computers became available in the 1990s. (These very powerful machines were a key to our success, but would have come along regardless of any of our technology efforts. We were not the tail that wagged that dog.) As was the case for comprehensive analyses, Wayne Johnson’s 30th Alexander Nikolsky Honorary Lecture (Ref. 60) provides a critical summary of developments in CFD.

The effort progressed in a logical approach of looking first at calculations in hover, then nonlifting rotors in forward flight, and finally lifting rotors in forward fight. Much of this work was driven by the calculation methods at the U.S. Army Aeroflightdynamics Directorate at Ames Research Center and experimental work at ONERA, all under a cooperative international agreement.

Early CFD development using a small-disturbance method (Ref. 106) showed the importance of the unsteady terms for a nonlifting rotor in forward flight, particularly for transonic flow on the advancing side. These methods were developed to the point where they could be applied to lifting model rotor data in forward flight (Ref. 107). Wake effects and blade motion were accounted for by using the measured control angles and a simple inflow model. Figure 41 shows a sample of these calculations at six blade azimuth angles, and both the development and strength of the transonic flow are well represented. Johnson (Ref. 60) has called the Caradonna et al. paper, “the start of this quest.”

These first results were followed by more accurate calculations using the full-potential and Euler equations in the mid-1980s. By the late 1980s, the first demonstrations occurred using the Navier–Stokes equations with a representation of viscosity.

The development of CFD methods up to the end of the 1990s was in some respects an “academic” exercise. The primary proof of predictive accuracy that was used was the comparison of pressure distributions (such as in Fig. 41). But the rotor designer had only a passing interest in pressure distributions. Instead, the designer wanted the distribution of lift, pitching moment, and drag along the blade span.

The CFD developers eventually provided their results in terms of the radial and azimuthal distributions of normal force as represented by C_N and pitching moment as represented by C_M, but then stumbled over the baggage of the fixed-wing/rotary-wing divide. Because C_N is equal to the dimensional normal force divided by $0.5\rho v^2 c$ it is affected by the local velocity v. For a fixed-wing aircraft, the local velocity does not vary greatly over the entire aircraft. But for a helicopter rotor, it varies with the blade radius and rotor azimuth. On the advancing side, where transonic effects are so important, the local velocity is high and C_N is low, whereas on the retreating side, the local velocity is low and C_N is high. Moreover, at the reverse flow boundary where the local velocity is zero, C_N becomes infinite. The dimensional reality is that the local

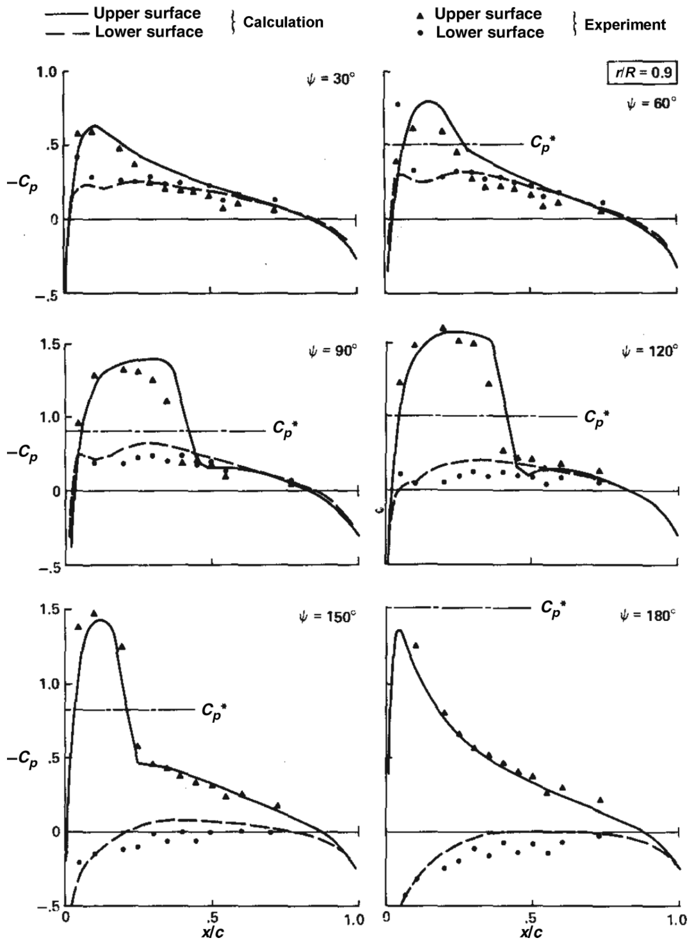

Fig. 41. Comparison of measured and computed chordwise pressure distribution at different azimuth angles; $\mu = 0.39$, $C_T/\sigma = 0.0665$, $r/R = 0.90$ (Ref. 107).

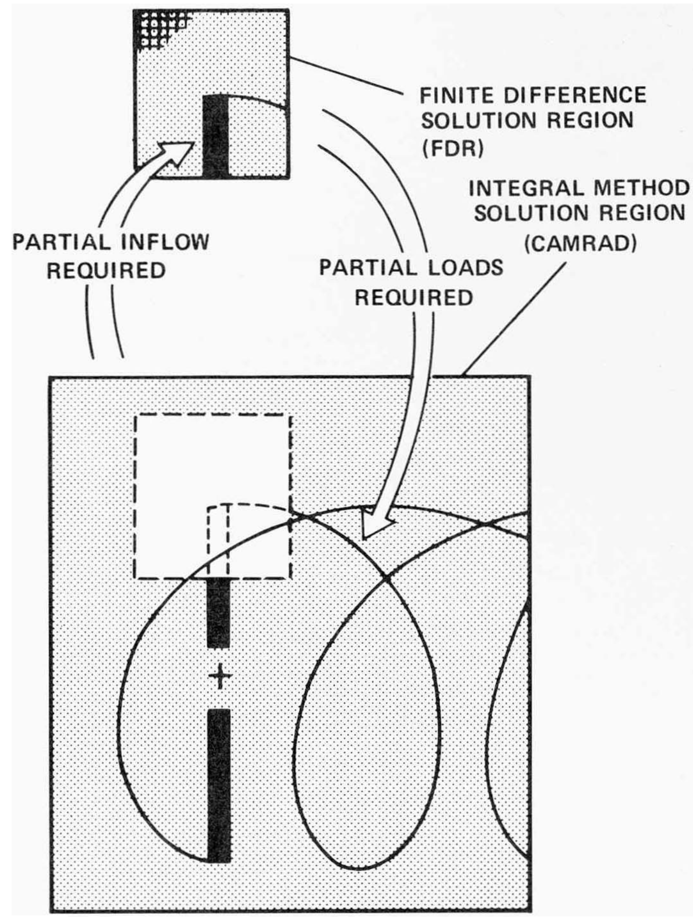

Fig. 42. Schematic of loads exchange in CFD and CSD coupling (Ref. 90).

normal forces are of the same order everywhere on the rotor, and these cannot be represented by C_N.

This was not a new problem, but it took time to resolve. For example, in examining the AH-1G/OLS airloads data, Cox (Ref. 108) plotted the section normal forces as C_N for a high-speed case and described a "stall" event inboard at $0.40R$. But that stall event was an artifact of using C_N as the reverse flow boundary was approached. Charlie Morris used the White Cobra at NASA Langley Research Center in the late 1970s to evaluate three different airfoils on the AH-1G rotor. In one of these reports (Ref. 109), he plotted normal force and pitching moments as M^2C_N and M^2C_M, where the speed of sound was used for nondimensionalization instead of the local velocity. No one picked up on Charlie's idea at that time to the best of my knowledge.

