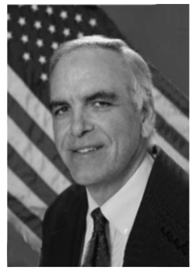
Flight Control Technology Advancements and Challenges for Future Rotorcraft *40th Alexander A. Nikolsky Honorary Lecture*



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The goal of my 40th Alexander A. Nikolsky Honorary Lecture and journal paper is to highlight the key flight control technology advances of the past 50 years and demonstrate how these advances are being applied and extended to the new family of rotorcraft: modern high-speed military rotorcraft, eVTOL urban air mobility, and advanced air mobility aircraft. The first part of this journal paper reviews flight control technologies drivers that are unique to rotorcraft and highlights key advances of the past 50 years in the areas of handling-qualities requirements (ADS-33), physics-based models, system identification, and flight control. A central theme is the shift from time-domain to frequency-domain based characterization of the closed-loop response and design methods for rotorcraft that have become increasingly dependent on sophisticated feedback control systems to achieve closed-loop stability, disturbance rejection, and most importantly closed-loop handling-qualities response for all-weather operations. Frequency-domain analysis, design, and test methods of the past 50 years are highlighted relating key advances in each discipline and two integrated example success stories. In the second part of this paper, we consider the key challenges, advancements, and needed future research for four new classes of rotorcraft: the military future vertical lift family of high-speed rotorcraft, unmanned autonomous systems/urban air mobility based on fielded conventional helicopters, small electric VTOL unmanned aerial vehicle rotorcraft, and larger eVTOL urban air mobility rotorcraft. The next sections look across the challenges and solution spaces that are common to these four new classes of rotorcraft as a blueprint for needed research advances. Finally, this paper takes a step back and considers the lessons-learned and key takeaways from the author's perspective as a career-long flight control engineer/researcher, Flight Control Technology Group leader, and senior technologist.

Introduction

This 40th Alexander A. Nikolsky Honorary Lecture paper summarizes the key accomplishments in flight control technology since the 1970s and then considers the recent advancements of these technologies and challenges for their application to future rotorcraft concepts. Some of the aircraft considered are shown in Fig. 1.

Personal connections

It is customary to start the Alexander A. Nikolsky Honorary Lecture by first establishing the personal connection of the honoree to Professor A. Nikolsky (Fig. 2(a)). Professor Howard "Pat" Curtiss (Fig. 2(b)) gave the 20th Nikolsky Lecture. He was a Ph.D. student of Professor Nikolsky at Princeton, and with him, developed the "Princeton Long Track." As described by Steven Schultz in the Office of Engineering Communications at Princeton, "the long track was unique in aerodynamics studies that functioned as a reverse wind tunnel where subscale models of aircraft were moved through the air instead of the air being moved past the aircraft. The facility, located on Princeton's Forrestal Campus, avoided problems of conventional wind tunnels in which the tunnel walls caused interference that skewed measurements" and facilitated major breakthroughs in rotorcraft stability and control understanding. Professor Curtiss was my career-long mentor, role model, and research collaborator. He always stressed the importance of understanding the first principles of each new research challenge. I greatly benefitted from discussions and research collaborations with Professor Curtiss and many other mentors that I have had the honor to work with. As coined by my Ph.D. advisor at Stanford University, Professor Arthur E. Bryson, Jr., a "student of a student" is a "grand student," and this is my connection to Professor Nikolsky. Previous Nikolsky Lectures by Professor Curtiss (Ref. 1) and Professor Padfield (Ref. 2) cover in detail the early history of rotorcraft flight dynamics, handling qualities, and stability and control in the period prior to the 1970s and up to their Nikolsky presentations. I highly recommend these outstanding lectures to the reader along with my coverage which starts in the 1970s.

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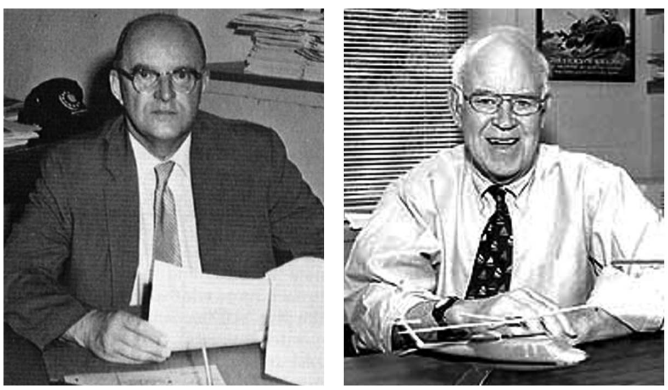
[1]Currently Tischler Aeronautics. Based on the 40th Nikolsky Honorary Lecture presented at the Vertical Flight Society 76th Annual Forum & Technology Display, Virtual, September 30, 2020. Manuscript received June 2022; accepted June 2022.

DOI: 10.4050/JAHS.67.041001

Fig. 1. Flight control technology advancements and challenges for future rotorcraft.



(a) Professor Alexander A. Nikolsky, Princeton University

(b) Professor Howard C. "Pat" Curtiss, Jr., Princeton University, PhD student of Prof. Nikolsky, 20th Nikolsky Honorary Lecture, 2000

Fig. 2. Professors A. A. Nikolsky and H.C. Curtiss, Jr., Princeton University.

Organization of Nikolsky Lecture journal paper

This Nikolsky Honorary Lecture journal paper will begin with a review of the key rotorcraft flight control drivers and technologies. Then, advancements in four key technical subdisciplines of rotorcraft flight control will be reviewed, covering the period starting with the 1970s: (1) Handling-qualities specification development, (2) physics-based simulation, (3) system identification, and (4) flight control systems.

The following section will consider how the integrated application of these four subdisciplines in flight control was central to the success of two recent rotorcraft development programs. The following major section will consider the progress and challenges of flight control technology for future rotorcraft: future vertical lift (FVL), unmanned aerial systems (UAS), and electric vertical take-off and landing (eVTOL). Then, the lecture paper will summarize future rotorcraft flight control challenges and relevant technology solutions. Finally, I will highlight my key lessons learned as a career-long flight control engineer/researcher, group leader, and senior technologist, and acknowledge the role of mentors throughout my career.

Four Key Flight Control Drivers for Rotorcraft

There are many flight control drivers, and this section summarizes the top four that are key to both the legacy and future fleet:

1) Inherently high-order dynamic systems require *high-order linear models* spanning the flight envelope for flight control design, and a *high-order nonlinear model* for flight simulation.

2) Rotorcraft are inherently multidisciplinary—i.e. problems are seldom solved without considering the interactions between different systems. To solve rotorcraft problems, engineers must also have strong multidisciplinary expertise.

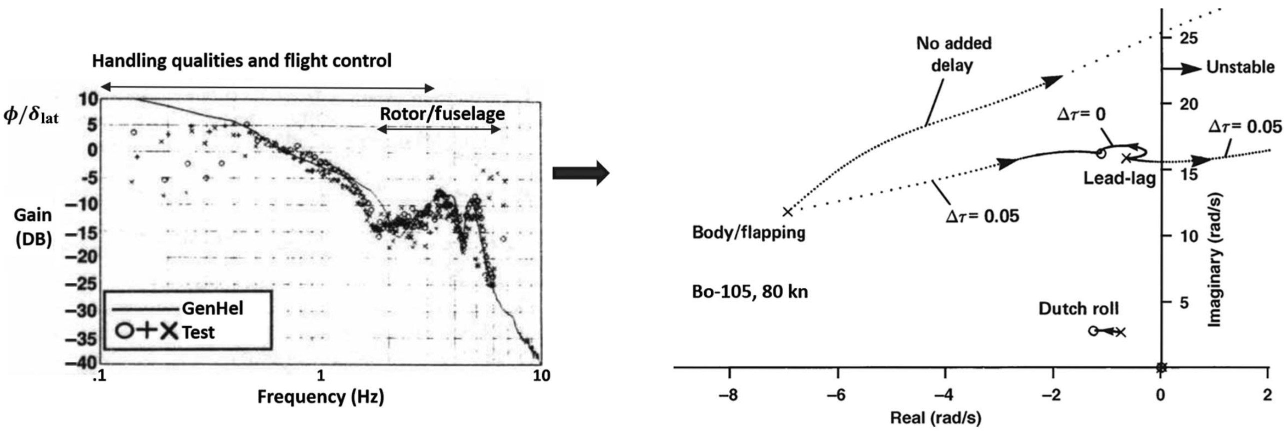
3) All hovering vehicles are unstable and very susceptible to gusts.

4) The presence of large equivalent time delays ($\tau_e = 70$ –100 ms) for the rotors to generate the necessary forces and moments for maneuvering the aircraft. These delays are dominated by the rotor flap (or Revolutions Per Minute, RPM) response.

The Bode plot of Fig. 3(a) shows flight-test and simulation data from Sikorsky for the CH-53E helicopter in Kaplita et al. (Ref. 3). The overlap in the dynamic range of handling qualities and flight control responses with the higher frequency dynamics of the rotor and fuselage structure is shown. This overlap translates to a strong coupling of the dynamic modes of these systems with angular rate feedback as illustrated in Fig. 3(b) for the Bo-105 helicopter in Tischler (Ref. 4). Even the bare airframe flap/fuselage dynamic response without feedback is highly coupled (second-order response). When a modest feedback system with an additional delay of $\Delta\tau = 50$ ms is added, which is characteristic of the digital system elements, the coupled lead–lag mode can become destabilized as shown in the figure as was seen on the Comanche program (Ref. 5). So, the higher order dynamics must be considered in the simulation (nonlinear and higher order linear) model and flight control system design. Accurate models and an integrated, transparent development process are essential to overcome these four key flight control drivers.

Key Advancements in Rotorcraft Flight Control Technology (Since the 1970s)

Four key advancements in rotorcraft flight control technology in the past 50 years are as follows: (1) Handling-qualities specification development, (2) physics-based simulation, (3) system identification, and (4) flight control systems.



(a) Roll response to lateral stick showing proximity of modes (CH-53E TEP program; Ref. 3)

(b) Roll-rate feedback and modest time delays couples rigid body and rotor modes (Ref. 4)

Fig. 3. Overlap and coupling of dynamics modes of rotorcraft.

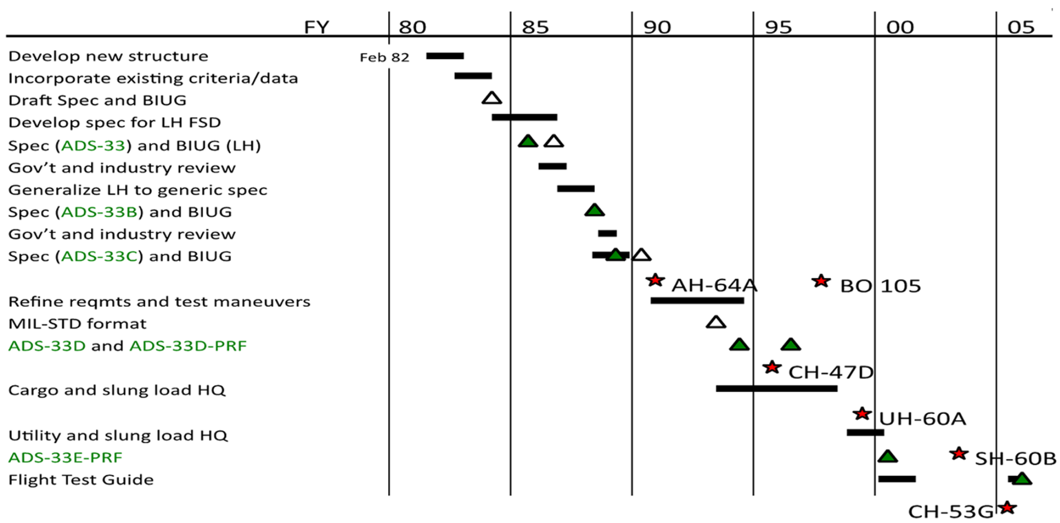
These advancements have been achieved through a sustained focus by the flight control community over the past five decades. The first area is handling-qualities specification development. A comprehensive history and perspective of rotorcraft handling qualities is given in the 32nd Nikolsky Honorary Lecture journal paper by Professor Gareth D. Padfield (Ref. 2).

Handling-qualities specification development

An excellent history of the development of the U.S. Army's modern aeronautical design (handling qualities) standard ADS-33 is given by Blanken et al. (Ref. 6). A timeline and key milestones in the development of this design standard are reproduced from Ref. 6 as Fig. 4(a). The timeline covers the 25-year development from the start (1982) until the completion of ADS-33E-PRF (2000) and the associated flight-test guide (2008).

The development of ADS-33 was a long-term effort, requiring dedicated research, and funding that resulted in a breakthrough for rotorcraft. This specification was a major update and departure from the legacy time-domain specification for helicopters, MIL-H-8501A, published in 1961 (Ref. 7). The endeavor to develop the new rotorcraft specification came on the heels of the fixed-wing update, MIL-F-8785C, released in 1980 (Ref. 8). This new fixed-wing update was the first to make extensive use of a frequency-domain characterization of the vehicle's dynamic response. Frequency responses obtained initially from analytical design models and then identified from flight-test data were shown to provide a much more robust characterization of the vehicle response, especially for aircraft with feedback flight control systems. A low-order equivalent system (LOES) approach was developed, which obtained the key response metrics of complex aircraft control systems in terms of classical transfer−function representations. In the development of ADS-33, the handling-qualities metrics were obtained directly from the frequency response plots. Verification of specification requirements in the frequency domain was revolutionary for rotorcraft; previously, under MIL-STD-8501A, all verification was performed in the time domain. As flight data for a variety of aircraft and flight control systems were collected, the results showed that rotorcraft with flight control augmentation systems were *better characterized in the frequency domain*. These early efforts also demonstrated that frequency response flight tests could be performed safely, efficiently, and at equal or less cost than traditional time-domain tests. Another innovation in ADS-33 was the inclusion of Mission Task Elements (MTEs) that defined mission-representative maneuvers and collected *assigned pilot handling qualities ratings* (HQRs) using the Cooper–Harper scale (Ref. 9) to crosscheck with the *predicted ratings*—the latter as obtained from the frequency response analysis against quantitative specification requirements. As described in detail by Blanken et al. (Ref. 6), the completed and final version of ADS-33E-PRF took shape over a 20-year period with its final release in 2000. Key leaders in this extensive effort were David Key, Christopher Blanken, Roger Hoh, and David Mitchell. Many research partners from the U.S. industry and international collaborators contributed significantly to the database for the development of the new specification. Some of these collaborative programs are shown in Fig. 4(b). Follow-on activities indicated in Fig. 4(a) included the incorporation of additional test data for cargo rotorcraft. Also, comprehensive flight-test guides were developed to explain the proper conduct of the needed flight tests and interpretation of the results against the ADS-33 handling-qualities criteria. The first test guide was developed at the DLR by Ockier (Ref. 10) and a second test guide by the U.S Army by Blanken et al. (Ref. 11).

While the new fixed-wing spec 8785C had adopted the frequency-domain characterization successfully, there was initial concern about the applicability and safety of this approach for rotorcraft. Frequency sweeps and frequency-domain system identification had been advanced at Systems Technology Inc. (STI) on fixed-wing aircraft (Ref. 12). These methods were first conducted in flight tests on rotorcraft using the XV-15 Tilt-rotor aircraft in Fig. 5 at the Ames Research Center by Tischler et al. and initially published in 1983 (Ref. 13). The XV-15 tests were followed by a major flight-test campaign at the U. S. Army's Aviation Engineering Flight Activity (AEFA) test center on the Bell 214 ST in 1987 by Tischler et al. (Ref. 14) and illustrated in Fig. 6. The test aircraft (Fig. 6(a)) and typical piloted frequency-sweep data for the hover flight condition are shown in Fig. 6(b). Chirp-Z (an advanced fast Fourier transform) analysis of the data provided the high-quality input–output frequency response and associated coherence (Fig. 6(c)). The high coherence $\gamma^2_{\delta_{\mathrm{LAT}}p}$ proved that the overall closed-loop aircraft response, including the feedback control, was highly linear. Also seen in Fig. 6(c) is that the response is well characterized by a lower order transfer function, analogous to the LOES development for fixed-wing aircraft. Finally, as shown in Fig. 6(d), the lower order transfer-function model predicts the flight-test response well in the time domain, for typical roll maneuvers of about ±10 deg/s. These results validated the frequency-domain characterization and linear system modeling for rotorcraft. In ADS-33, the approach was taken to determine



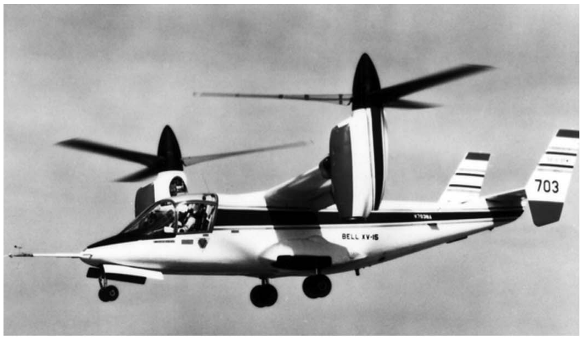
(a) Handling-qualities specification development (ADS-33E) - 1980–2000 (Ref. 6)

(b) Examples of flight and simulator tests conducted by the US (Army/NASA) and international partners

Fig. 4. ADS-33E development timeline and key associated test facilities.

the needed key handling-qualities metrics (ω_{BW}, τ_p) *directly from the attitude frequency response plots* as shown in Fig. 7. The handling-qualities bandwidth ω_{BW} is the frequency up to which the pilot (as a pure gain) can close the loop during maneuvers while maintaining 45 deg of phase margin or 6 dB gain margin. The phase delay τ_p characterizes the rate of phase roll-off beyond the -180 deg phase frequency and correlates well with the equivalent time delay τ_e, as obtained using a LOES transfer-function fit. The XV-15 and Bell 214 ST flight-test campaigns validated the safety and efficacy of the frequency-domain characterization of rotorcraft. A frequency-sweep flight-test manual was developed by Williams et al. (Ref. 15), detailing the instrumentation and flight-test procedures as based on a flight test of the OH-58D helicopter at AEFA.

The next key advancement in the development of modern handling-qualities criteria was gaining an understanding of the role of time delays for rotorcraft handling qualities, especially for fly-by-wire (FBW) control systems (Fig. 8). This was well understood in the fixed-wing community with John Hodgkinson being the leading researcher in this field (Ref. 16). As seen in Fig. 8(a), the fixed-wing data showed a significant degradation in the Cooper–Harper HQRs for equivalent time delays exceeding $\tau_e > 120$ ms. The advanced digital optical control system (ADOCS) developed by Boeing Helicopters on the UH-60 was the first production-representative FBW/fly-by-light helicopter. While this demonstration aircraft performed well overall, rendering good HQRs (Ref. 17), it did encounter pilot-induced oscillations for high-gain tasks,



(a) Hover configuration

(b) Cruise configuration

Fig. 5. XV-15 tilt-rotor aircraft program developed frequency-domain testing and modeling methods for rotorcraft (Ref. 13).

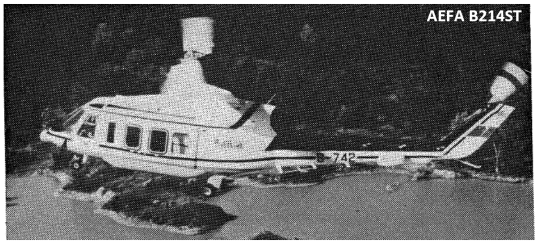
for example, in slope landings as seen in Fig. 8(b). Transfer-function identification of the closed-loop ADOCS aircraft response (i.e., LOES fit) indicated relatively large time delays of $\tau_e = 238$ ms (equivalent time delay from an exact transfer-function fit) or $\tau_p = 202$ ms (characterizes the rate of phase roll-off and correlates well with the equivalent time delay τ_e). The significant degradation in rotorcraft handling qualities for the large time delays was consistent with the fixed-wing data (Fig. 8(a)) and indicated the need to limit allowable delays in ADS-33. Parametric flight-test investigations were conducted in the United Kingdom by Houston and Horton (Ref. 18), which indicated the need for a $\tau_p \leq 200$ ms cap. Then in 1993, Pausder and Blanken (Ref. 19) conducted extensive flight tests at the DFVLR (now DLR) on the FBW Bo-105 in-flight simulator, which supported a cap of $\tau_p \leq 120$ ms for high-gain tasks, in agreement with the fixed-wing data (Fig. 8(a)). This cap was adopted in ADS-33E for target acquisition and tracking MTEs and is slightly looser than the fixed-wing specification (Ref. 8), which limits the LOES delay to $\tau_e \leq 100$ ms. Large effective time delays are a key handling-qualities risk for FBW rotorcraft, with primary contributions associated with the rotor, control system filters, and actuator rate limiting.

Another important innovation in ADS-33E was the development of a modern disturbance rejection criteria for rotorcraft. The U.S. Army developed the disturbance rejection bandwidth (DRB) criteria as obtained directly from the sensitivity function frequency response based on a frequency sweep injected into the relevant hold variable. As shown in Fig. 9(a), an automated frequency sweep is added to the sensed hold attitude (roll attitude, in this case), and the associated sensitivity function is determined as ϕ'/ϕ_d. The DRB value is defined as the -3 dB frequency of the sensitivity function (Fig. 9(b)). Early parametric flight tests were conducted on the UH-60 RASCAL by Mansur et al. (Ref. 20) to develop methods and initial DRB criteria values for Level 1 handling qualities ("satisfactory without improvement") in turbulent conditions. The value of the DRB increases with increased values of the relevant attitude hold proportional gain, in this case, the roll attitude gain. The RASCAL flight tests confirmed that increasing DRB was associated with a faster return to trim and position hold in turbulence while there is a trade-off in the overall damping ratio as the feedback gains are increased. Additional flight tests on the UH-60 showed that good handling qualities could be achieved even with very low values of DRB when the atmospheric conditions were calm as shown in Fig. 9(c); however, with turbulence and winds, the same configuration degrades to Level 2 handling qualities ("deficiencies warrant improvement") as seen in the figure. The DRB has proven to be a key flight control feedback loop design driver. Increased DRB results in improved aircraft hold performance and elicit pilot comments of "improved trimmability." The disturbance rejection criteria were included in the 2008 ADS-33 Test Guide (Ref. 11). Berger et al. (Ref. 21) worked with the industry to compile a comprehensive database for a wide range of rotorcraft that validated the DRB boundaries for attitude, velocity, and position hold performance.

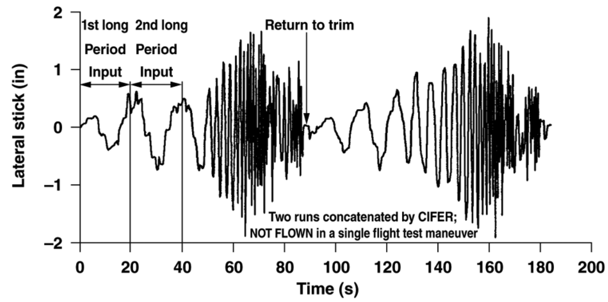
The development of ADS-33 has been a breakthrough for rotorcraft control system design, development, and procurement. Many U.S. and international rotorcraft flight control systems, including both partial and full authority control flight systems, have been designed with ADS-33 as guidance. In 2003, the NH90 was the first FBW helicopter designed to meet ADS-33 and demonstrated excellent handing qualities, including shipborne landings in high sea states, documented in Bellera and Varra (Ref. 22). ADS-33 has provided comprehensive flight control design guidance for flight-test development in both military and commercial rotorcraft programs. Even when not explicitly required in procurement, *ADS-33 provides the guidance that flight control designers need* (as reported by flight control engineers). Going forward, updates to the ADS-33E rotorcraft handling-qualities criteria will be integrated into the redesignated MIL-DTL-32703.

Physics-based simulation

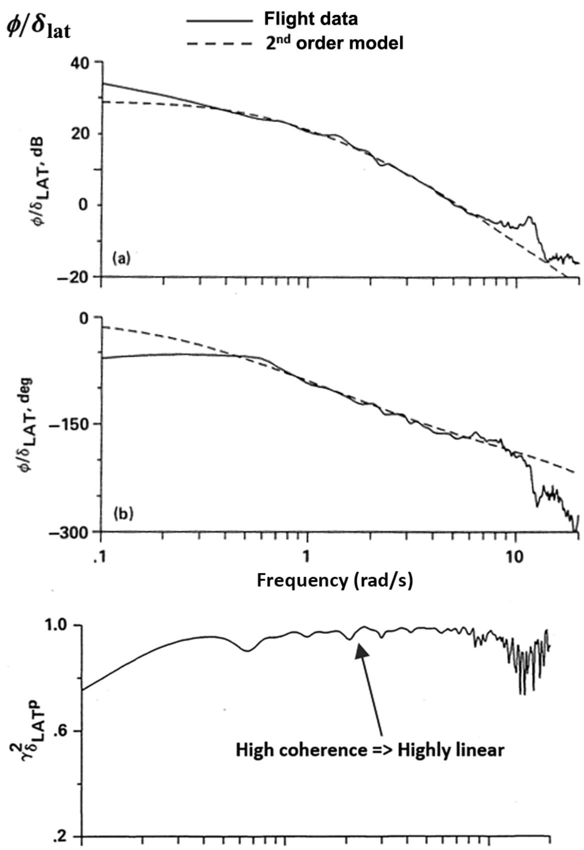
The next major advancement is in physics-based rotorcraft simulation methods for flight dynamics and control applications. An excellent reference in this area is the 20th Nikolsky Lecture journal paper by Professor Curtiss (Ref. 1). Initially, real-time simulation models for handling qualities and flight control development were based on tip-path plane methods. A pioneer in this area was Chen at NASA with his development of the ARMCOP simulation as documented in Ref. 23. This was a long-time standard for both offline and real-time piloted simulations. There were many similar tip-path plane type models developed at other institutions worldwide during this period. In the 1980s, simulation fidelity was improved with the development of blade element models as pioneered by Howlett, who developed the GenHel nonlinear simulation, at Sikorsky (Ref. 24). The blade element representation became, and is still, an industry standard for flight dynamics and control analysis. While not initially real time, as computational power increased, these simulation models were used in real-time piloted ground-based simulator studies. Validation and improvement of blade element models were achieved using system identification comparisons of the simulation model frequency responses with flight-test data, as shown in Fig. 10 for hover by Ballin and Dalang-Secretan (Ref. 25). These results were obtained using Ames-GenHel, an advancement of the original GenHel simulation. Figure 10(a) shows the piloted frequency-sweep input (δ_{lat}). The recorded piloted input signal was also used as the nonlinear simulation model input. Figure 10(b) shows the improvements in the fidelity of the roll rate frequency response (p/δ_{lat}) from the baseline simulation with advancements in the Pitt–Peters dynamic inflow model. The



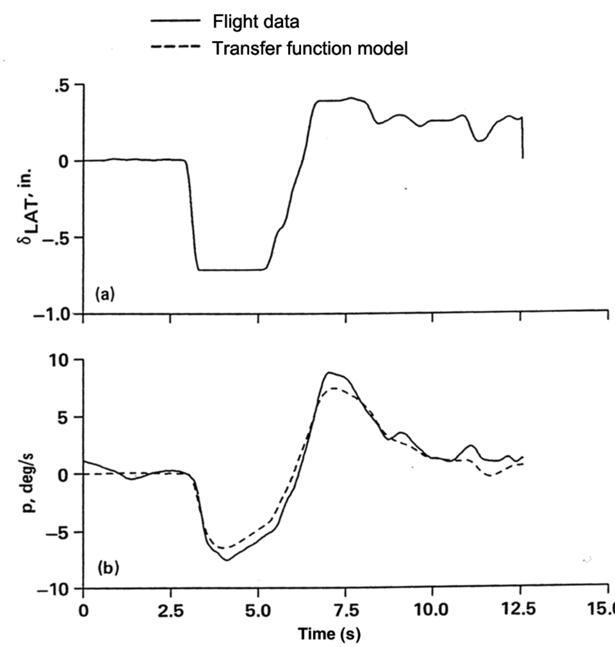
(a) B214ST flight test effort at the U.S. Army AEFA test center



(b) B214ST piloted frequency-sweep test data



(c) Frequency response and coherence determination with transfer-function identification



(d) Good agreement of time response of identified lowerorder transfer function model with flight data

Fig. 6. Validation of frequency domain testing and characterization methods for helicopters on B214ST (Ref. 14).

simulation response (p/δ_{lat}) with the Pitt–Peters rigid wake (dashed line, Fig. 10(b)) shows excellent agreement with the system identification flight response.

Initially, linearization of the blade element models using the perturbation methods could only provide a six-degree-of-freedom (DOF, "quasi-steady") linear state-space model for flight control application; however, as shown earlier in Fig. 3, the higher order rotor dynamics are critical in the flight control design process. Miller and White (Ref. 26) were the first to achieve a high-order linear time-invariant (LTI; i.e., "state-space") model extracted from a blade element nonlinear simulation (M97) for flight control design and analysis applications. Kim et al. (Ref. 27) developed the capability for higher order linear model extraction from the GenHel simulation of the UH-60 in a tool named FORECAST. Since the initial development of M97 and GenHel/FORECAST, many organizations worldwide have developed real-time blade element simulation and high-order linearization. The FLIGHTLAB commercial rotorcraft simulation model is one such widely used tool (Ref. 28).

Starting in the 1990s to the present, high-order aerodynamic representations were incorporated to further improve the fidelity of flight dynamics models. A key breakthrough by Rosen and Isser (Ref. 29), using a prescribed vortex wake model (TEMURA), demonstrated that inflow distortion with tip-path plane angular rate (Figs. 11(a) and 11(b))

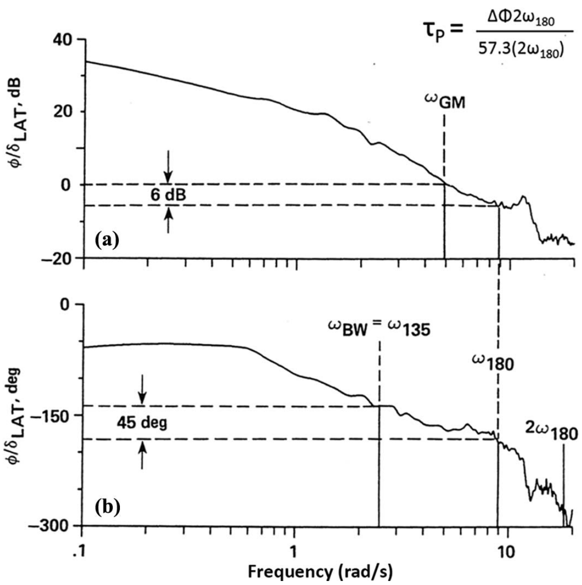
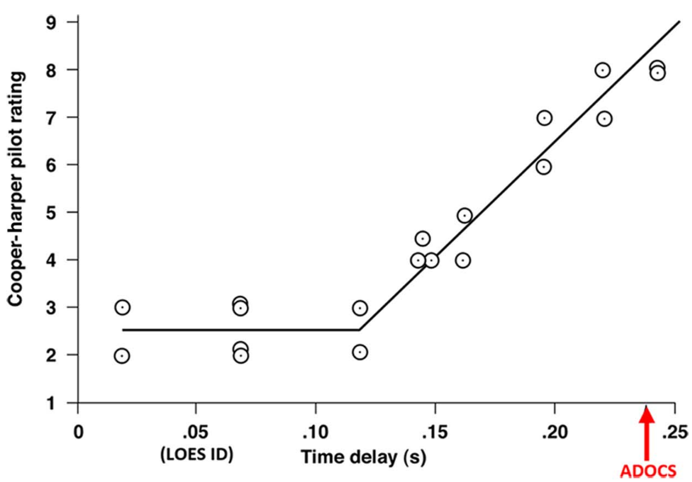
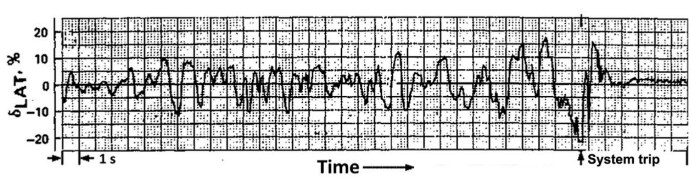


Fig. 7. ADS-33 metrics were obtained from frequency response identification of B214ST (Ref. 14).