Hooper (Ref. 53) recognized this problem in his study of the rotor loads measured on disparate aircraft. He simply showed the forces as dimensional data and selected appropriate axes to allow qualitative comparisons.

The turnaround came in the late 1980s when we started an international program to compare CFD calculations with measurements obtained on the research Puma (Ref. 89). In our planning discussions, Jim McCroskey suggested the use of M^2C_N and M^2C_M as a way of avoiding the distortion introduced by C_N and C_M. The use of M^2C_N and M^2C_M is now largely universal.

The last of the contributions to the workshops that I discuss (but not the least) was the technique developed to couple the comprehensive analyses (also referred to as CSD) to the CFD analyses. The coupling between the two analyses is accomplished by a transfer of integrated airloads and blade deformations. Over time, two basic schemes have been developed: (1) loose coupling, where the transfer takes place after a revolution, and (2) tight coupling, where the transfer is made at each time step (as driven by the CFD code).

The loose coupling efforts started in early 1984 when Chee Tung and Frank Caradonna decided to approach the problem of CFD calculations for a lifting rotor by using the transonic small-disturbance code called FDR as the means of calculating the lift on the outer blade on the advancing side to provide to the comprehensive analysis CAMRAD, which would then provide the rotor trim and blade deformations (Ref. 90). They encountered difficulties in making the coupling work and asked Wayne Johnson for his help, and he developed the coupling methodology and made the necessary modifications to CAMRAD (Ref. 60). A schematic of the coupling process is shown in Fig. 42. The FDR analysis provided only lift to the comprehensive analysis and only over a limited domain.

Datta et al. (Ref. 61) and Johnson (Ref. 60) have provided summaries of the development of these coupling methods. Strawn and Tung (Ref. 110) coupled the full-potential code FPR with CAMRAD, and this time the lift was calculated by FPR over the entire rotor.

The next step was to have the CFD code provide pitching moments as well as lift, but this approach encountered many difficulties. Beaumier (Ref. 111) was one of the first to successfully accomplish this task, using an unsteady full potential code FP3D coupled with the comprehensive analysis R85/METAR. Although the coupling was successful, the pitching moment predictions were no better than the CSD predictions alone, a problem with many of the CFD codes at the time because they had no way of handling viscosity.

In the 1990s, a number of investigators had shown that Navier–Stokes calculations could be used to predict rotor airloads. The final step was in 2004 when Potsdam et al. (100) coupled the Navier–Stokes code OVERFLOWD with CAMRAD II using the lift and chord forces, and the pitching moments simultaneously.

Concluding Remarks

My narrative has focused on the history of the 12 major airloads measurements performed in the United States, and I have shown how these measurements have supported new analytical approaches. I have concluded that with the data from the UH-60A Airloads Program and the recent advances in computational methods we have undergone a transformation in the capability of our analytical methods. But that transformation is not complete until these new methods are trusted and used by designers. Until that happens, they remain an academic exercise.

I see five challenges in the next decade or two for the use of these new tools if we are indeed to obtain a transformation:

1) We must integrate the new coupled CFD/CSD methods into design.

2) We need to accept that nonlinear aerodynamic loads at high speed and in maneuvers will depend on the rotor design—each rotor is different.

3) We need to understand the remaining deficiencies in our prediction accuracy. One of these is the prediction of the higher harmonics of structural loads so that we can address the problems of vibration.

4) We must address the loss of experimental data, particularly large data sets stored on digital media.

5) Finally, we have to find cheaper ways to obtain airloads from flight or wind tunnel tests.

The Five Challenges

Integrating the new methods

There is a rule of thumb in the aviation business that it takes 20 years from the discovery of new materials or methods to their application in a successful commercial product. Roughly, this process follows a sigmoid curve as shown in the schematic of Fig. 43. In the beginning, there is a burst of enthusiasm for a new idea and there appears to be a clear and certain path to a final product, what I call the "early exploration stage." But then, there is a long period of time where all aspects of the new idea must be tested for their efficacy, cost, and safety. Participants in this "main movement of technology" can become frustrated at the costs and delays that are always part of something new. At the end of the process are the "final details," all of them essential, but frustrating with the goal so near at hand.

Currently, we are still at the beginning, convinced that this transformation in our methods will provide improved designs in the future. Some of the funding for the main movement first occurred under the HI-ARMS program, a Department of Defense (DOD) initiative to bring computational methods to bear on many of our many military system design problems. That program has transitioned to the present CREATE-AV program that sponsors the continuing work (Ref. 112). The UH-60A data set is now an integral part of the CREATE-AV program, and I am optimistic that that program's funding will push forward the integration of these new methods.

To achieve progress, we must also convince the rotor designer that the new methods are accurate, trustworthy, and practical. Each of the rotorcraft companies has cases where the predicted performance, loads, or vibration of one of their new helicopter rotors were missed and required redesign. Few of these rotor "skeletons" are public knowledge, but if we can encourage the companies to test the new methods against a known design failure, we may be able to convince the rotor designer that the methods are accurate and practical.

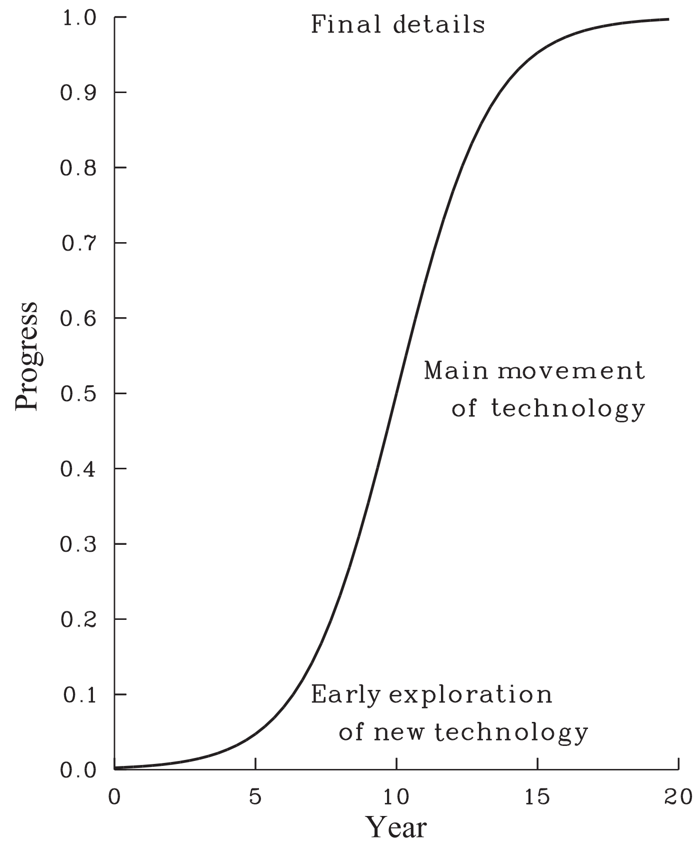

Fig. 43. Curve of technology improvements.

A generation ago, Professor Richard Shevell examined his fixed wing aircraft design experience at Douglas Aircraft and addressed the question as to whether the CFD methods available in the 1980s and earlier might have helped prevent some of the design problems they encountered with such famed aircraft as the DC-8, DC-9, and DC-10 (Ref. 113). His answer was "no," but in some cases those methods might have provided some useful information. Commercial aircraft and rotorcraft are far apart in the aviation spectrum, but Shevell's experience with the complexity of the design process and the overconfidence that sometimes occurs provides a welcome cautionary note as we implement these methods in the future.

Nonlinear aerodynamics: Each rotor is different

I refer to the problem of nonlinear aerodynamics as the Tolstoy problem. In his novel Anna Karenina, published in Russia in 1888 (Ref. 114 is more recent), the first sentence is "Happy families are all alike; every unhappy family is unhappy in its own way." I think this is an apt description of nonlinearities if paraphrased: linear aerodynamics are all alike; every nonlinear aerodynamic problem is different in its own way.

Previously, I showed John Ward's redigitization of data for the CH-34 as Fig. 23. In Fig. 44, I use Ward's format, but substitute data from the UH-60A flight test. The baseline behavior for both rotors shows moderate 1/rev variation. For the highly loaded condition, what is notable is that

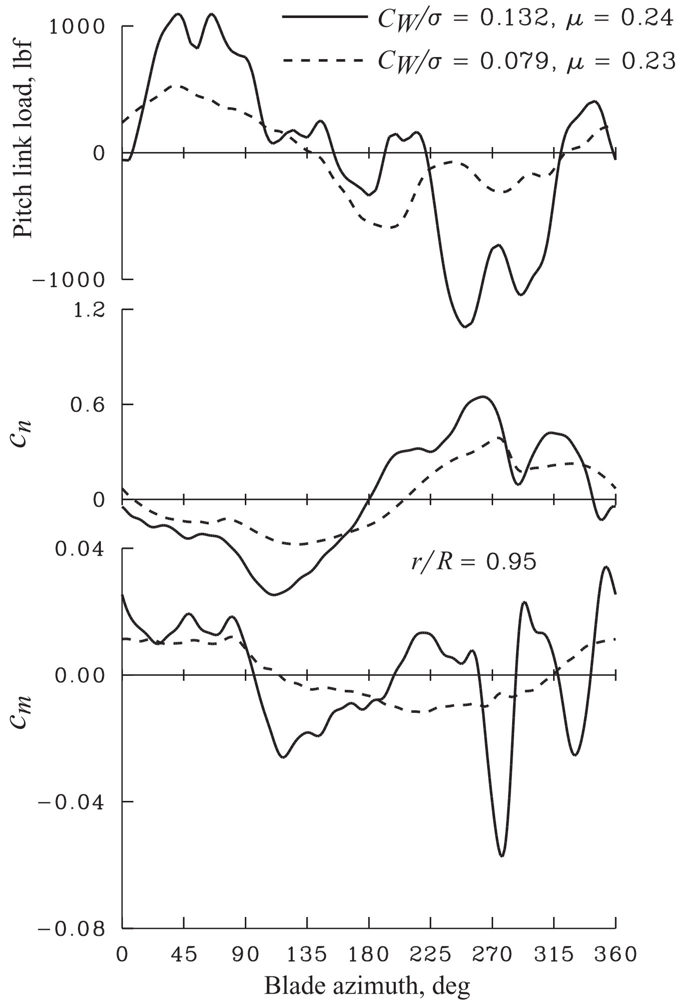

Fig. 44. UH-60A flight-test data, same format as used in Fig. 23 for the CH-34 flight-test data.

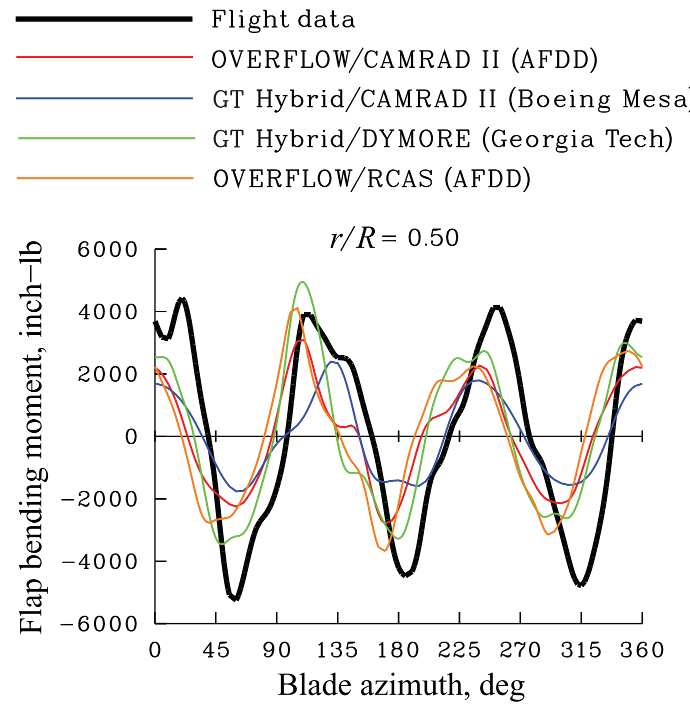

Fig. 45. Comparison of measured flap bending moment at 0.50R for the UH-60A with four coupled CFD/CSD methods, μ = 0.37, C_W/σ = 0.078, 3-24 harmonics.

the CH-34 has three dynamic stall oscillations in the fourth quadrant whereas there are only two for the UH-60A. Ward (Ref. 74) has pointed out that dynamic stall for the CH-34 occurred at the second torsion mode frequency. But for the UH-60A, the dynamic stall occurs at the first torsion mode frequency. The initiation of dynamic stall is caused primarily by blade aerodynamics, but repetition of the dynamic stall cycles is caused primarily by dynamic response (Ref. 75).

The transformation that we have accomplished in our abilities to predict rotor loads in the past decade may lead us to the hubris that Professor Shevell wrote about 30 years ago in the commercial aircraft business (Ref. 113). We must show that these methods are accurate across a broad range of rotorcraft, or we are just fooling ourselves. Unfortunately for the challenge I have shown here, Ward's redigitized data for the CH-34 have been lost. The loss of experimental data is another challenge that I will address below.

Remaining deficiencies

The significantly improved accuracy in the airloads calculation that has been accomplished in the past decade has not been fully extended to the calculation of structural loads. The normal force prediction at the maximum level flight speed for the UH-60A in Fig. 38 for five coupled CFD/CSD methods is quite accurate. An examination of the structural loads at the blade midspan at 0.50R in Fig. 45 shows that prediction of peak-to-peak loading that is important for fatigue is also quite good. But all of the calculations show a phase lead of about 10°. Vibration on this rotor is dominated by the 3–5/rev structural loads as shown in Fig. 45 for four of the five calculations. Here the phase lead is more apparent and the various methods show as much disagreement with each other as with the measurements.

We do not currently understand the source of these differences. Is it in the CFD part of the calculation or the CSD part or both? Also, these results are for just one rotor—we do not know whether similar differences would be seen on other rotors.

Beyond the problems with the structural load calculations, the good results in airloads predictions are not consistent. We appear to do best with unsteady transonic flows, less well when there is significant vortex wake loading, and poorest when dynamic stall is present. Uniformly, normal force is predicted better than pitching moment, a trend that is worrying to all aeroelasticians because the pitching moments directly affect the torsional elastic deformation.