(a) Extensive fixed-wing flight-test studies on the importance of time delay to handling qualities, F-8, NT-33 (Ref. 16)



(b) ADOCS - 1 Hz PIO in slope landing (high-gain task) (Ref. 17)

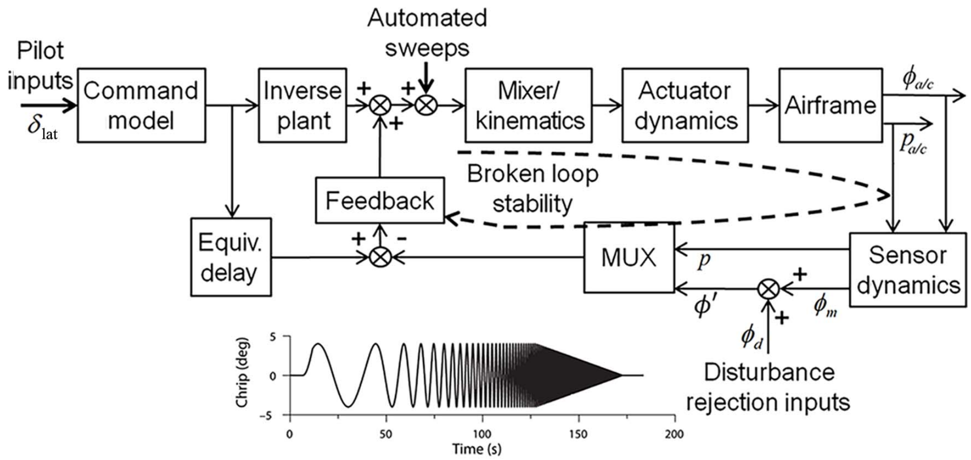
Fig. 8. Importance of time delay to rotorcraft handling qualities.

was the source of the pitch-roll cross-coupling discrepancy that had been seen in rotorcraft simulation models prior to this time. Figure 11(b) shows that the incorporation of this distortion effect provides the correct sign and magnitude of the key cross-coupling response derivative L_q for the UH-60. Tischler first proposed a simple *aerodynamic phase lag* (ψ_a) that corrected the frequency response agreement with flight data, as documented in Takahashi et al. (Ref. 30) and Mansur and Tischler (Ref. 31). In a first-of-its-kind frequency-sweep test of a full-scale rotor in the wind tunnel, Tischler et al. (Ref. 32) used system identification to accurately extract the frequency responses of the Sikorsky bearingless main rotor and then identified the ψ_a correction from the isolated rotor response (Ref. 33). In Keller and Curtiss's pioneering work (Ref. 34), they developed a simple wake distortion term K_R to augment the widely used Pitt–Peters dynamic inflow model, which also provides cross-coupling agreement comparable to the ψ_a correction, as seen in Fig. 11(c) for the UH-60 (Ref. 35).

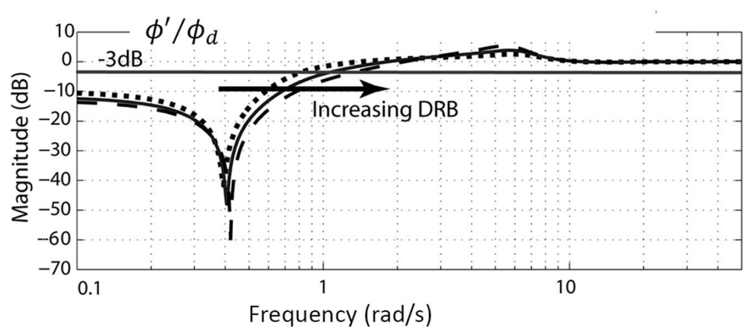
As demonstrated in this section, physics-based models have seen considerable improvement in fidelity over the past 50 years. However, there remains uncertainty in many of the primary input parameter values, such as moments of inertia, blade properties, interference effects, as well as limitations of the theory and how well the new rotorcraft configurations align with the theoretical assumptions. As a result, physics-based models inevitably require additional tuning and corrections to achieve good agreement in the frequency domain for their use in piloted simulation and flight control design. Also, the higher fidelity aerodynamics calculations (e.g., free wake and CFD) that can be incorporated into the off-line nonlinear simulation models for configuration design may not run in real time or yield an LTI representation as needed for flight control designs. Therefore, these higher fidelity aerodynamic models must be approximated as LTI systems using system identification methods for simulation and flight control applications, as discussed later (see the Future Vertical Lift section).

An approach growing in usage within the simulation community is continuous full flight envelope *stitched models*. These stitched models combine lookup tables of identified point linear identification (LTI) models and trim data from flight tests, or the linearized output of a nonlinear physics-based model. The gravity, Coriolis, and Euler equations are represented in full nonlinear form. The stitched model comes under the general category of quasi-linear parameter varying simulation (Ref. 36). The stitched model concept for aircraft simulation was first proposed in the early 1980s by Aiken (Ref. 37) and Tischler (Ref. 38). The initial applications were to create a real-time continuous quasi-nonlinear simulation model from discrete LTI point models as obtained from the linearized output of a physics-based non-real-time simulation models. This application is also demonstrated for the generic future vertical lift (FVL) simulation studies by Berger (see the Future Vertical Lift section). Later, Zivan and Tischler (Ref. 39) demonstrated the development of a full flight envelope helicopter simulation using point models of a Bell 206 as obtained from system identification of frequency-sweep flight-test data. Tischler initially set out the complete stitched model architecture and example results for fixed-wing and rotorcraft (Ref. 40).

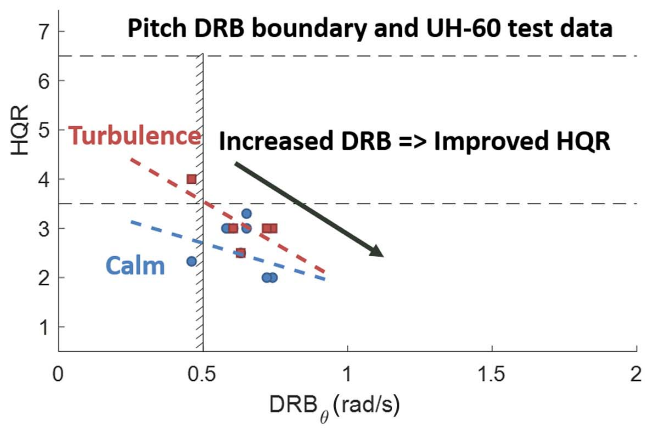
A comprehensive discussion of the theoretical background of the model stitching approach with detailed examples for both fixed-wing and rotary-wing aircraft is given by Tobias and Tischler (Ref. 41). The completed top-level architecture of the stitched model is depicted in Fig. 12(a). Lookup tables store the stability and control derivatives, trim controls, and trim states. These are interpolated as a function of instantaneous forward airspeed. Research results in Ref. 41 show that for a full-scale rotorcraft, four-point models are adequate for simulation of low-altitude flight with an additional four point models at medium altitude (6000 ft). In rotorcraft applications, linear interpolation for intermediate and higher altitudes provides an accurate solution. Finer trim data is needed, as was pointed out based on stitched model flight results of the Bell 206 (Ref. 39). Figure 12(b) from Tischler with Remple (Ref. 40) shows a comparison of the stitched model of the UH-60 based on point models and trim data from FORECAST with the GenHel nonlinear simulation model for a maneuver sequence. In this way, a back-to-back check was possible of the stitched model fidelity versus the original GenHel nonlinear simulation for a representative maneuver sequence, as can



(a) Automated frequency-sweep flight-test method to determine DRB (roll attitude hold)



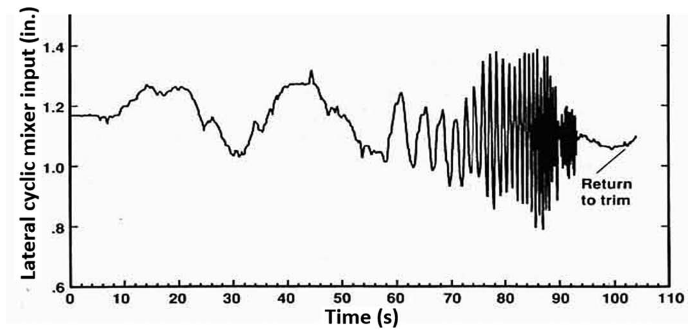
(b) Determination of roll DRB for three different control system configurations (JUH-60A RASCAL flight test) criteria



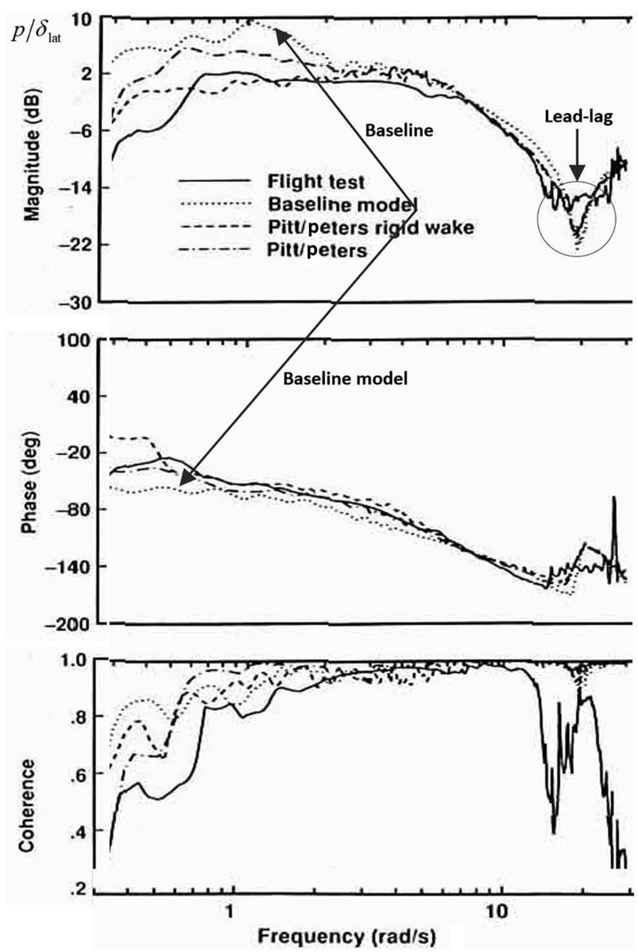
(c) UH-60 test data pitch DRB boundary and comprehensive database (Ref. 21)

Fig. 9. Test technique and validation of DRB.

be seen in the figure. The time histories of aircraft states and controls agree nearly perfectly. There is a small bias offset in the lateral stick input, but the shape of the response is well-captured. Once the stitched model is complete, the values of aircraft mass, moments of inertia, and center of gravity can be changed in the simulation model (see m_{sim} and I_{sim} in Fig. 12(a)) to accurately simulate fuel burn-off and other changes in the vehicle configuration that affect the mass characteristics. Also, the stitched model can be relinearized at many off-nominal trim points for use in control system design and robustness analysis. The U.S. Army has instantiated the stitched model architecture within a user-friendly graphical user interface in the STITCH software package (Ref. 42). Greiser and Seher-Weiß at the DLR have also been leaders in advancing the theory and application of rotorcraft stitched models (Ref. 43). The model stitching approach has seen application in the training, research, and aircraft development simulator communities. Rotorcraft training simulation developers in Canada (Refs. 44, 45) have widely adopted this stitched modeling approach, which allows them to instrument an existing rotorcraft and quickly develop a full-flight envelope real-time piloted simulation with high fidelity. Harding has implemented stitched models in the AvMC simulation facilities and trainers (unpublished). Berger et al. (Ref. 46) developed real-time stitched models of advanced coaxial and tilt-rotor configurations from high-order linear models extracted



(a) Piloted flight-test frequency sweep input δ_{lat} in hovering flight (UH-60)



(b) UH-60 blade element model correlation with system identification flight-test data (p/δ_{lat}, hover)

Fig. 10. Sikorsky–Ames GENHEL blade element flight-dynamics simulation model validation in hover (Ref. 25).

using perturbation techniques from a high-fidelity nonlinear simulation (HeliUM). While the nonlinear simulation was too complex to run in real time, fidelity was retained in this stitched model for a real-time piloted simulation.

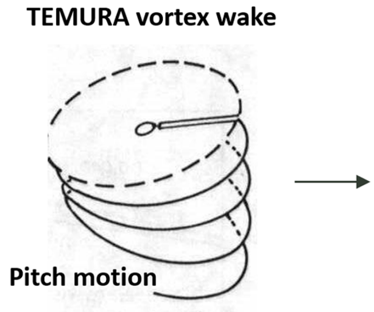
The stitched model approach is ideally suited to the simulation of small unmanned aerial vehicles (UAVs) whose vehicle characteristics rarely conform to traditional physics-based rotorcraft modeling assumptions, and whose input parameters are generally not well known or accurately measured. Further, small UAVs often go through rapid changes in design, so it is not practical to update and validate a physics-based model for each design iteration. The last consideration is the generally limited airspeed envelope of subscale UAV rotorcraft, which greatly limits the number of LTI point models and trim data points required to build up the stitched model. A flight-test example of a UAV stitched model is given later in Fig. 30 for a package delivery application. Nadell et al. (Ref. 47) developed a stitched model from flight tests of the ADAPT™ Winged Compound Helicopter Scaled Demonstrator, a 10% scale version of the Piasecki X-49A. Frequency-domain system identification was performed using the Comprehensive Identification from FrEquency Responses (CIFER®) software suite at four flight conditions and combined with the trim data using STITCH to achieve a continuous full-flight envelope simulation model to support flight control development.

Under the auspices of the NATO Research and Technology Organization (RTO), a 4-year research effort was conducted to develop modern simulation fidelity assessment and update methods based on system identification results from flight tests. There were seven simulation update methods in total, ranging from simple corrections to incorporating complex high-order aerodynamic modeling and stitched models. This NATO Research Task Group (AVT-296) was comprised of 31 contributors from 20 organizations in nine NATO countries (flags shown in Fig. 13). Contributing organizations included research labs, academic institutions, and simulation model development companies. As shown in Fig. 13, there were eight flight-test databases in total, ranging from legacy conventional helicopters to an advanced high-speed configuration and a small quadrotor UAV. A comprehensive final report by Tischler et al. (Ref. 48) provides detailed information on the research methods and results available in an unlimited distribution version. A companion lecture series was also presented in Europe and North America in 2021.

System identification

This section reviews the significant advances in rotorcraft System Identification (ID) over the past 50 years. A comprehensive reference in this area is the textbook by Tischler with Remple, published by AIAA (Ref. 40). The pioneering work in system identification was conducted in the fixed-wing community led by Iliff and Maine (Ref. 49) in the 1970s with their development of the maximum likelihood (MMLE) time-domain approach. Molusis from Sikorsky adapted the fixed-wing MMLE approach for application to rotorcraft (Ref. 50). His work stressed the unique aspects of rotor–body coupling in rotorcraft and the associated need for higher order identification model structures in agreement with Fig. 3(b). While decoupled 3-DOF model structures were adequate for fixed-wing applications, the 6-DOF and higher order structures were necessary to capture the important rotor–body coupling dynamic characteristics. Significant advances in rotorcraft system identification methods and applications were made in the 1980s, especially with work completed using rotorcraft *flight-test data* as compared to earlier work that used simulation data.

Starting in 1987, a ground-breaking international collaborative effort was led by Dr. Peter G. Hamel of the DFVLR (now DLR) under the NATO AGARD Working Group (WG-18) on *Rotorcraft System Identification*. The AGARD team was comprised of 16 team members spanning 15 research centers. The 4-year effort developed and compared identification methods and 6-DOF system identification results for three flight-test databases, resulting in a landmark research study and final report led by Hamel (Ref. 51), and a follow-on lecture series. A unique aspect of this work was the dedicated flight tests conducted specifically for this system ID working group, most extensively for the Bo-105. Figure 14 shows the three flight-test databases that were analyzed in this working group: Bo-105, Puma, and AH-64A. In each case, the flight-test databases were shared among the members, different identification approaches

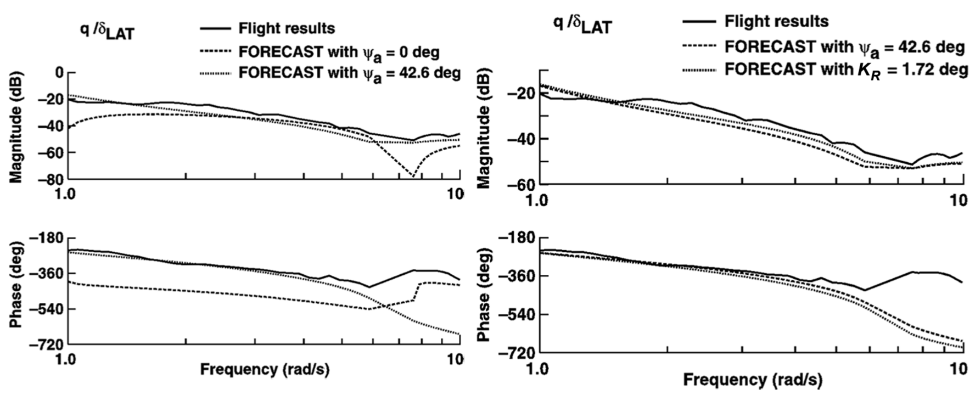


(a) Inflow distortion due to tip path plane angular rate (Ref. 29)

UH-60 results

Deriv.	Sys ID	GENHEL	TEMURA
Mq	−0.50	−0.56	−0.69
Lq	**1.02**	**−0.91**	**1.46**
Mp	**−0.31**	**0.05**	**−0.17**
Lp	−4.24	−4.56	−5.81

(b) TEMURA corrects sign error in key crosscoupling derivative (L_q) (Ref. 29)



(c) Cross-coupling frequency-response agreement with Ψ_a and K_R connections for the UH-60 (hover) (Ref. 35)

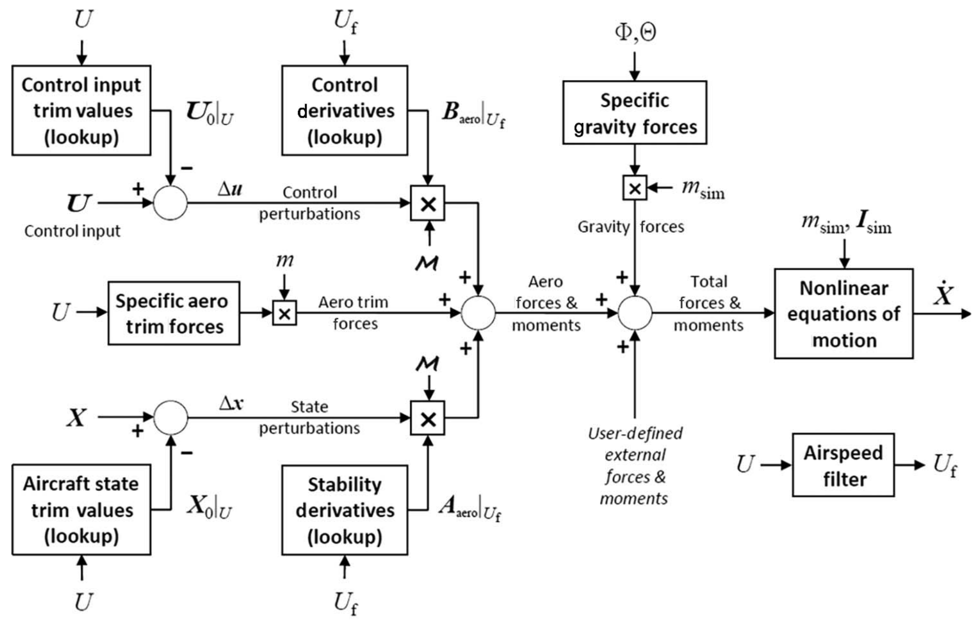
Fig. 11. Wake distortion as the source of cross-coupling sign-error discrepancy.

were applied, and the results were compared. Detailed tables of 6-DOF stability and control derivatives and the time-domain predictive accuracy were illustrated and compared for the various ID methods in use by the team members.

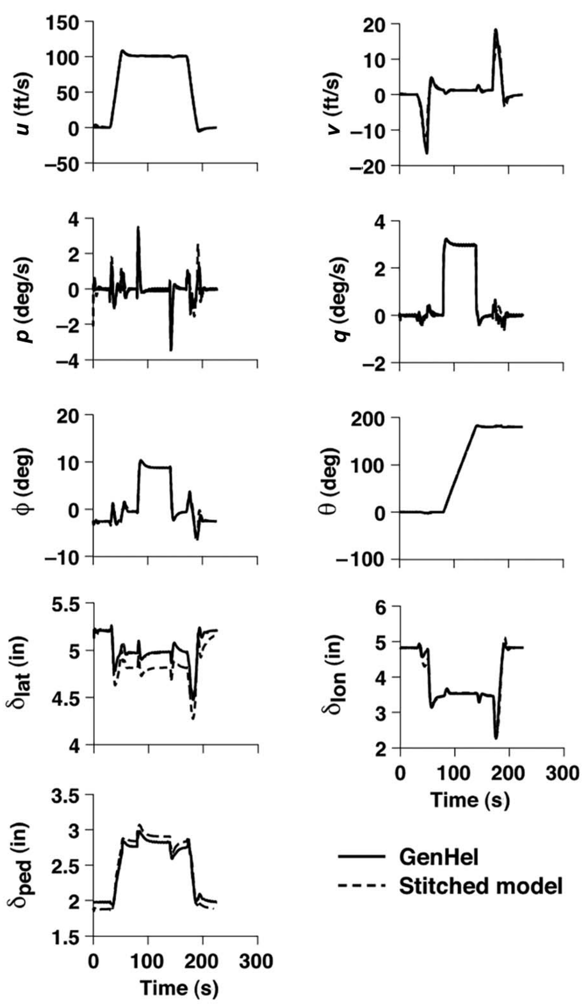
Significant advances in rotorcraft system ID were also achieved in collaborative research efforts by the United States and the Federal Republic of Germany under the bilateral memorandum of understanding (MOU) research agreement which evaluated time- and frequency-domain methods for XV-15 and Bo-105 flight databases. Key research results were presented in joint U.S./FRG publications (Refs. 52, 53). One key outcome of this effort in the United States was the development of the frequency response method for system identification as instantiated in the CIFER® software suite used for the U.S. Army work in WG-18. While the methods and the software were developed specifically for rotorcraft application, they found great use in the fixed-wing community as well (see Ref. 40). The development of this method was adapted in part from work by Tischler during his tenure (1980–1982) at STI. The STI system ID method and software which had been applied to fixed-wing aircraft were adapted and advanced by Tischler and Cauffman (Ref. 54) at the U.S. Army with several key innovations for their application to rotorcraft in the completed *frequency response identification method* and CIFER® software.

The first step in the CIFER® frequency response method is the identification of a set of nonparametric identification responses—in this case, a frequency response matrix. A key innovation was the use of the *Chirp-Z transform*, an advanced version of the FFT allowing for increased accuracy and user flexibility. Another innovation was the identification of a *multi-input/multioutput (MIMO) frequency response matrix*, which was necessary for rotorcraft applications where pilot inputs were generally present in all axes and partially correlated. Finally, *composite window averaging* allowed for multiple windows applicable to different frequency ranges to be combined using an optimization-based approach. The result was a very high-quality set of frequency responses for the MIMO rotorcraft system over a wide dynamic bandwidth.

The next step in the CIFER® method is parametric identification, first using transfer functions and then state-space models. A robust Secant optimization scheme determines a higher order parametric stability and control derivative model that simultaneously matches all of the input-to-output frequency response pairs (typically a maximum of 36 pairs in total) that comprise the frequency response matrix. The frequency range of *each frequency response pair is selected individually* based on the respective coherence function, thereby emphasizing that the data have the best accuracy. Another advancement allowed for including complex constraints among the terms of the equations of motion of a physical model as illustrated later in this paper for the X2TD high-speed coaxial rotorcraft. A key innovation adapted from Milne (Ref. 55) is a *sensitivity analysis* that determines the Cramér–Rao bounds and Insensitivities and uses these in a methodical model structure determination procedure. The result is a model with excellent parameter accuracy and reliability. The Cramér–Rao bounds of the final model provide the $\pm 1\sigma$ confidence intervals of the stability and control derivatives and are used to assess control system robustness to uncertainty (Ref. 56). The last step in the CIFER® method is time-domain verification. Here, dissimilar inputs such as steps and multisteps are used in contrast to frequency sweeps used in the identification process. This validates the *predictive accuracy* of the extracted linear models for inputs that are more representative of maneuvering type inputs and ensures that the model is not overly tuned to the frequency-sweep type input.



(a) Stitched model architecture (Ref. 41)



(b) UH-60A stitched model from linear point models (Ref. 40)

Fig. 12. Stitched full flight-envelope simulation from linear point models and trim data for UH-60.

Fig. 13. NATO AVT-296: Rotorcraft flight simulation model fidelity improvement and assessment (Ref. 48).

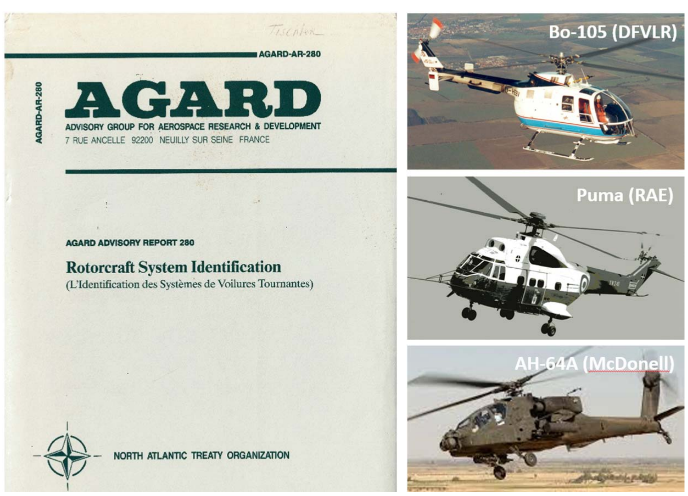


Fig. 14. NATO AGARD WG-18 "rotorcraft system ID" (Ref. 51).

There are several key advantages of the frequency response method for rotorcraft flight control applications. One key advantage is that the frequency response method is not based on time-marching simulation and so is applicable to rotorcraft, which are often dynamically unstable over their entire flight envelope. A second key advantage of the frequency response method for rotorcraft flight control applications is that the model is assessed based on its ability to track the flight response in *Bode plot form*. Since modern handling-qualities criteria and flight control methods are based on Bode plots, it is critical that the model tracks the frequency responses best in this form. Then, there is a close transfer of the flight control design characteristics to flight with a minimum of flight tuning.

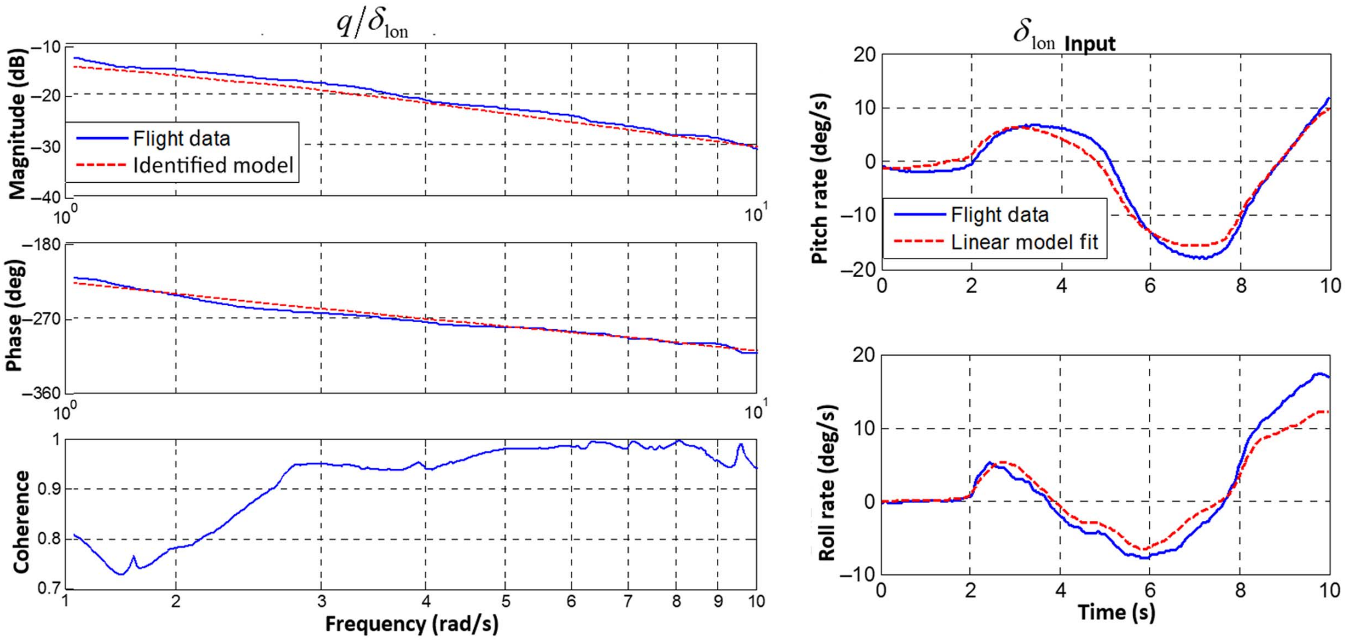
CIFER® was initially developed with a user-friendly graphical user interface and later a command-line interface, which could be called from any MATLAB® script, thereby automating the identification process. Initial distribution of the software began in 1992 with user sites now worldwide. CIFER® is the only commercial system ID tool using the frequency response method, and there have been many short course trainings offered and a companion reference textbook by Tischler with Remple (Ref. 40) to enable technology transfer. Another system identification toolbox (FITLAB) was developed by Seher-Weiß of the DLR, which incorporates both the frequency response method and a variety of other time- and frequency-domain approaches within a single toolbox (Ref. 57).

An example of the frequency response method results from CIFER® is shown in Fig. 15 for the Armed Reconnaissance Helicopter (ARH) prototype helicopter (Ref. 58) shown in Fig 15(a). Excellent agreement in the frequency domain for the pitch rate response to longitudinal stick q/δ_{lon} is shown in Fig. 15(b) for the 6-DOF identified model and frequency response data. The very high coherence $\gamma^2_{\delta_{\text{lon}}q} \geq 0.6$ indicates a high degree of linearity and a high signal-to-noise ratio in the frequency range of interest for control (1–10 rad/s). The excellent agreement of the identified 6-DOF bare-airframe model with the flight data in the frequency domain leads to a similar excellent agreement of the verification response for a longitudinal stick input in the time domain. It is important to note that the time-domain verification inputs are associated with large maneuvering of the order of 30 deg/s peak-to-peak pitch rate response (on-axis) and 20 deg/s peak-to-peak roll rate response (off-axis). As can be seen, the linear model tracks the flight-test data extremely well. In this case, the coupling between the rotor and the fuselage was not severe, so the rotor dynamics could be well-approximated in quasi-steady form with a simple time delay representation of the rotor dynamics. Then, the overall identification model structure was 6-DOF with dynamic coupling among the four control axes. Figure 15(c) shows the validation of the flight control system model (Simulink®) and flight-test data. The excellent agreement indicates accurate instantiation of the real-time control laws in the flight computer.

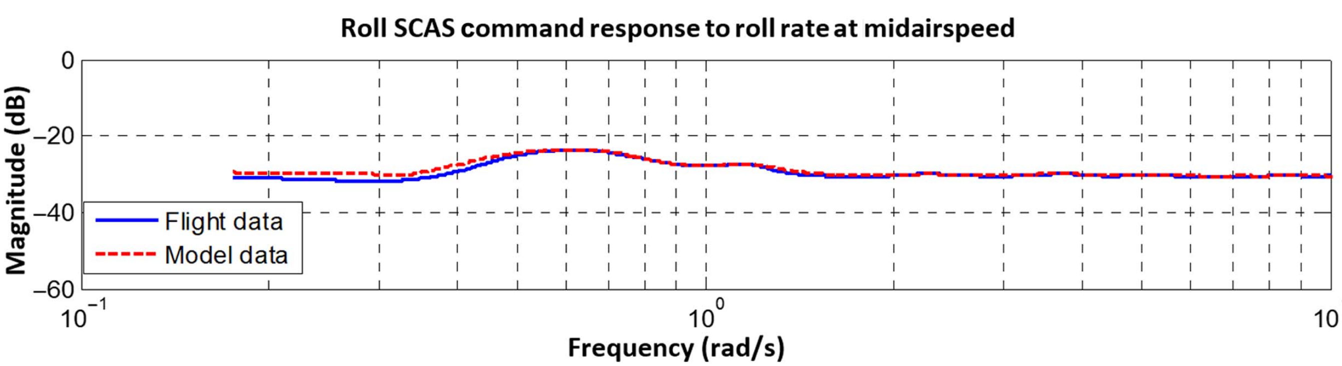
Modern rotorcraft with higher effective hinge offsets, reduced lead–lag damping, and low roll inertia exhibit a strong dynamic coupling between the roll/flap and the lead–lag modes as was indicated earlier in Fig. 3(b). Shown in Fig. 16 is the roll rate-to-lateral stick frequency response for the Bo-105 at 80 kt (same response as shown in Fig. 3(b)). The 6-DOF quasi-steady model structure that was used in the previous example (Fig. 15(b)) cannot capture the key coupled fuselage/rotor characteristics that are important for flight control feedback as can be seen in the short, a dotted line in the frequency range of 10–20 rad/s. Rather, a higher order *hybrid identification model structure* was initially proposed by Tischler and Cauffman (Ref. 54) to include the coupled rotor regressive-flap/regressive lead–lag/fuselage dynamics demonstrated using the Bo-105 flight-test data. As can be seen in Fig. 16, this higher order model accurately captures the frequency response for the key on-axis coupling response p/δ_{lat} over a broad frequency bandwidth. Tischler and Tomashofski (Ref. 59) added rotor coning-inflow, engine dynamics, and generalized the implementation for the full airspeed envelope. The full hybrid identification model structure is presented in Tischler with Remple (Ref. 40).

The significant advances in rotorcraft system identification of the past nearly 40 years have provided truth models for validation and update of physics-based simulation models, as well as highly accurate flight control design models. In many cases, the identified models replace the physics-based models once system identification flight-testing and analysis can be completed. Throughout this paper, a common theme is that system identification provides a life cycle and cost-saving tool for flight control systems and simulator development of modern military and civil rotorcraft. The system ID truth models ensure an accurate transfer of the flight control design to flight without the extensive iterative approach that led to high costs in the development of early FBW systems.