If we are to be successful in moving up the sigmoid curve, we need better understanding of and better calculations for these problems.

Loss of experimental data

Euan Hooper chaired a panel at the Second Decennial Specialists' Meeting that was held at NASA Ames in November 1984 (Ref. 63). The timing of the panel was appropriate considering Hooper's recent use of many of the airloads data sets that are the centerpiece of my narrative (Ref. 53). In addition, the value of this panel was enhanced by the transcription of the panel presentations and all subsequent discussions.

Most of the presenters were aware of the history of the airloads data bases. Ten of the 12 airloads data bases had already been obtained by the date of the conference. Jim Biggers commented (p. 457),

> ... we are caught in a trap. The papers and things that we have heard the past couple of days indicate a need for increasingly detailed test information with which to compare our increasingly capable theories. And yet we are not terribly well equipped to handle the test information that we can go out and acquire. We also have the ability to go out and acquire a great deal of detailed test data with many surface pressures and things of the nature you have described .... So we have a problem of data volume versus accessibility.

Concerning the permanence of test data, Mike Bondi, the program lead for the TRENDS data base at NASA Ames, said somewhat wistfully (p. 464), "... industry should request NASA ... to support that function." Jim McCroskey, unimpressed, said, "If you ask industry to set up congress to get NASA funded to preserve this stuff for 20 years, I don't think it will happen."

The rotorcraft community is small compared to the larger world of science and engineering. Are our problems caused by our small size? Is all of our handwringing about unwieldy and lost data so much navel gazing? A special section in the 11 February 2011 issue of *Science* on "Dealing with Data" may provide some insight into the problems facing the larger scientific community.

In that special section of *Science*, Andrew Curry (Ref. 115) examined difficulties faced by physicists at the LHC. Salvatore Mele, a physicist and data preservation expert at CERN described the more typical problems with retaining data, "There's funding to build, collect, analyze, and publish data, but not to preserve data." Dr. Mele's experience was no different from that of anyone in the rotorcraft community who has worked with some of our larger rotor data sets.

As Curry reports, things are changing within the high-energy physics community. In that community, there is the need for a data archivist who would be a mix of librarian, IT expert, and physicist. For a modern physics experiment, they estimate that it would cost only 1% of a collider's total budget to archive and maintain the data. I doubt that costs for improved handling of our rotorcraft experimental data would be anymore expensive relative to our testing budgets.

We have had libraries based on print media for thousands of years. They are not always permanent, as shown by the history of the Royal Library of Alexandria first begun in 3000 BC. But by comparison to digital media, they are solid as rock. Moreover, we always have the chance to save duplicate copies, should one of our modern libraries suffers a catastrophe. But digital data can disappear in an instant, sometimes by accident, sometimes on purpose.

The last two tests, the UH-60A flight test in 1993–1994 and the UH-60A wind tunnel test in 2010, are both saved on digital media within the temperature-controlled computer centers at NASA Ames Research Center. The data are restricted and ephemeral. Since the data were placed on a DEC VAX using an optical jukebox for storage, we have gone through four storage media changes and one operating system change. So far, we have lost only 0.3% of the data. But in August 2013, the current computer crashed and the data were inaccessible for the next five or six months. We believe the data are now okay, but a certain demonstration of their adequacy is not trivial.

As for the most recent wind tunnel test, we have already had our data distribution system shut down by hackers. It is a new world out there. As Dr. Johnson said in 1984, "putting things down on paper and saving them has a lot to be recommended."

Alternatives to full-scale airloads tests

All of the airloads tests that have made up my narrative have cost too much. Some worked and some did not. There is much to be learned from our failures, but more from our successes. There are alternatives. I list here four possibilities: (1) model rotor tests, (2) full-scale rotor tests, but with measurements at fewer radial stations, (3) simplified measurements that use fewer pressure transducers, and (4) new measurement techniques and technologies.

Model rotor tests

A number of examples of successful Mach-scaled model rotor tests including a 1/5.73-scale rotor of the UH-60A were tested in hover at Sikorsky Aircraft and in forward flight at the Duits Nederlandse Windtunnel (DNW) (Refs. 116–117), the 7A and 7AD rotors tested in ONERA's Modane tunnel (Ref. 118), and the HART I and II tests, also in the DNW tunnel (Refs. 119–121). All of these tests, to some degree, have been affected by lack of Reynolds number scaling. Moreover, not all of the tests have been able to test to the full flight envelope because of structural limitations. The new model construction technology, however, can provide a full test envelope (Ref. 122). No cost comparisons with full-scale tests have been made, but I believe that these model tests have been substantially less expensive.

Full-scale rotor tests with limited instrumentation

The 12 tests that have been the focus of my narrative had sufficient pressure transducers installed at five or more radial stations, so that the normal force could be accurately measured at these locations and the blade thrust calculated. Other flight tests have been accomplished with fewer radial measurement stations. Two that are notable were multiple tests including two different rotors on an Aerospatiale Puma (AS 330) at the RAE (Refs. 88, 89) and tests of a special-purpose rotor on an Aerospatiale Gazelle (SA349/2) flown at Marignane (Ref. 123).

The research Puma tests were undertaken in a cooperative program between the RAE and ONERA. The first test used an interesting mixed-bladed rotor with a rectangular tip opposite a swept tip whereas the second test used four swept tips. Pressure measurements were obtained at three radial stations at the blade tip in both tests: $0.92R$, $0.95R$, and $0.978R$. These radial stations were selected to better understand the unsteady transonic flow at the blade tip. These data have been useful despite the limited number of radial stations (Refs. 91–93).

The SA349/2 test was flown with special-purpose Grand Vitesse blades designed for high speed. Pressure transducers were installed at three blade stations distributed over two blades: $0.75R$, $0.88R$, and $0.97R$. A joint research program to examine these data was established between NASA and the French Ministry of Defense. Level flight cases were selected from $C_W/\sigma = 0.062$ to 0.090 and μ from 0.13 to 0.36. Maneuver cases were also examined.

Simplified measurements

A number of simplified approaches have been tried that are cheaper than the fully instrumented rotors discussed in this paper. But each has its own limitations. Brotherhood (Ref. 124) demonstrated that two pressure transducers could be used to provide section normal force. One transducer was installed near the leading edge at about $0.02c$ and the second near the trailing edge. An instrumented airfoil section was tested in a wind tunnel, and a linear relation between the section lift and the leading edge transducer was established. The linear relation was effective in the regime of linear aerodynamics, including blade–vortex loading. But during blade stall (indicated by the blade trailing edge transducer), the linear relationship failed. The trade-off, then, was a significant reduction in blade instrumentation, but an inability to make measurements in the regimes of nonlinear aerodynamics.

Bousman (Ref. 125), using data from the airloads test of the CH-34 rotor in the wind tunnel (Ref. 27), demonstrated that flap bending structural measurements could be used to derive the distribution of section normal force by a least-squares fit. Although the method was robust, it has not been applied to more complicated rotors nor have the blade torsion and chord bending moments been used to improve the fit.

New measurement techniques and technologies

Creativity in measurement techniques and technologies may provide some significant cost reductions in the future. The continuing miniaturization of pressure measurements and instrumentation and related cost reductions may provide opportunities for significantly less expensive testing.

New measurement techniques such as dynamic pressure sensitive paint measurements may also one day allow cost savings by eliminating the on-blade instrumentation.

Acknowledgments

I obtained a great deal of help from many people while preparing this lecture and the present paper. I thank them all. These many helpful people included Ed Austin, Ken Bartie, Ed Beno, Mahendra Bhagwat, Joe Chambers, Bruce Charles, Dave Conner, Jeff Cross, Frank Harris, Danny Hoad, Euan Hooper, Terry Hornbuckle, Larry Jenkins, Wayne Johnson, Bob Kufeld, Tom Lawrence, Al Lizak, Tom Maier, Wayne Mantay, Bobby Mathew, Jim McCroskey, Don Merkley, Jorge Morillo, Tom Norman, Bob Ormiston, Ray Piziali, Mark Potsdam, Ray Prouty, Art Ragosta, Nischint Rajmohan, Mike Scully, Marilyn Smith, Karen Studebaker, Barbara Trippe, John Vorvald, John Ward, Bill Warmbrodt, Bob Wood, Gloria Yamauchi, and Hyeonsoo Yeo.

References

[1]Bousman, W. G., and Hodges, D. H., "An Experimental Study of Coupled Rotor-Body Aeromechanical Instability of Hingeless Rotors in Hover," *Vertica*, Vol. 3, 1979, pp. 221–244.

[2]Stepniewski, W. Z., "Alexander A Nikolsky," *Journal of the American Helicopter Society*, Vol. 27, (2), April 1982, pp. 3–5.

[3]Stepniewski, W. Z., "Factors Shaping Conceptual Design of Rotary-Wing Aircraft," *Journal of the American Helicopter Society*, Vol. 27, (2), April 1982, pp. 6–20.

[4]Rabbott, J. P., Jr., and Churchill, G. B., "Experimental Investigation of the Aerodynamic Loading on a Helicopter Rotor Blade in Forward Flight," NACA RM L56I07, October 1956.

[5]Norman, T. R., Shinoda, P., Peterson, R. L., and Datta A., "Full-Scale Wind Tunnel Test of the UH-60A Airloads Rotor," American Helicopter Society 67th Annual Forum Proceedings, Virginia Beach, VA, May 3–5, 2011.

[6]Lawler, A., and Bhattacharjee, Y., "Massive Cost Overrun to Webb Threatens Other NASA Missions," *Science*, Vol. 330, November 2010, pp. 1028–1029.

[7]Bhattacharjee, Y., "House Panel Would Kill Space Telescope," *Science*, Vol. 330, (15), July 2011, pp. 275–276.

[8]Ward, J. F. "NACA-NASA and the Rotary Wing Revolution," *NASA's Contributions to Aeronautics*, edited by R. P. Hallion, Vol. 1, NASA SP-2010-570-Vol 1, 2010, pp. 134–179.

[9]Snyder, W. J., Cross, J. L., and Kufeld, R. M., "NASA/Army Rotor Systems Flight Research Leading to the UH-60 Airloads Program," American Helicopter Society Specialists Meeting "Innovations in Rotorcraft Test Technology for the 90's," Phoenix, AZ, October 8–12, 1990.

[10]Bugos, G. E. *Atmosphere of Freedom: 70 Years at the NASA Ames Research Center*, NASA SP-2010-4314, 2010, pp. 282–283.

[11]McHugh, F. J., "What Are the Lift and Propulsive Force Limits at High Speed for the Conventional Rotor?" Preprint 78-2, American Helicopter Society 34th Annual National Forum Proceedings, Washington, DC, May 15–17, 1978.

[12]McHugh, F. J., Ross, C., and Solomon, M. "Wind Tunnel Investigation of Rotor Lift and Propulsive Force at High Speed—Data Analysis," NASA CR 145217-1, October 1977.

[13]Gustafson, F. B., "Flight Test of the Sikorsky HNS-1 (Army YR-4B) Helicopter, I—Experimental Data on Level-Flight Performance with Original Rotor Blades," NACA MR L5C10 (reissued as L-595), March 1945.

[14]Gustafson, F. B., and Gessow, A., "Tests of the Sikorsky HNS-1 (Army YR-4B) Helicopter, II—Hovering and Vertical-Flight Performance with the Original and an Alternate Set of Main-Rotor Blades, Including a Comparison with Hovering Performance Theory," NACA MR L5D09a (reissued as L-596), April 1945.

[15]Gustafson, F. B., and Myers, G. C., Jr., "Stalling of Helicopter Blades," NACA Report No. 840, April 1946.

[16]Gustafson, F. B., and Gessow, A., "Effect of Blade Stalling on the Efficiency of a Helicopter Rotor as Measured in Flight," NACA TN 1250, April 1947.

[17]Ludi, L. H., "Flight Investigation of Effects of Atmosphere Turbulence and Moderate Maneuvers on Bending and Torsional Moments Encountered by a Helicopter Rotor Blade," NACA TN 4203, February 1958.

[18]Ludi, L. H., "Flight Investigation of Effects of Retreating-Blade Stall on Bending and Torsional Moments Encountered by a Helicopter Rotor Blade," NACA TN 4254, May 1958.

[19]Ludi, L. H., "Flight Investigation of Effects of Transition, Landing Approaches, Partial-Power Vertical Descents, and Droop-Stop Pounding on the Bending and Torsional Moments Encountered by a Helicopter Rotor Blade," NACA MEMO 5-7-59L, May 1959.

[20]Ludi, L. H., "Flight Investigation of Effects of Additional Selected Operating Conditions on Bending and Torsional Moments Encountered by a Helicopter Rotor Blade," NASA TN D759, 1961.

[21]Patterson, J. L., "A Miniature Electrical Pressure Gage Utilizing a Stretched Flat Diaphragm," NACA TN 2659, April 1952.

[22]Burpo, F. B., and Lynn, R. R., "Measurement of Dynamic Air Loads on a Full-Scale Semirigid Rotor," TCREC TR 62-42, December 1962.

[23]Rabbott, J. P., Jr., "Static-Thrust Measurements of the Aerodynamic Loading on a Helicopter Rotor Blade," NACA TN 3688, July 1956.

[24]Mayo, A. P., "Comparison of Measured Flapwise Structural Bending Moments on a Teetering Rotor Blade with Results Calculated from the Measured Pressure Distribution," NASA MEMO 2-28-59L, March 1959.

[25]Scheiman, J., and Ludi, L. H. "Qualitative Evaluation of Effect of Helicopter Rotor-Blade Tip Vortex on Blade Airloads," NASA TN D-1637, May 1963.

[26]Scheiman, J., "A Tabulation of Helicopter Rotor-Blade Differential Pressures, Stresses, and Motions as Measured in Flight," NASA TM X-952, March 1964.

[27]Rabbott, J. P., Jr., Lizak, A. A., and Paglino, V. M., "A Presentation of Measured and Calculated Full-Scale Rotor Blade Aerodynamic and Structural Loads," USAAVLABS TR 66-31, 1966.

[28]Rabbott, J. P., Jr., Lizak, A. A., and Paglino, V. M., "Tabulated Sikorsky CH-34 Blade Surface Pressures Measured at the NASA/Ames Full Scale Wind Tunnel," Sikorsky Aircraft SER 58399, January 1966.

[29]Golub, R., and McLachlan, W. "In-flight Measurement of Rotor Blade Airloads, Bending Moments, and Motions, Together with Rotor Shaft Loads and Fuselage Vibration, on a Tandem Rotor Helicopter, Volume I, Instrumentation and In-flight Recording System," USAAVLABS TR 67-9A, May 1967.