(a) ARH prototype aircraft



(b) Bare-airframe model identification and verification



(c) Control system model validation

Fig. 15. System ID for ARH FCS development in hover (Ref. 58).

Flight control systems

The next major flight control technology advancement in the past 50 years has been in the development of flight control system architectures and associated design methods. Good references in these areas with technical and historical perspectives are the textbook by Tischler et al. (Ref. 56), compendia of flight control case studies by Tischler, Editor (Ref. 60), and a compendium of FBW case studies and best practices by Moorhouse, Editor (Ref. 61). As in the other areas of advancements covered herein, once again the fixed-wing community-led advancements in FBW flight control technologies. NASA's digital F-8 was the first fixed-wing research aircraft with a full authority FBW flight control system. The *first production digital FBW combat aircraft* was the McDonnell F/A-18, with the first flight in 1978. At about the

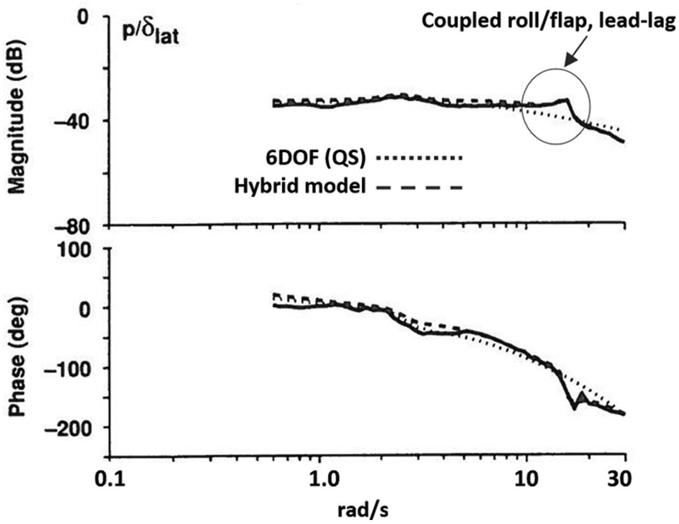


Fig. 16. Bo-105 higher order rotor/fuselage model identification, 80 kt (Ref. 54).

same time, Boeing Helicopters was developing a prototype demonstrator of a heavy-lift helicopter (HLH) based on their Model 347 tandem rotor helicopter as documented by Davis et al. (Ref. 62). This program was a key rotorcraft flight control technology breakthrough: the HLH demonstrator was the *first digital FBW* rotorcraft without a mechanical backup; the demonstrator aircraft incorporated advanced augmentation modes and active slung-load stabilization that used feedback to the primary control system as well as an innovative system of active arms that directly moved the cables. The U.S. Army Advanced Rotorcraft Technology Integration Program (ARTI, 1983–1986) further advanced the state of the art in rotorcraft flight control, with control and display augmentation modes, side-stick piloted inceptors, and two flight-test demonstrators by Boeing Helicopters (Ref. 63) and Bell Helicopter (Ref. 64).

Following the above efforts, a major technology breakthrough was the Boeing ADOCS demonstrator (1980s) based on a UH-60 helicopter as led by Glusman et al. (Refs. 65, 66). The ADOCS demonstrator shown in Fig. 17(a) was the *first production representative* FBW/fly-by-light demonstrator. The complete implementation of an explicit model following (EMF) architecture depicted for the pitch axis in Fig. 17(b) was a key aspect of the ADOCS system (Ref. 67). The EMF control system proved to be an important enabler of the then recently released ADS-33 requirements on response types. The EMF architecture, as compared to a classical Proportion/Integral/Derivative (PID) controller, provided a "two-degree-of-freedom (2-DOF) architecture." In the 2-DOF EMF concept, the feedback characteristics, associated stability margins, and gust rejection characteristics are designed independently of the response to pilot inputs—the latter contained within the command model. This allows for significant simplification and transparency of the design and development process. Other important aspects of the ADOCS system were a production representative quad-redundant fly-by-light system with no mechanical backup, advanced pilot inceptors with unique trim, and pilot-selectable outer-loop modes. The EMF architecture and FBW technologies, proven on the ADOCS demonstrator and further advanced on many production aircraft such as the NH-90 (Ref. 22) and S-92 (Ref. 68), have been widely adopted on modern rotorcraft.

Another major flight control advance in the past 50 years has been the development of algorithms and software tools for *multiobjective parametric optimization*-based design (Ref 56). The three key features of this approach are as follows:

1) User-selected control system architecture and associated design parameters

2) User-selected design specifications are given in the physical units of the requirements (e.g., required ADS-33 bandwidth and maximum allowable phase delay in rad/s and seconds(s), respectively).

3) Vector optimization process varies the design parameters until *all of the specifications* are met with the minimum use of the actuators and therefore, minimizes overdesign—referred to as the *Pareto-optimum design.*

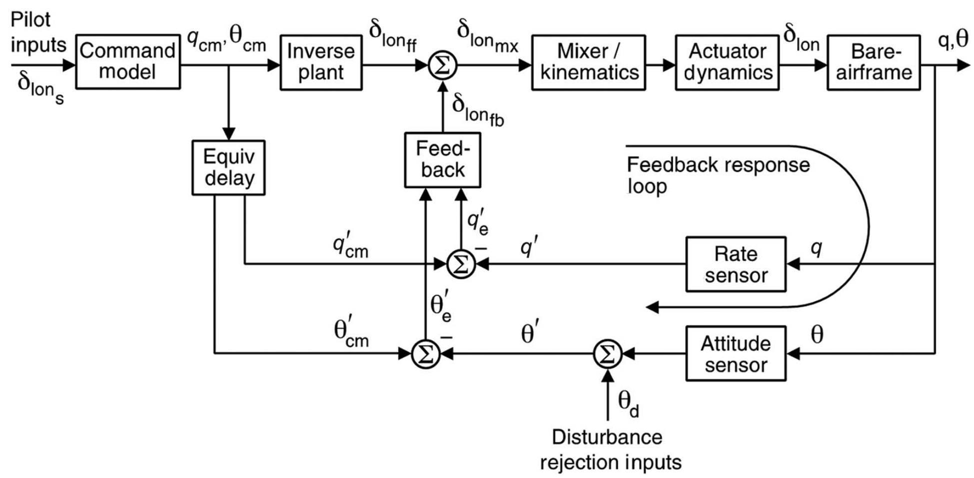
The multiobjective parametric optimization approach was initially proposed in Europe by Kreisselmeier and Steinhauser (DFVLR) (Ref. 69) and illustrated for a fixed-wing flight control design study (Ref. 70). The authors point out that designer efforts are almost entirely based on the selection of the design specifications and associated boundaries—as they should be. The resulting design process is "specification driven," rather than control theory driven. This method was instantiated in the associated Multi-Objective Parameter Synthesis (MOPS) software tool used to design the Eurofighter flight control system. In the United States, the initial development of this design approach and software involved collaborations among UC Berkeley, Lawrence Livermore National Laboratory, and the U.S. Army. This was followed by collaborations of the U.S. Army with the University of Maryland and Cal Poly San Luis Obispo, eventually resulting in the CONtrol Designer's Unified InTerface (CONDUIT® software suite), which was initially released in 1999 (Ref. 71).

A key innovation of CONDUIT® was that it was an integrated "one stop shop," providing comprehensive libraries of validated design specifications for rotorcraft and fixed-wing aircraft [ADS-33E (rotorcraft handling qualities), MIL-STD-1797B (fixed-wing handling qualities), SAE-AS94900 (flight control requirements); see Ref. 56 for more background on these specifications]. The user rapidly sets up the control system design problem, with their desired system architecture (e.g., classical, EMF, LQR, etc.) and associated design parameters in Simulink®, and then refers to the "picture book" libraries of design requirements to select the relevant specifications.

A second major innovation in CONDUIT® was that all design scoring and weighting were done *directly from the geometry of the specification boundaries*. As such, an analysis point lying anywhere on the Level 1 boundary would be scored as $f_i = 1$ for that specification (i). A design on the Level 2 boundary would be scored as a $f_i = 2$ for that specification. Designs lying at the midpoint between the Level 1 and Level 2 boundaries would be scored $f_i = 1.5$ (and etcetera for all analysis results) as determined by the "distance algorithm." This eliminates all weighting and scoring responsibilities by the user and normalizes all requirements with predicted HQRs as they are in the handling-qualities literature. The result is a *vector* of specification scores $\boldsymbol{f}$. CONDUIT® design is appropriately focused entirely on the selection of the appropriate control system architecture and design parameters as well as the design specifications and associated boundaries, rather than the details of a particular control theory. The CONDUIT® design algorithm uses a vector optimization algorithm (FSQP) discussed in Tischler et al. (Ref. 56) ensuring that *all* specifications of the optimized design are in the Level 1 region and *not just a single average score*. This *Pareto optimum* design meets all of the specifications, with minimum overdesign, making the best use of the installed control authority to achieve the design requirements.

A third key innovation in CONDUIT® is *design margin optimization* (DMO). The DMO is an automated process in which the key specification boundaries are systematically tightened, and the control system is reoptimized. Each successive optimized design achieves improved

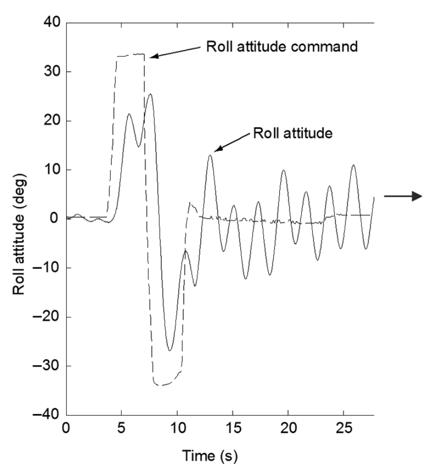
(a) Advanced digital/optical control system (ADOCS) demonstrator on a UH-60



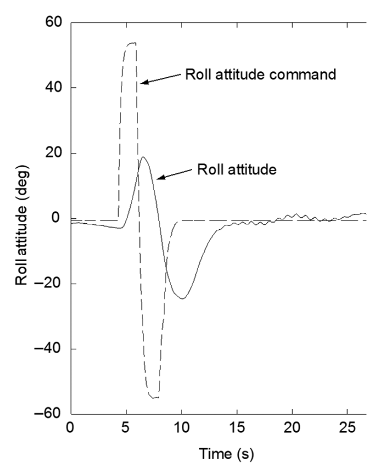
(b) Explicit Model Following (EMF) architecture

Fig. 17. ADOCS demonstrator based on a UH-60 with an EMF control system (Ref. 67).

(a) Unmanned K-MAX ("Burro")



(b) Roll response for initial FCS design based on estimated delay

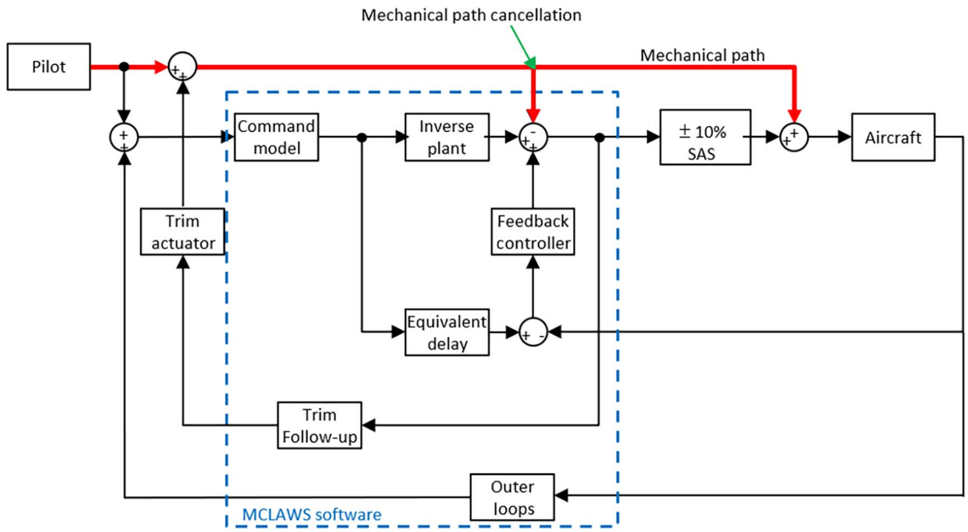


(c) Re-design based on identified delay $\tau_e = 290$ ms

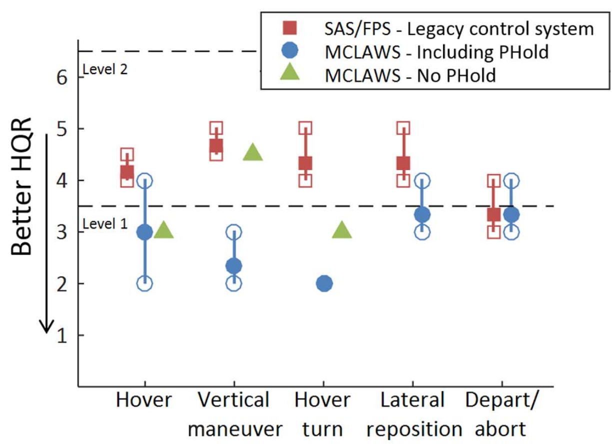
Fig. 18. Unmanned K-MAX and flight-test performance (Ref. 72).

responsiveness at the cost of increased associated control usage (within the available control authority of the aircraft) and reduced stability. The DMO process stops when one or more of the design specifications cannot be achieved. The result is a family of optimized designs or the *Pareto-optimum trade-off front*, and a few of these design points can be tested in piloted simulation and flight-tested for final selection. The combination of an accurate design model and selection of a comprehensive set of specifications will ensure that the final selected optimized design will transfer successfully to good handling qualities and control in flight.

A final key innovation in CONDUIT® is the sensitivity analysis that is conducted on an optimized design. This analysis maps out the design space to provide excellent physical insight into the specification



(a) UH-60 MCLAWS architecture



(b) Handling-qualities ratings results for MCLAWS in DVE

Fig. 19. MCLAWS concept and handling-qualities performance (Ref. 77).

trade-offs that caused the optimization process to stop at the final Pareto design point. The sensitivity analysis adopted from CIFER® assesses the robustness of solution convergence, and stability/performance degradations due to modeling uncertainty.

There have been many published applications since the development and release of CONDUIT®, including rotorcraft, fixed-wing civil and commercial aircraft, and UAVs. The initial commercial distribution of the software was in 2001, with current user sites worldwide, supported by training courses, and the comprehensive textbook by Tischler et al. (Ref. 56). An example of the use of CONDUIT® for flight control design and flight-testing of the autonomous K-MAX® for military resupply is shown in Fig. 18 in results presented by Frost et al. (Ref. 72). The unmanned K-MAX® also referred to as the Broad Area Unmanned Response Resupply (BURRO) aircraft, is shown in Fig 18(a). The bare airframe model was obtained entirely from flight tests of the aircraft and system identification point models were obtained using CIFER®. The analysis showed a fast roll instability due to the relatively small roll inertia of the aircraft. The total time delay associated with the flight control hardware (actuators and sensors) was initially estimated from manufacture specifications at about $\tau_e = 95$ ms (excludes the bare airframe). This delay was incorporated in the original CONDUIT® flight control design, and the design architecture was optimized accordingly. In the initial flight tests, the aircraft exhibited persistent roll oscillations (Fig. 18(b)). System identification of the flight-test data showed that the flight control system hardware time delays, principally the control system actuators, were much slower than expected. The overall control system hardware time delay was identified from the flight-test data as $\tau_e = 290$ ms, some $\Delta\tau_e = 200$ ms greater than the original estimate. Once the corrected value of system delay was included in the design and the optimization was updated, the aircraft flew very well as can be seen in the roll test data of Fig. 18(c). As discussed later, the BURRO system performed extremely well in fielded operations over a multiyear period, delivering essential supplies to forward operating bases in extremely hostile environments.