[30]Grant, W. J., and Pruyn, R. R., "In-Flight Measurement of Rotor Blade Airloads, Bending Moments, and Motions, Together with Rotor Shaft Loads and Fuselage Vibration, on a Tandem Rotor Helicopter, Volume II, Calibrations and Instrumented Component Testing," USAAVLABS TR 67-9B, May 1967.

[31]Obbard, J. W. In-flight Measurement of Rotor Blade Airloads, Bending Moments, and Motions, Together with Rotor Shaft Loads and Fuselage Vibration, on a Tandem Rotor Helicopter, Volume III, Data Processing and Analysis System. USAAVLABS TR 67-9C, May 1967.

[32]Pruyn, R. R., "In-Flight Measurement of Rotor Blade Airloads, Bending Moments, and Motions, Together with Rotor Shaft Loads and Fuselage Vibration, on a Tandem Rotor Helicopter, Volume IV, Summary and Evaluation of Results," USAAVLABS TR 67-9D, May 1967.

[33]Pruyn, R. R., "In-Flight Measurement of Rotor Blade Airloads, Bending Moments, and Motions, Together with Rotor Shaft Loads and Fuselage Vibration, on a Tandem Rotor Helicopter, Volume V, Investigation of Blade Stall Conditions," USAAVLABS TR 67-9E, April 1968.

[34]Fenaughty, R., and Beno, E., "NH-3A Vibratory Airloads and Vibratory Rotor Loads," Sikorsky Aircraft SER 611493, Volume I, January 1970.

[35]Fenaughty, R., and Beno, E., "NH-3A Vibratory Airloads and Vibratory Rotor Loads," Sikorsky Aircraft SER 611493, Volume II, 1970.

[36]Bartsch, E. A., "In-Flight Measurement and Correlation with Theory of Blade Airloads and Responses on the XH-51A Compound Helicopter Rotor, Volume I —Measurement and Data Reduction of Airloads and Structural Loads," USAAVLABS TR 68-22A, May 1968.

[37]Bartsch, E. A., "In-Flight Measurement and Correlation with Theory of Blade Airloads and Responses on the XH-51A Compound Helicopter Rotor, Volume II —Measurement and Data Reduction of Airloads and Structural Loads Appendixes V Through IX," USAAVLABS TR 68-22B, May 1968.

[38]Sweers, J. E., "In-Flight Measurement and Correlation with Theory of Blade Airloads and Responses on the XH-51A Compound Helicopter Rotor, Volume III —Theoretical Prediction of Airloads and Structural Loads and Correlation with Flight Test Measurements," USAAVLABS TR 68-22C, May 1968.

[39]Beno, E. A., "CH-53A Main Rotor and Stabilizer Vibratory Airloads and Forces (Volume I)," Sikorsky Aircraft SER 65593, June 1970.

[40]Beno, E. A., "CH-53A Main Rotor and Stabilizer Vibratory Airloads and Forces (Volume II)," Sikorsky Aircraft SER 65593, 1970.

[41]Shockey, G. A., Williamson, J. W., and Cox, C. R., "AH-1G Helicopter Aerodynamic and Structural Loads Survey," USAAMRDL-TR-76-39, February 1977.

[42]Cross, J. L., and Watts, M. E., "Tip Aerodynamics and Acoustics Test," NASA RP 1179, 1988.

[43]Cross, J. L., and Tu, W., "Tabulation of Data from the Tip Aerodynamics and Acoustics Test," NASA TM 102280, November 1990.

[44]Kufeld, R. M., Balough, D. L., Cross, J. L., Studebaker, K. F., Jennison, C. D., and Bousman, W. G. "Flight Testing the UH–60A Airloads Aircraft," American Helicopter Society 50th Annual Forum Proceedings, Washington, DC, May 11–13, 1994.

[45]Bousman, W. G., and Kufeld, R. M., "UH-60A Airloads Catalog," NASA TM 2005–212827, August 2005.

[46]Bousman, W. G., "Rotorcraft Airloads Measurements—Extraordinary Costs, Extraordinary Benefits," NASA TP, to be published.

[47]Prouty, R. W., "The Lockheed Helicopter Experience," American Helicopter Society 65th Annual Forum Proceedings, Grapevine, TX, May 27–29, 2009.

[48]Bowden, T. H., and Shockey, G. A., "A Wind-Tunnel Investigation of the Aerodynamic Environment of a Full-Scale Helicopter Rotor in Forward Flight," USAAMRDL TR 70-35, July 1970.

[49]Lunn, K., and Knopp, J. L., "Real Time Analysis for Helicopter Flight Testing," *Vertica* Vol. 5, (3), 1981, pp. 217–241.

[50]Philbrick, R. B., and Eubanks, A. L., "Operational Loads Survey—Data Management System, Volume 1 User's Manual," USARTL TR 78-52A, January 1979.

[51]Philbrick, R. B. "The Data from Aeromechanics Test and Analytics—Management and Analysis Package (DATAMAP), Volume 1—User's Manual," USAAVRADCOM-TR-80-D-30A, December 1980.

[52]Johnson, W., Discussion, in Hooper, W. E., "Panel Two: Data Bases—The User's Viewpoint, Prepared Comments," Rotorcraft Dynamics 1984, NASA CP 2400, November 1985.

[53]Hooper, W. E., "The Vibratory Airloading of Helicopter Rotors," Paper 46, Ninth European Rotorcraft Forum, Stresa, Italy, September 13–15, 1983.

[54]Nakamura, Y., "Prediction of Blade–Vortex Interaction Noise from Measured Blade Pressure," *Vertica*, Vol. 6, (4), 1982, pp. 295–309.

[55]Succi, G. P., "Limits on Prediction of Helicopter Rotor Noise Using Thickness and Loading Sources: Validation of Helicopter Noise Prediction Technique," NASA CR-166097, April 1983.

[56]Dompka, R. V., and Cronkhite, J. D., "Summary of AH-1G Flight Vibration Data for Validation of Coupled Rotor-Fuselage Analysis," NASA CR-178160, November 1986.

[57]Kvaternik, R. G., "The NASA/Industry Design Analysis Methods For Vibrations (DAMVIBS) Program—A Government Overview," in A Government/Industry Summary of the Design Analysis Methods for Vibrations (DAMVIBS) Program, NASA CP 10114, January 1993.

[58]Yeo, H., and Chopra, I, "Coupled Rotor/Fuselage Vibration Analysis for a Teetering Rotor and Comparison with Test Data," *Journal of Aircraft*, 38, (1), January 2001, pp. 1035–1054.

[59]Yeo, H., and Chopra, I., "Coupled Rotor/Fuselage Vibration Analysis Using Detailed 3-D Airframe Models, *Mathematical Modeling and Analysis of Rotary-Wing Systems*, Vol. 33, (10–11), 2001, pp. 111–121.

[60]Johnson, W., "Milestones in Rotorcraft Aeromechanics, Alexander A Nikolsky Honorary Lecture," *Journal of the American Helicopter Society*, **56**, 031001 (2011).

[61]Datta, A., Nixon, M., and Chopra, I., "Review of Rotor Loads Prediction with the Emergence of Rotorcraft CFD," *Journal of the American Helicopter Society*, Vol. 52, (4), October 2007, pp. 287–317.

[62]Miller, R. H., "A Discussion of Rotor Blade Harmonic Airloading," CAL/TRECOM Symposium on Dynamic Load Problems Associated with Helicopters and V/STOL Aircraft, Buffalo, NY, June 1963.

[63]Hooper, W. E., "Panel Two: Data Bases—The User's Viewpoint," Prepared Comments, in Rotorcraft Dynamics 1984, NASA CP 2400, November 1985.

[64]Piziali, R. A., and DuWaldt, F., "A Method for Computing Rotary Wing Airload Distributions in Forward Flight," TRECOM Report No. TCREC TR 62-44, November 1962.

[65]Wood, E. R., and Hilzinger, K. D., "A Method for Determining the Fully Coupled Aeroelastic Response of Helicopter Rotor Blades," American Helicopter Society 19th Annual National Forum, Washington, DC, May 1–3, 1963.

[66]Miller, R. H., "Unsteady Air Loads on Helicopter Rotor Blades," *Journal of the Royal Aircraft Society*, Vol. 68, (640), April 1964, pp. 217–229.

[67]Piziali, R., Daughaday, H., and DuWaldt, F., "Rotor Airloads," CAL/TRECOM Symposium on Dynamic Load Problems Associated with Helicopters and V/STOL Aircraft, Buffalo, NY, June 1963.

[68]Piziali, R. A., "A Method for Predicting the Aerodynamic Loads and Dynamic Response of Rotor Blades," USAAVLABS TR 65-74, January 1966.

[69]Piziali, R. A., "Method for the Solution of the Aeroelastic Response Problem for Rotating Wings" *Journal of Sound and Vibration*, Vol. 4, (3), 1966, pp. 445–489.

[70]Ham, N. D., and Young, M. I., "Torsional Oscillations of Helicopter Blades Due to Stall," *Journal of Aircraft*, Vol. 3, (3), May–June, 1966, pp. 218–224.

[71]Ham, N. D., "Stall Flutter of Helicopter Rotor Blades: A Special Case of the Dynamic Stall Phenomenon," *Journal of the American Helicopter Society,* Vol. 12, (4), October 1967, pp. 19–21.

[72]Ham, N. D., and Garelick, M. S., "Dynamic Stall Considerations in Helicopter Rotors," *Journal of the American Helicopter Society,* Vol. 13, (2), April 1968, pp. 49–55.

[73]Harris, F. D., and Pruyn, R. R., "Blade Stall—Half Fact, Half Fiction. *Journal of the American Helicopter Society,* Vol. 13, (2), April 1968, pp. 27–48.

[74]Ward, J. F., "Helicopter Rotor Periodic Differential Pressures and Structural Response Measured in Transient and Steady-State Maneuvers," *Journal of the American Helicopter Society,* Vol. 16, (1), January 1971, pp. 16–25.

[75]Bousman, W. G., "A Qualitative Examination of Dynamic Stall from Flight Test Data," *Journal of the American Helicopter Society,* Vol. 43, (4), October 1998, pp. 279–295.

[76]McCroskey, W. J., and Fisher, R. K. Jr., "Detailed Aerodynamic Measurements on Model Rotor in the Blade Stall Regime," *Journal of the American Helicopter Society,* Vol. 17, (1), January 1972, pp. 20–30.

[77]McCroskey, W. J., McAlister, K. W., Carr, L. W., and Pucci, S. L., "An Experimental Study of Dynamic Stall on Advanced Airfoil Sections Volume 1. Summary of Experiments," NASA TM 84245, July 1982.

[78]Johnson, W., "The Response and Airloading of Helicopter Rotor Blades Due to Dynamic Stall," Massachusetts Institute of Technology, ASRL TR 130-1, May 1970.

[79]Gormont, R. E., "A Mathematical Model of Unsteady Aerodynamics and Radial Flow for Application to Helicopter Rotors," USAAVLABS TR 72-67, May 1973.

[80]Leishman, J. G., and Beddoes, T. S., "A Semi-Empirical Model for Dynamic Stall," *Journal of the American Helicopter Society,* Vol. 24, (3), July 1989, pp. 3–17.

[81]Petot, D., "Differential Equation Modeling of Dynamic Stall," La Recherche Aerospatiale, No. 1989-5, 1989.

[82]Truong, V. K., "A 2-D Dynamic Stall Model Based on a Hopf Bifurcation," 19th European Rotorcraft Forum, Cernobbio, Italy, September 14–16, 1993.

[83]Leishman, J. G. *Principles of Helicopter Aerodynamics*, Cambridge University Press, Cambridge, UK, 2000.

[84]Nguyen, K., and Johnson, W., "Evaluation of Dynamic Stall Models with UH-60A Airloads Flight Test Data," American Helicopter Society 54th Annual Forum Proceedings, Washington, DC, May 20–22, 1998.

[85]Bousman, W. G, "The Response of Helicopter Rotors to Vibratory Airloads," *Journal of the American Helicopter Society,* Vol. 35, (4), October 1990, pp. 53–62.

[86]Ormiston, R. A., "Comparison of Several Methods for Predicting Loads on a Hypothetical Helicopter Rotor," *Journal of the American Helicopter Society,* Vol. 19, (4), October 1974, pp. 2–13.

[87]Cowan, J., Dadone, L., and Gangwani, S., "Wind Tunnel Test of a Pressure Instrumented Model Scale Rotor," American Helicopter Society 42nd Annual Forum Proceedings, Washington, DC, June 2–4, 1986.

[88]Riley, M. J., and Miller, J. V., "Pressure Distributions on a Helicopter Swept Tip from Flight Testing and from Calculations," Ninth European Rotorcraft Forum, Stresa, Italy, September 13–15, 1983.

[89]Riley, M. J., "Measurements of the Performance of a Helicopter Swept Tip Rotor in Flight," Twelfth European Rotorcraft Forum, Garmisch-Partenkirchen, Germany, September 22–25, 1986.

[90]Tung, C., Caradonna, F. X., and Johnson, W., "The Prediction of Transonic Flows on an Advancing Rotor," *Journal of the American Helicopter Society,* Vol. 31, (3), July 1986, pp. 4–9.

[91]Strawn, R. C., Desopper, A., Miller, J., and Jones, A., "Correlation of Puma Airloads—Evaluation of CFD Prediction Methods," Fifteenth European Rotorcraft Forum, Amsterdam, The Netherlands, September 12–15, 1989.

[92]Bousman, W. G., Young, C., Gilbert, N., Toulmay, F., Johnson, W., and Riley, M. J., "Correlation of Puma Airloads—Lifting-Line and Wake Calculation," Fifteenth European Rotorcraft Forum, Amsterdam, The Netherlands, September 12–15, 1989.

[93]Bousman, W. G., Young, C., Toulmay, F., Gilbert, N. E., Strawn, R. C., Miller, J. V., Maier, T. H., Costes, M., and Beaumier, P., "A Comparison of Lifting-Line and CFD Methods with Flight Test Data from a Research Puma Helicopter," NASA TM 110421, October 1996.

[94]Watts, M. E., and Cross, J. L., "The NASA Modern Technology Rotors Program," AIAA 86-9788, AIAA/AHS/CASI/DGLR/IES/ISA/ITEA/SETP/SFTE 3rd Flight Testing Conference, Las Vegas, NV, April 2–4, 1986.