In addition to new aircraft with full authority flight control systems, there was a concerted research effort to implement the EMF architecture and design optimization methods for improvement of the handling qualities of the legacy *partial-authority* fleet. Typically, the legacy fleet has stability augmentation control system authority limits of about ±10%, selected to ensure pilot controllability in the case of an actuator hardover. A key research testbed was the U.S. Army EH-60L Black Hawk test bed helicopter. Under a collaborative agreement between Sikorsky and the

U.S. Army, the modern control laws (MCLAWS) concept was developed to achieve the ADS-33 requirements for the degraded visual environment (DVE) within the installed ±10% partial authority control system limits of the UH-60 legacy fleet (Ref. 73). In doing so, the incorporation of the MCLAWS control system required a software upgrade only and not a hardware upgrade. The addition of trim follow-up by Sahasrabudhe et al. (Ref. 74) using the slower trim actuators allowed an expansion of the MCLAWS flight envelope to 50 kt. Harding et al. made key advancements in the MCLAWS concept (Ref. 75). They introduced a *mechanical path canceller* and the complete inner-loop EMF architecture, achieving improved handling qualities as compared to the legacy control laws in the ground-based AH-64 simulation trials. Fujizawa made further advancements to the MCLAWS concept in a dedicated research effort over a multiyear time frame (2012–2020) (Refs. 76, 77). The completed system is shown in Fig. 19(a). The electronic mechanical path canceller is indicated in the red line of the schematic. This eliminated the input by the mechanical control system, replacing it with an EMF inner loop. The trim follow-up recenters the ±10% authority actuators for steady-state inputs. Finally, the outer loops provide velocity and position hold. This high level of stability and control augmentation is maintained as long as the stability augmentation system (SAS) actuators are not saturated on their ±10% limits. Both the UH-60 and AH-64 MCLAWS development efforts made extensive use of system ID (CIFER®) to validate the control system implementation and document the flight-test performance. Flight control optimization (CONDUIT®) was used at all stages of development to achieve satisfactorily (Level 1) predicted characteristics, while minimizing actuator usage. In-flight testing by Fujizawa (Ref. 77), Fig. 19(b) shows the UH-60 control system handling qualities for five ADS-33 MTEs in the DVE. With the addition of the MCLAWS control system including position hold (PHold), Level 1 handing qualities were achieved in the DVE for all MTEs, as compared to the generally Level 2 handling qualities for the legacy UH-60 Stability Augmentation System/Flight Path Stabilization (SAS/FPS). The MCLAWS partial authority system is a viable approach to achieving an operational capability in the DVE for the legacy fleet with only a flight control system software update.

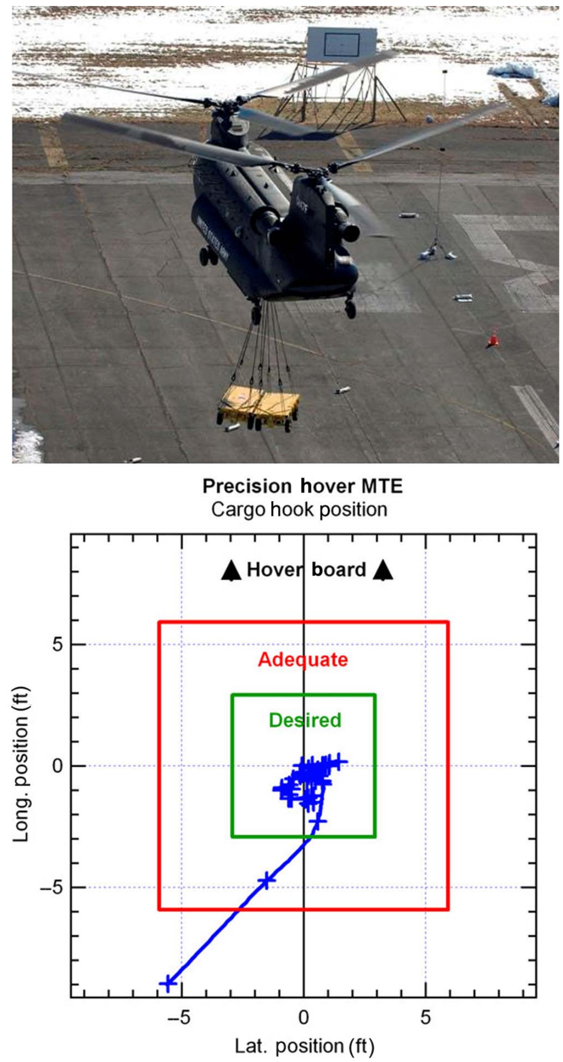
Integrated Technology Success: Example Case Studies

This section highlights how the four significant flight control advancements discussed above were integrated to achieve important new operational capabilities in two example case studies.

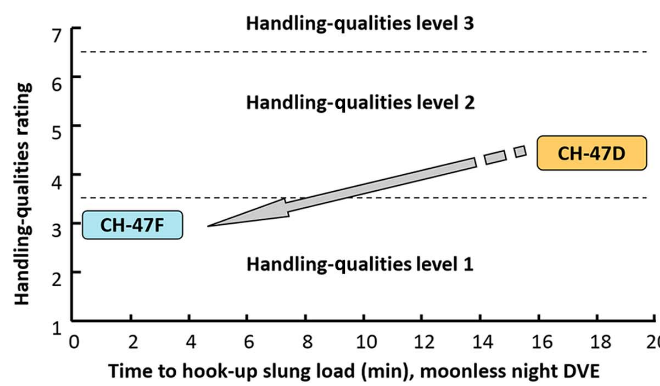
CH-47F digital advanced flight control system

Boeing Helicopters embarked on a program to upgrade the CH-47D flight control system to achieve increased reliability with a digital automatic flight control system (DAFCS) and the necessary handing-qualities characteristics for operational flight in the DVE as documented by Einthoven et al. (Ref. 78) and Irwin et al. (Ref. 79) and summarized in Fig. 20. Many improvements in the CH-47F DAFCS were achieved through leveraging advances that had been made under the RAH-66 Comanche program (Ref. 80) and Helicopter Active Control Technology (HACT) Science and Technology program (Ref. 81). Some examples of these advances were automatic speech recognition, tactile cueing, carefree maneuvering, and task-tailored control laws. A key aspect of the CH-47F DAFCS flight control was the use of an EMF architecture within the legacy partial authority actuator capabilities.

In the summary paper by Einthoven et al. (Ref. 78), Boeing Helicopters credited the integrated use of several key flight control



(a) Level 1 handling-qualities performance of CH-47F DAFCS Advanced Partial Authority Control Laws in hover MTE with external load (Ref. 79)



(b) Comparison of time-to-hookup load on a moonless night in operational tests: CH-47F DAFCS vs. CH-47D (data released by U.S. Army DAFCS program office)

Fig. 20. CH-47E DAFCS Level 1 handling qualities for hover MTE and associated dramatic improvement in load pick-up time in the DVE.

	Mass Configuration		
AFC/Maneuver	60K Mid	74K Fwd	27K Ext
Hover	2.5	3*	3
Vertical Man.	5	3*	3
Depart - Abort	2	3*	3
Lateral Repo.	3	2.5*	3

Fig. 21. CH-53K preliminary AFCS HQRs (*night UCE 2) (Ref. 83).

technologies to achieve Level 1 predicted and assigned handling qualities (Fig. 20(a)) and maintain the aggressive program goals and development schedule:

> It is clear that the advanced tools utilized on the DAFCS program, the Blade Element Simulation model, VISVEC, CIFER® and CONDUIT®, all made valuable contributions to the program and the CH-47F is a better aircraft as a result of the utility of these tools. It would also have been impossible to maintain aggressive program schedule and goals without these tools.

In a convincing operational test, the hookup time for an external load was compared for the legacy CH-47D versus the CH-47F DAFCS system on a moonless night in a DVE. The lack of visual cues made it very difficult for CH-47D pilots to maintain a position to efficiently hook up an external load, as reflected in the Level 2 HQRs, and compared to the Level 1 HQRs for the CH-47 DAFCS. The resulting load hookup time for the CH-47D was 18 min (Fig. 20(b)), about an order of magnitude longer than what was achieved for the CH-47F DAFCS with its advanced augmentation system (Fig. 20(b)). In follow-on reports, the CH-47F DAFCS was highlighted for its improved safety in theater, especially in the DVE resulting from the use of the ADS-33 methodology, advanced response types, and modern control laws.

Fly-by-wire CH-53K

The second integrated technology case study highlights the use of flight control technology advancements by Sikorsky Aircraft to achieve outstanding handling qualities and flight control characteristics of the CH-53K heavy-lift helicopter. In this aircraft program, the bare airframe math model was the GenHel blade element model augmented with a NASTRAN model of the fuselage bending modes. Existing flight-test data from the CH-53E were used to validate the physics-based math model methods, including the structural modes, as shown by Sahasrabudhe et al. (Ref. 82). The results demonstrated excellent agreement between the physics-based flight dynamics and structural model, confirming the importance of accurately modeling the fuselage bending modes and associated sensor placement to achieve a successful flight control design. Other aspects critical to the success of the CH-53K program were an FBW full-authority EMF system with advanced response types and flight control modes.

Flight control capabilities included an attitude-command/velocity-hold response type, and deceleration to hover/position hold override (DTH/PHO) with x–y control. The DTH/PHO capability allowed for a much wider usable speed range than was possible for a conventional transitional rate command (TRC) system. Initial flight control design efforts made extensive use of GenHel and CONDUIT®, especially in setting proper stability margin criteria for the CH-53K when lifting a very high load-mass ratio (Ref. 82). The in-flight simulation was used extensively for risk reduction. The U.S. Army's UH-60 RASCAL in-flight simulator was used for flight control law validation, while the NRC Bell 412 in-flight simulator was used extensively for all aspects of pilot vehicle interface and cueing. Figure 21 by Spoldi et al. (Ref. 83) shows preliminary handling-qualities data, including results for an external load as well as flights at night. These results for five MTEs show that nearly all the preliminary HQRs achieved Level 1 handling qualities, including in the DVE and heavily loaded.

These two integrated success stories show how advancements in the four key flight control technology areas of the past 50 years, as highlighted herein, have transformed rotorcraft operations from mostly daytime missions in the 1970s to safe and routine nighttime missions today.

Flight Control Technology Progress and Challenges for Future Rotorcraft

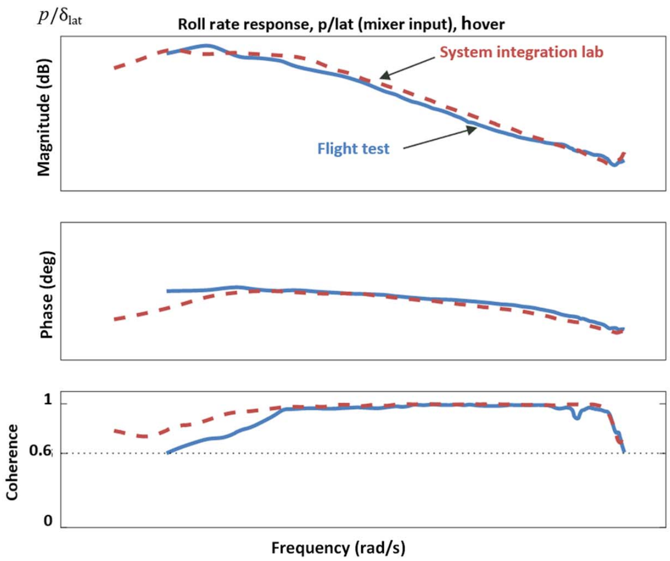
This section considers how the four key technology advancement areas have been applied and seen further progress for future rotorcraft, as well as the key remaining challenges in these technology areas.

Future vertical lift

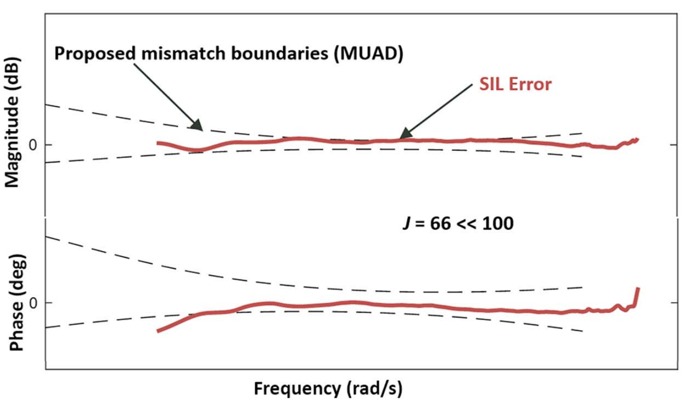
The future of advanced manned military vertical lift aircraft is embodied in the future vertical lift (FVL) concepts: the Future Long-Range Assault Aircraft (FLRAA) and the Future Attack Reconnaissance Aircraft (FARA). FVL envisions revolutionary new designs that will fly faster and further than the legacy fleet of today. FVL technology risk reduction was achieved in the development and limited flight test of the joint multirole (JMR) high-speed technology demonstrators—the V-280 tiltrotor configuration and the SB > 1 lift offset coaxial pusher configuration. If the final FVL configuration is winged, the aircraft will fly at high-speed with the stability and control characteristics of a fixed-wing configuration. Even if the configuration does not have a wing, a single main rotor or coaxial configuration at high speeds exhibits the stability and control characteristics more resembling that of a fixed-wing configuration than a hovering and low/moderate-speed rotorcraft. Dynamic inflow theory central to rotorcraft physics-based simulation for conventional rotorcraft configurations must be updated for the advanced configuration concepts. This section considers the recent advances and remaining technology challenges for manned FVL configurations.

The frequency-domain flight validation of physics-based JMR simulation models as described above was conducted for the V-280 advanced tilt-rotor configuration with results are shown by Berrigan et al. (Refs. 84, 85) in a collaborative research effort between Bell Helicopter and the U.S. Army. Figure 22 shows a comparison of the physics-based simulation model in the V-280 System Integration Lab (SIL) compared to flight tests for the hover condition. The aircraft hover configuration is shown in Fig. 22(a). In Fig. 22(b), there is a comparison of the SIL model and flight-test data for the roll rate to lateral stick (p/δ_{lat}) frequency response in hover, both obtained using frequency sweeps and system ID (CIFER®). As can be seen in the figure, there is very high coherence across a wide frequency range for both the lateral response of the SIL and flight-test results. This indicates a high signal-to-noise ratio of the dataset and, most importantly, that the input–output response is highly linear—thus, well represented by an LTI stability and control derivative model for handling

(a) V-280 in hover configuration



(b) Comparison of System Integration Lab (SIL) model and flight-test data for roll response in hover; p/δ_{lat}



(c) Model meets fidelity criteria for mismatch and integrated cost function

Fig. 22. Validation of V-280 roll response hover model and flight-test identification (data released by Bell V-280 program office).

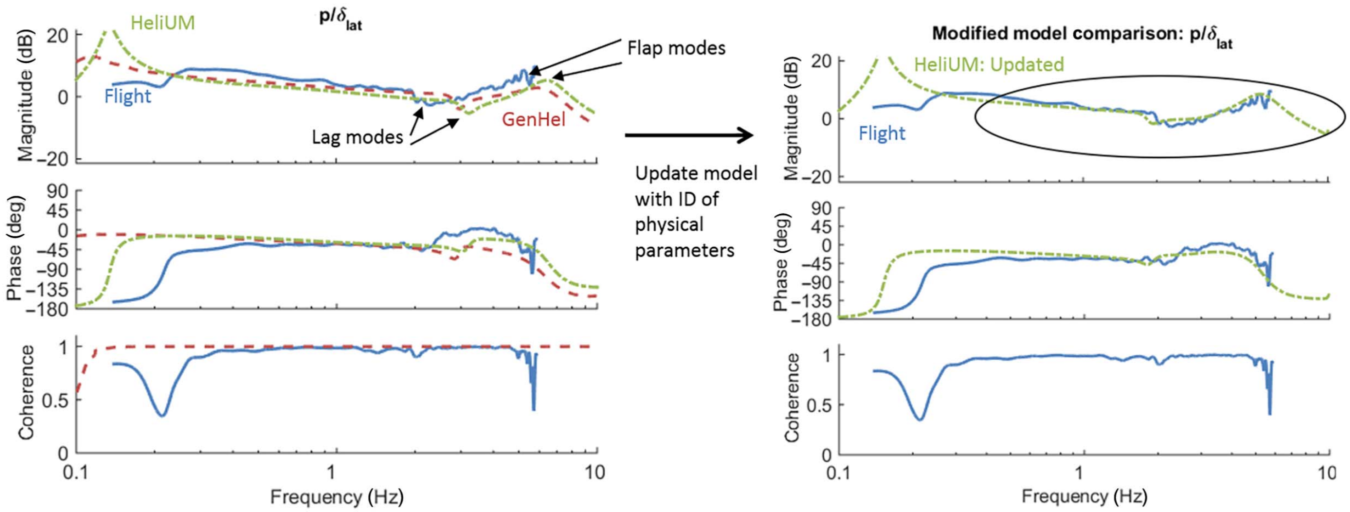
qualities and flight control analyses. These characteristics can also be seen in the XV-15 tilt-rotor technology demonstrator results of Tischler with Remple (Ref. 40). An important aspect seen in both the smaller XV-15 as well as the V-280 is the broad frequency range over which the magnitude of the response shows a *k/s* frequency response magnitude characteristic. This means that the linear model is well-represented by a quasi-steady approximation. In the case of the XV-15 and V-280 configurations, the symmetry causes the dynamics to break into two 3-DOF linear models.

As can be seen in Fig. 22(b), the agreement of the SIL and flight-test responses is excellent in both magnitude and phase. From the NATO AVT-29 Research Task Group activities (Ref. 48), the model fidelity can be assessed based on the mismatch function in comparison with the maximum unnoticeable added dynamics (MUAD) boundaries in Fig. 22(c). The figure shows that the V-280 model remains within the proposed Level D simulation boundaries for nearly the entire frequency range, indicating excellent model fidelity. The integrated cost function J shows a nearly perfect model with a value of $J = 66$, where a model with $J < 100$ is considered acceptable agreement and $J < 50$ is considered perfect agreement where the pilot cannot distinguish between the model and flight-test data. These results show that the SIL fidelity is well suited for the handling qualities and flight control design applications.

In another application of the model update methods developed under the NATO Research Task Group, a collaborative team of Sikorsky Aircraft and the U.S. Army researchers evaluated simulation fidelity and model updates for the X2 Technology Demonstrator™ (Fig. 23(a)), a high-speed coaxial rotorcraft. Figure 23(b) by Fegely et al. (Ref. 86) shows the roll rate response to lateral stick (p/δ_{lat}) for hover. Once again, the coherence is very high for the flight-test and simulation data, indicating high signal-to-noise and a strong linear input-to-output characteristic even for the relatively complex aerodynamic environment of the coaxial rotor configuration. The researchers used two distinct physics-based models in comparison with the flight-test data and considered both hover and forward flight in their work. Figure 23(b) shows the results for the hovering flight condition. Sikorsky used their GenHel simulation (Ref. 24) augmented with flexible blade dynamics, for example, as given by Johnson (Ref. 87). The U.S. Army used the HeliUM2 flexible blade model, originally developed at the University of Maryland by Celi and his colleagues (Ref. 88) and further advanced by the U.S. Army. The original comparison on the left side of Fig. 23(b) demonstrates that the two simulation models agree well *with each other.* There is, however, considerable disagreement between both models and the flight-test data, especially in the higher frequency range associated with the rotor lag and flap modes. In this collaborative work, Juhasz and co-workers (Ref. 86) from the U.S. Army used CIFER® system identification with the physical equations of the rotor dynamics to identify the key rotor parameters, such as effective hinge offset, Lock number, etc., and updated these in the HeliUM model. As seen on the right side of Fig. 23(b), the updated HeliUM model shows excellent agreement with flight responses at mid and high frequencies where there were earlier significant discrepancies.

A system identification methodology for extracting lower order three-state dynamic inflow models from higher order free wake aerodynamic models, applicable to advanced coaxial and multirotor configurations, was developed under the United States–Israel Rotorcraft Project Agreement (RPA). Frequency sweeps are injected into the aerodynamic forcing functions, and the data were collected and processed (e.g., by the U.S. Army using CIFER®) to obtain an equivalent three-state dynamic inflow model for each rotor as well as interference models. The resulting models have a Pitt–Peters *dynamic inflow form*, however with updated coefficients. The methodology development was initially conducted using free wake models of the UH-60 with the identification results compared to the well-known, closed-form, three-state Pitt–Peters dynamic inflow model of the same aircraft. The results in Rand et al. (Ref. 89) showed excellent agreement with the Pitt–Peters model, thereby validating the identification-based approach. In follow-on work under the RPA, Rand and Khromov (Ref. 90) and Hersey et al. (Ref. 91), extended their pioneering work to the generic coaxial configuration shown in Fig. 24(a). System identification was shown to be a practical and accurate method for obtaining state-space (LTI) models of dynamic inflow for

(a) X2 Technology™ demonstrator



(b) Updated sim shows considerable improvement in correlation for rotor dynamics and mid-freq. response (hover)

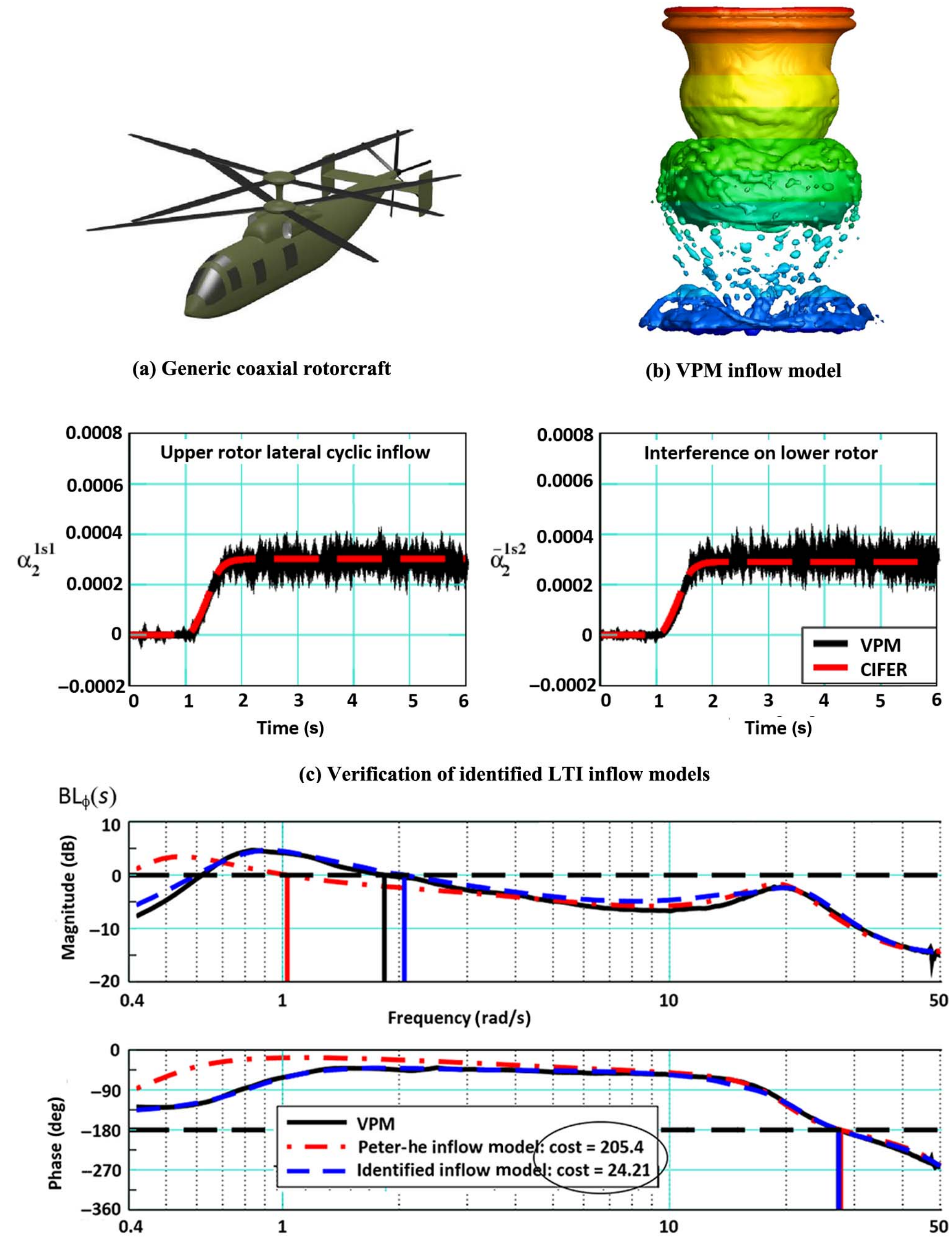
Fig. 23. Significant improvement in fidelity of physics-based model of X2TD coaxial configuration via system ID of key rotor parameters (Ref. 86).

advanced configurations, where the traditional closed-form inflow models are not available. This new capability is especially useful for coaxial and multirotor (e.g., eVTOL) configurations and configurations where aerodynamic interference between the rotors and lifting surfaces is significant to the flight dynamics characteristics.

Building on the methods developed under the RPA and the same generic coaxial configuration (Fig. 24(a)), Continuum Dynamics, Inc. (CDI) and Advanced Rotorcraft Technology, Inc. (ART), in collaboration with the U.S. Army, advanced the LTI inflow theory formulation and identification using CIFER®, as based on their respective high-order rotor wake models. Keller and his colleagues at CDI (Ref. 92) used their CHARM advanced free wake, while Gladfelter and his colleagues at ART (Ref. 93) used their first-principle-based viscous particle method (VPM). Both teams identified state-space inflow representations of the self-induced rotor inflow dynamics, angular rate wake distortion, interference coupling of the rotor-on-rotor, and rotor on empennage aerodynamics over the full flight speed envelope. LTI model validation was based on a comparison with the accurate time-marching nonlinear simulation response. Finally, both teams instantiated the identification process in their respective proprietary rotorcraft software tools. The integration of higher order aerodynamic wake models has greatly improved the flight dynamics and control analysis fidelity for future configuration concepts.

An example of this work to obtain LTI models from the higher order aerodynamic models is shown in Fig. 24(b–d) by ART for the generic coaxial rotorcraft in hover (Ref. 93). The time-marching VPM provides detailed modeling of the self-induced and interference inflow between the two coaxial rotors-on-rotor and rotor-on-fuselage/tail interference (Fig. 24(b)) but not in LTI form as needed for flight dynamics and control applications. LTI state-space inflow models were identified for each rotor using CIFER® from the VPM time simulation data, using a three-state Peters–He *inflow structure* for each rotor with mutual rotor interference, K_r angular wake distortion, and rotor-on-airframe interference. As seen in the results of Fig. 24(c), there is an excellent agreement between the dominant low-order identified linear inflow models with the VPM nonlinear aerodynamic model. While there is some high-frequency noise in the VPM data (Fig. 24(c)), the overall dynamic response characteristics (e.g., rise time and steady-state inflow) agree very well. Then, the VPM–LTI model is coupled with the nonlinear flight dynamics to achieve a flight-dynamics model of the bare-airframe generic coaxial configuration. Finally, a simplified PID feedback flight control system was designed to stabilize the bare-airframe model. The overall accuracy of the LTI model was assessed based on a comparison with the nonlinear FLIGHTLAB/VPM coupled with the same control system in a time-marching simulation ("truth model"). The critical characteristic of the integrated system is the broken-loop response (e.g., $BL_\theta(s) \equiv \delta_{\text{lon}_{\text{fb}}}/\delta_{\text{lon}_{\text{mx}}}$ for the pitch axis as shown in Fig. 17(b)), with the associated crossover frequency ω_c (where the gain curve crosses the 0 dB point) and the gain and phase stability margins.

Due to the lower inertia and associated tight roll-flap coupling, the critical axis for the coaxial configuration is in the roll. The broken-loop roll axis response $BL_\phi(s)$ is shown in Fig. 24(d) (Ref. 93). The VPM curve (solid black line) is the "truth model" obtained in the time-marching non-real-time nonlinear simulation and compared with the identified lower



(a) Generic coaxial rotorcraft **(b) VPM inflow model**

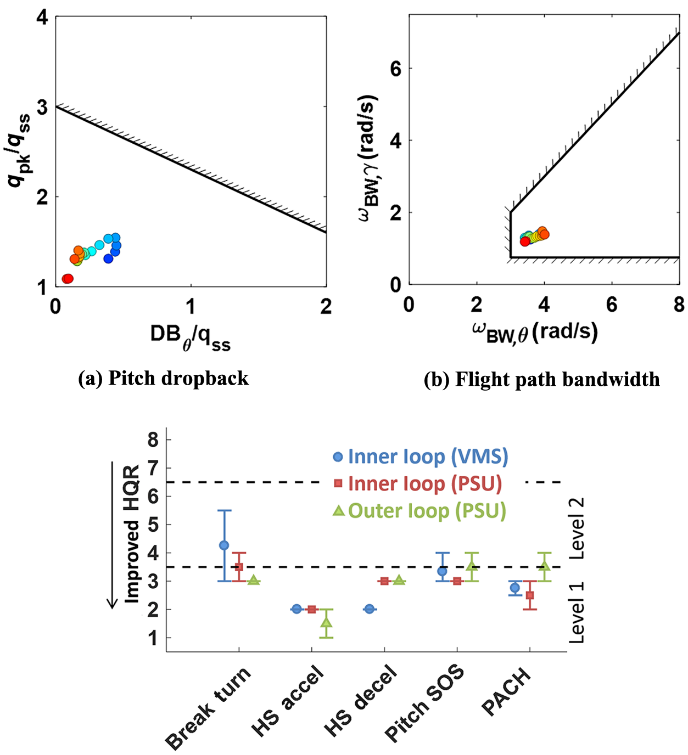
(c) Verification of identified LTI inflow models

(d) Excellent agreement of broken-loop roll response using extracted VPM LTI inflow model

Fig. 24. Extraction and validation of VPM LTI inflow model for generic coaxial configuration in hover (Ref. 93).

order LTI inflow model that now runs in real-time and can also be used for linearized flight mechanics analysis and flight control design. As can be seen in the figure, there is an excellent agreement of the VPM–LTI identified inflow model (the dashed blue line) with the nonlinear VPM truth model (black solid line). When the broken-loop response is repeated using a conventional Peters–He inflow model (the dot-dashed red line), there is a considerable mismatch relative to the VPM nonlinear truth model. This can be seen most importantly in the magnitude response, with the poor agreement of the crossover frequency for the conventional Peters–He model ($\omega_c = 1.03$ rad/s) as compared to the VPM truth model ($\omega_c = 1.83$ rad/s), and poor general agreement at lower frequencies. The underestimation of the crossover frequency will result in a predicted slow speed of response to disturbances and commands; this may result in the control system design process attempting to increase the crossover frequency and thereby reduce loop stability margins or exceed the actuator authority limits. The integrated cost function for the Peter–He inflow model broken-loop roll axis response as compared to the nonlinear VPM truth model is also very poor $J = 205.4$. Then, using the VPM–LTI identified inflow model determined from CIFER®, the broken-loop response (and associated crossover frequency) agrees very closely with the non-real-time VPM nonlinear truth model as indicated in the dashed blue line. Now the integrated cost function for the broken-loop roll-axis response is $J = 24.21$, where integrated cost $J < 50$ indicates an essentially perfect model.

Much progress has also been made on control law concepts, MTEs, and proposed handling-qualities specifications for inclusion in a future



(a) Pitch dropback **(b) Flight path bandwidth**

(c) Handling-qualities ratings for high-speed flight MTES

Fig. 25. Validated adoption of fixed-wing experience and outer loop control to the high-speed regime for generic coaxial-pusher configuration (Ref. 98).

update to ADS-33 for advanced high-speed concepts. Four new high-speed MTEs were proposed and evaluated in piloted simulation studies as part of a multiyear effort under the National Rotorcraft Technology Center. An example of these new MTEs is the proposed break turn MTE by Xin et al. (Ref. 94). This MTE was subsequently validated in flight-test studies by Bumbaugh et al. (Ref. 95) and by Berger et al. (Ref. 96). High-speed flight control law concepts and associated handling-qualities requirements for advanced rotorcraft configurations have been extensively developed in analytical design studies and ground-based piloted simulations by Berger et al. (Refs. 97, 98) with key results illustrated in Fig. 25. These studies used the same generic coaxial configuration of Fig. 24(a) and an analogous generic tiltrotor configuration; both modeled in HeliUM, and rendered in stitched full-flight envelope real-time simulations (Ref. 99). Berger's flight control and handling-qualities work (Ref. 98) made extensive use of the fixed-wing response types and lower order equivalent system (LOES) handling-qualities specifications of MIL-STD-1797 for the high-speed flight regime. In the results of Figs. 25(a) and 25(b) for the coaxial-pusher configuration, the high-speed control laws provide for Level 1 predicted handling qualities as based on the fixed-wing quantitative specifications. Then, piloted simulation assessments were conducted in the Penn State University (PSU) simulator and NASA Ames Vertical Motion Simulator for specially developed maneuvers of high-speed rotorcraft. As seen in Fig. 25(c), Level 1 pilot handling-qualities ratings were assigned when the outer loop control was included for workload reduction in airspeed and flight path control. The assigned handling qualities agreed well with the predicted handling qualities as based on the fixed-wing quantitative specifications, thereby reinforcing the use of the fixed-wing specifications for the high-speed regime of modern rotorcraft.