[95]Dadone, L., Dawson, S, and Ekquist, D., "Model 360 Rotor Test at DNW—Review of Performance and Blade Airload Data," American Helicopter Society 43rd Annual Forum Proceedings, St. Louis, MO, May 18–20, 1987.

[96]Kufeld, R., and Loschke, P., "UH-60 Airloads Program: Status and Plans. AIAA 91-3142, AIAA Aircraft Design Systems and Operations Meeting, Baltimore, MD, September 23–25, 1991.

[97]Kufeld, R. M., and Bousman, W. G., "High Load Conditions Measured on a UH-60A in Maneuvering Flight," *Journal of the American Helicopter Society*, Vol. 43, (3), July 1998, pp. 202–211.

[98]Kufeld, R. M., and Bousman, W. G., "UH-60A Helicopter Rotor Airloads Measured in Flight," 22nd European Rotorcraft Forum, Brighton, UK, September 16–19, 1996.

[99]Ormiston, R. A., "An Investigation of the Mechanical Airloads Problem for Evaluating Rotor Blade Structural Dynamics Analysis," American Helicopter Society 4th Decennial Specialists' Conference on Aeromechanics, San Francisco, CA, January 21–23, 2004.

[100]Potsdam, M. A., Yeo, H., and Johnson, W., "Rotor Airloads Prediction Using Loose Aerodynamic/Structural Coupling," *Journal of Aircraft*, Vol. 43, (3), May–June 2006, pp. 732–742.

[101]Bousman, W. G., and Norman, T., "Assessment of Predictive Capability of Aeromechanics Methods," *Journal of the American Helicopter Society,* **55**, 012001 (2010).

[102]Hirschberg, M., "The Rotorcraft Centers of Excellence," *Vertiflite*, Vol. 47, (2). 2001, pp. 38–52.

[103]Newman, D., Doligalski, T., and Minniti, R., "Advances in Modeling and Simulation of Rotorcraft Noise and Associated Impacts on Survivability," DARPA, 2008.

[104]Kufeld, R. M., and Bousman, W. G., "UH-60A Airloads Program Azimuth Reference Correction," *Journal of the American Helicopter Society,* Vol. 50, (2), April 2005, pp. 211–213.

[105]MacNeal, R. H., "Panel 1: Prediction of Rotor and Control System Loads. Question and Answers," in Rotorcraft Dynamics 1974, NASA SP-352, 1974.

[106]Caradonna, F. X., and Isom, M. P., "Numerical Calculation of Unsteady Transonic Potential Flow over Helicopter Rotor Blades, *AIAA Journal*, Vol. 14, (4), December 1976, pp. 482–488.

[107]Caradonna, F. X., Tung, C., and Desopper, A., "Finite Difference Modeling of Rotor Flows Including Wake Effects," *Journal of the American Helicopter Society,* Vol. 29, (2), April 1984, pp. 26–33.

[108]Cox, C. R., "Helicopter Rotor Aerodynamic and Aeroacoustic Environments," AIAA Preprint 77-1338, 4th Aeroacoustics Conference, Atlanta, GA, October 3–5, 1977.

[109]Morris, C. E. K., Jr., Stevens, D. D., and Tomaine, R. L., "A Flight Investigation of Blade-Section Aerodynamics for a Helicopter with NLR-1T Airfoil Sections," NASA TM 80166, January 1980.

[110]Strawn, R. C., and Tung, C., "The Prediction of Transonic Loading on Advancing Helicopter Rotors," AGARD CP 412, April 1986.

[111]Beaumier, P. A, "Coupling Procedure Between a Rotor Dynamics code and a 3D Unsteady Full Potential Code," American Helicopter Society Aeromechanics Specialists Conference, San Francisco, CA, January 19–21, 1994.

[112]Post, D. E., "Highlights of the CREATE Program," DoD HPCMP User Group Conference, Schaumburg, IL, June 15–17, 2010.

[113]Shevell, R. S, "Aerodynamic Anomalies: Can CFD Prevent or Correct Them?" *Journal of Aircraft*, Vol. 23, (8), August 1986, pp. 641–649.

[114]Tolstoy, L., *Anna Karenina*, Random House, New York, NY, 1965.

[115]Curry, A., "Rescue of Old Data Offers Lesson for Particle Physicists," *Science,* 331, February 2011, pp. 694–695.

[116]Lorber, P. F., Stauter, R. C., and Landgrebe, A. J., "A Comprehensive Hover Test of the Airloads and Airflow of an Extensively Instrumented Model Helicopter Rotor," American Helicopter Society 45th Annual Forum Proceedings, Boston, MA, May 22–24, 1989.

[117]Lorber, P. F., "Aerodynamic Results of a Pressure-Instrumented Model Rotor Test at the DNW," *Journal of the American Helicopter Society,* Vol. 36, (4), October 1991, pp. 66–76.

[118]Petot, D., Arnaud, G., Harrison, R., Stevens, J., Teves, D., van der Wall, B. G., Young, C., and Szechenyi, E., "Stall Effects and Blade Torsion—An Evaluation of Predictive Tools," 23rd European Rotorcraft Forum, Dresden, Germany, September 16–18, 1997.

[119]Yu, Y., Gmelin, B., Heller, H., Phillipe, J. J., Mercker, E., and Preisser, J. S., "HHC Aeroacoustics Rotor Test at the DNW—The Joint German/French/US HART Project," Twentieth European Rotorcraft Forum, Amsterdam, The Netherlands, October 4–7, 1994.

[120]Yu, Y. H., Tung, C., van der Wall, B., Pausder, H.-J., Burley, C., Brooks, T., Beaumier, P., Delreiux, Y., Mercker, E., and Pengel, K., "The HART-II Test: Rotor Wakes and Aeroacoustics with Higher-Harmonic Pitch Control (HHC) Inputs—The Joint German/French/Dutch/US Project," American Helicopter Society 58th Annual Forum Proceedings, Montreal, Canada, June 11–13, 2002.

[121]van der Wall, B. G., Junker, B., Burley, C. L., Brooks, T. F., Yu, Y., Tung, C., Raffel, M., Richard, H., Wagner, W., Mercker, E., Pengel, K., Holthusen, H., Beaumier, P., and Delrieux, Y., "The HART II Test in the LLF of the DNW—A Major Step towards Rotor Wake Understanding," 28th European Rotorcraft Forum, Bristol, UK, September 17–20, 2002.

[122]Lorber, P. F., Stauter, R. C., Haas, R. J., Anderson, T. J., Torok, M. S., and Kohlhepp, F. W., "Techniques for Comprehensive Measurement of Model Helicopter Rotor Aerodynamics," American Helicopter Society 50th Annual Forum Proceedings, Washington, DC, May 11–23, 1994.

[123]Heffernan, R. and Gaubert, M., "Structural and Aerodynamic Loads and Performance Measurements of an SA349/2 Helicopter with an Advanced Geometry Rotor," NASA TM 88370, November 1986.

[124]Brotherhood, P., "An Appraisal of Rotor Blade-Tip Vortex Interaction and Wake Geometry from Flight Measurements," in Prediction of Aerodynamic Loads on Rotorcraft, AGARD CP 334, London, UK, May 1982.

[125]Bousman, W. G., "Estimation of Blade Airloads from Rotor Blade Bending Moments," Thirteenth European Rotorcraft Forum, Arles, France, September 8–11, 1987.