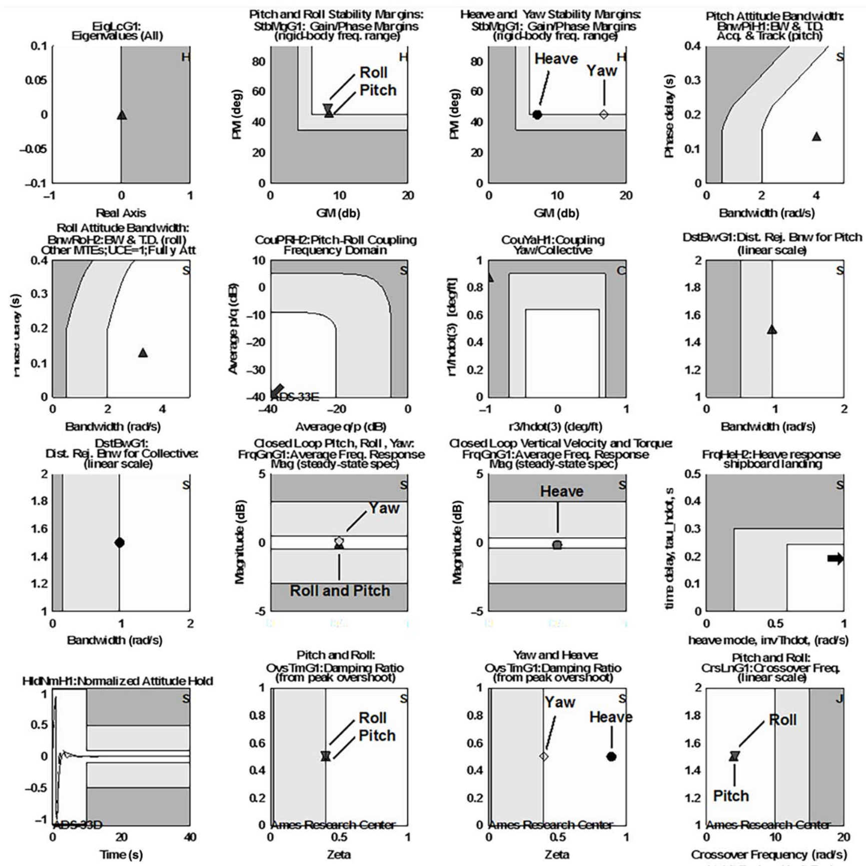
There have been several additional key flight control achievements relevant to the FVL program. Ivler et al. (Ref. 100) designed and flight-tested a rotor-state feedback system on the RASCAL FBW UH-60, which improved tracking performance in winds/turbulence for most MTEs on the order of 10–50%. Blanken et al. (Ref. 101) published proposed revisions to ADS-33E in a comprehensive report that revised some of the existing criteria based on recent flight-test experience and proposed new handling-qualities requirements, and new hover/low-speed MTEs. Many of these advancements will be included in the forthcoming revision to ADS-33 to be redesignated MIL-DTL-32703. Under the ADAPT™ program, a team of researchers led by the Piasecki Aircraft Corporation (Ref. 102) developed damage-tolerant control schemes for a unique compound rotorcraft configuration having redundant control effectors.

There are still notable challenges for FVL flight control and handling qualities. Simulation and flight-test results from the JMR program should be published in the open literature to advance the state-of-the-art of physics-based simulation modeling, flight control, and handling qualities for these modern high-speed rotorcraft configurations. As was done extensively in the development of the earlier versions of ADS-33, parametric ground-based and in-flight simulation handling-qualities research studies must also be conducted to "populate" the database needed for new specifications appropriate to the advanced high-speed configurations. Together, these flight-test and simulation results will be the basis for a future update to the handling-quality specification that will be critical to the FVL flight control development efforts. Also, a highly compressed development schedule is expected for FVL, thereby emphasizing the need to minimize the flight-test tuning of control laws. This can be achieved with the extensive use of system identification (CIFER®) to validate and update physics-based models and optimization-based design (CONDUIT®) to achieve Level 1 handling qualities with the most efficient use of the installed control power. In my view, we are perhaps at the "90% point" in the advancement of flight control technology for *conventional single main rotor* and *tandem rotor configurations*; however, we are only at the *starting gate (perhaps the 10% point)* for flight control technologies of the new FVL (and UAM) configurations.

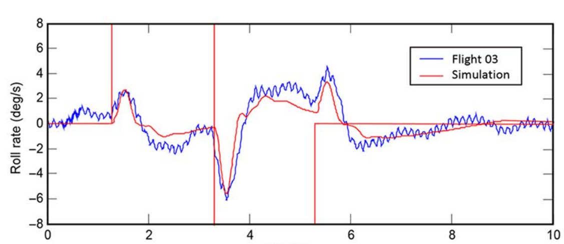
UAS/UAM based on fielded conventional helicopters

Some proposed full scale unmanned aerial systems (UAS), including for surveillance, cargo delivery, and UAM operations, are based on currently fielded conventional manned helicopter designs. This approach has the advantage that the primary effort can be spent on the development of the autonomous flight control laws rather than the simultaneous development and certification for a new build helicopter. A notable example is the Fire Scout system, a ship-based surveillance system for the U.S. Navy. The initial autonomous Fire Scout configuration (RQ-8A) was based on the Schweitzer 333 manned helicopter and proved out the UAS concept with the completion of extensive autonomous flight trials including autonomous shipboard landing. The operational MQ-8B Fire Scout variant (Fig. 26(a)) is an outgrowth of the RQ-8A with increased performance capabilities. In the Fire Scout flight control development, flight dynamics models were obtained from system identification (CIFER®) using frequency sweep inputs. Six-DOF LTI models were identified at multiple points spanning the flight envelope, as documented by Downs et al. (Ref. 103) in a collaboration between Northrop Grumman Corporation and the U.S Army. Figure 26(b) shows the results of CONDUIT® optimization of the hover control laws to meet ADS-33 (manned) requirements as the aircraft components were designed for loads typical of piloted maneuvering flight. In the figure, all of the ADS-33 requirements were met, resulting in excellent *autonomous rotorcraft* stability and control, and ship-board launch and recovery in challenging atmospheric and sea-state

(a) MQ-8B Fire Scout shipboard landing



(b) CONDUIT® optimization of control laws using system ID LTI model (hover)



(c) Good agreement of simulation model with flighttest response

Fig. 26. MQ-8B FireScout control system optimization and model validation (Ref. 103).

conditions. Control system robustness was assessed by randomly perturbing the identified stability and control derivatives based on the respective Cramér–Rao bounds (confidence intervals) and assessing the stability margins. The control system design process was repeated for the identified models at each flight condition to generate a gain schedule. A full flight envelope stitched simulation model was developed from the identified LTI point models and trim data for use in a hardware-in-the-loop facility (HIL) for full mission evaluation using key flight components of the autonomous control system. Figure 26(c) shows excellent agreement of the simulation model and flight-test results with a well-damped response for a typical maneuver, thereby validating the overall model development and control system design approach. The MQ-8B Fire Scout began initial operational deployment on U.S. Navy ships in 2011 and has been a very successful autonomous rotorcraft system based on the key flight control methodologies covered herein.

Additional progress highlights have been achieved for other UAS/UAM systems based on conventional helicopters. As mentioned briefly earlier, autonomous control laws were developed for the unmanned K-MAX® in a collaboration between the Kaman Corporation and the U.S. Army. LTI point models were identified using piloted frequency sweeps and CIFER® for hover and forward flight and at low and high altitudes, thus spanning the flight envelope. The control system was optimized at each identification condition using CONDUIT® to meet ADS-33 manned handling-qualities requirements (Ref. 104) and implemented in a gain schedule. A full flight envelope stitched simulation model was developed for system evaluation and UAS operator training. A novel aspect of the K-MAX® control system was the feedback of sling-load cable angle motion to the vehicle control system to improve the system stability. Similar improvements in sling-load stability and control system performance were achieved by Ivler et al. (Ref. 105) using cable angle feedback in their application to the RASCAL FBW UH-60 aircraft. The K-MAX® system was highly successful in 3 years of operational trials conducted in the combat theater with thousands of delivery missions achieved, as reported in Ref. 106. Additional experience with conventional manned helicopters in both UAS and UAM applications has confirmed ADS-33 as good guidance for a starting point in control system design and evaluation. A final area of considerable technology advancement has been in the development and flight-test demonstration of autonomous control laws for obstacle field navigation and safe landing area determination on the RASCAL UH-60 by Takahashi et al. (Ref. 107).

An important remaining challenge is the characterization of realistic (CETI) turbulence models for shipboard and rooftop operations, which are critical for future military and UAS/UAM operations. Also important are the associated shipboard and rooftop disturbance rejection requirements (DRB) for the flight control design to ensure safe landing and take-off in these hazardous conditions. Appropriate autonomous MTEs, assigned handling qualities (precision ratings), and resulting quantitative specification boundaries are also needed for these operations. These challenges are relevant to UAS/UAM operations based both on legacy and future rotorcraft.

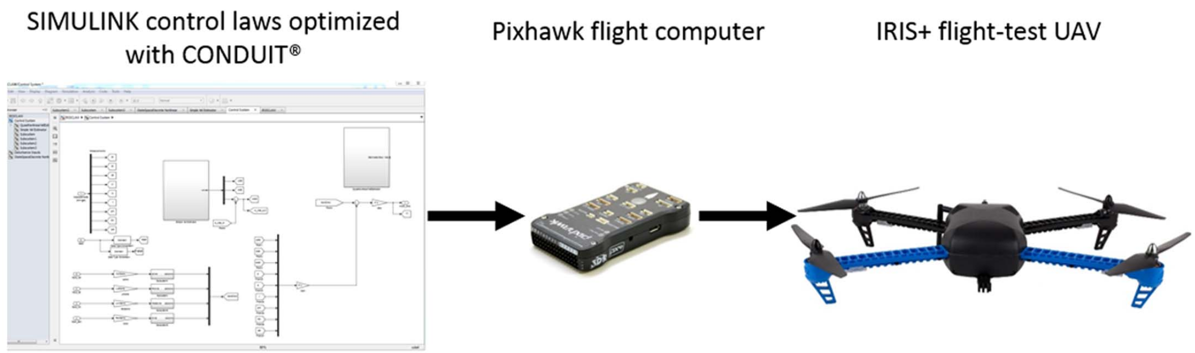
Small eVTOL UAVs

This section considers flight control technology progress and remaining challenges for the development of small eVTOL UAV multicopters and single main rotor helicopters for imaging/surveillance and package delivery. There is a very wide range of configurations in this design/application area. Many of the configurations utilize multiple (overactuated) fixed pitch propellers with only RPM control, thereby improving failure reconfiguration as well as overall vehicle simplicity. An early question was the extent to which flight control technologies developed for full-scale rotorcraft would be applicable and scale to small multirotor eVTOL configurations. Early work was led by Wei et al. (Ref. 108) at the University of Cincinnati with an Aeroquad Cyclone quadcopter. This work demonstrated that frequency-domain system identification using CIFER® and PID controller optimization using CONDUIT® were well suited to a small eVTOL UAV. An unexpected finding of this early research on the small quadcopter was that the system identification model results were *superior* in comparison to large-scale conventional rotorcraft. This is due to several simplifying aspects of the small UAV quadrotor: essentially a flying multipropeller air vehicle which is highly linear without significant rotor/airframe interference; dynamically simple due to configuration symmetry; lacking rotor flapping dynamics, and simple RPM-based control. One of the key takeaways from Wei's work was the importance of the speed stability derivatives L_v and M_u which dominate the vehicle dynamic response throughout the entire flight regime. This renders the multicopter both highly unstable and very gust sensitive.

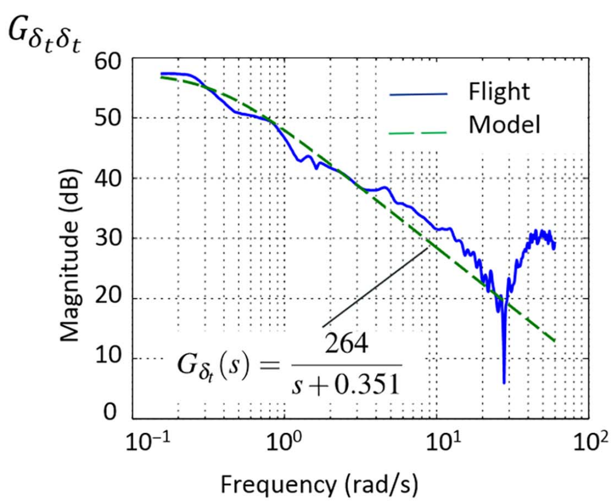
Cheung et al. (Ref. 109) conducted a multiyear comprehensive study at the U.S. Army's Aviation Development Directorate (Moffett Field)/Technology Development Directorate (TDD) to demonstrate the effectiveness of full-scale rotorcraft flight control technologies for small autonomous quadcopters. Key project achievements in this and follow-on studies are shown in Fig. 27. The research used an off-the-shelf IRIS+ quadcopter UAV. The relatively inexpensive PixHawk IMU/flight computer provided an excellent sensor platform for system ID and allowed for the automated pictures-to-code process for flight control system implementation (Fig. 27(a)) typical of full-scale FBW aircraft/rotorcraft. The system ID results showed the importance of including the motor RPM dynamic lag in the LTI flight dynamics equations of motion for this RPM-controlled rotorcraft since this had an important impact on vehicle flight dynamics and control at higher frequencies. Other products of the Army project team were the (1) the implementation and comparison of common full-scale control system architectures (PID, EMF, dynamic inversion); (2) the development of MTEs appropriate to the subscale eVTOL mission and associated performance scoring metrics; and (3) system identification of a control equivalent turbulence input (CETI) model (Ref. 110) for the accurate simulation of the quadrotor flight dynamics response to turbulence. The longitudinal axis results of Fig. 27(b) show that a simple first-order transfer function well characterizes the turbulence in terms of an equivalent pitch control input up to at about 10 rad/s.

In Fig. 27(c), Berrios and his colleagues at the U.S. Army (Ref. 111) used the CETI turbulence model in a *performance-based optimization strategy* to achieve a more than 13-fold improvement in hover accuracy compared to the legacy Arducopter control laws. Another key finding by Berrios shown in Fig. 27(d) was a close correlation of hover hold performance with DRB requirements. This indicates that the full-scale optimization method of maximizing DRB and crossover frequency ω_c is applicable to small-scale UAVs as well.

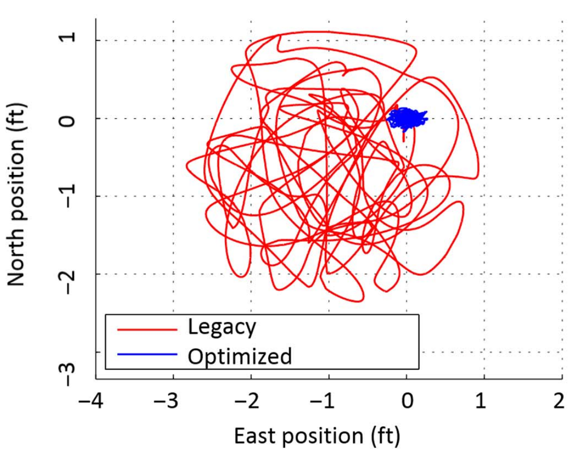
Ivler and her research team at the University of Portland (UP) have led the field of eVTOL UAV dynamic scaling of ADS-33 quantitative requirements and associated MTEs. They validated Froude-scaling concepts for eVTOL dynamics and DRB handling-qualities requirements as shown in Fig. 28. The test vehicle for this work was a small hexacopter (Fig. 28(a)) using RPM control. The first step of their research (Ref. 112) was to identify an LTI model using CIFER®. Figure 28(b) shows that the identified model is highly accurate in capturing the flight-test response for very large amplitude maneuvering flight, exceeding 180 deg/s peak-to-peak. Figure 28(c) shows that Froude-scaling based on *hub-to-hub distance* can accurately scale up the UP hexacopter dynamics to a larger hexacopter UAV of about twice its size, as based on flight results by Lopez et al. (Ref. 113). This research validated the



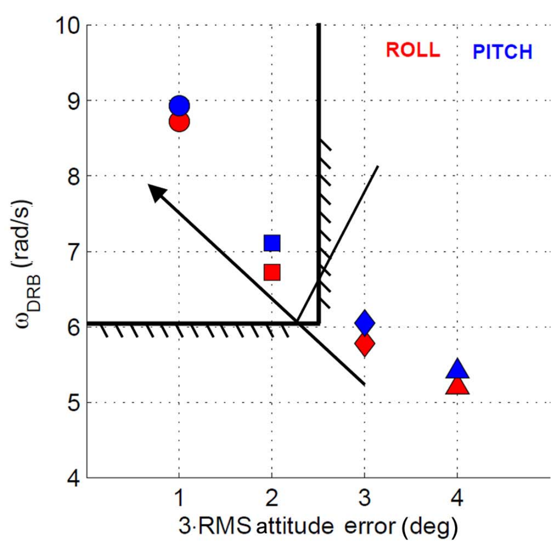
(a) Pictures-to-code process and flight-test platform (Ref. 109)



(b) Longitudinal CETI turbulence identification from flight (Ref. 110)



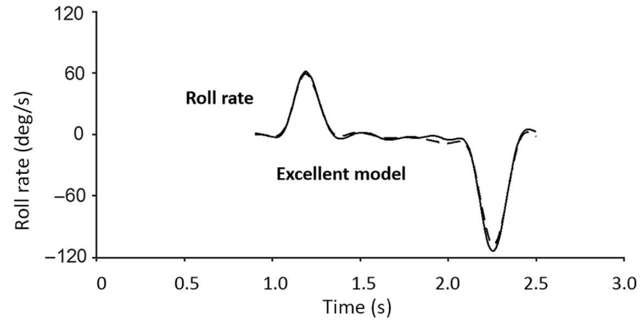
(c) Large flight-test improvement of optimized control system over legacy system (Ref. 111)



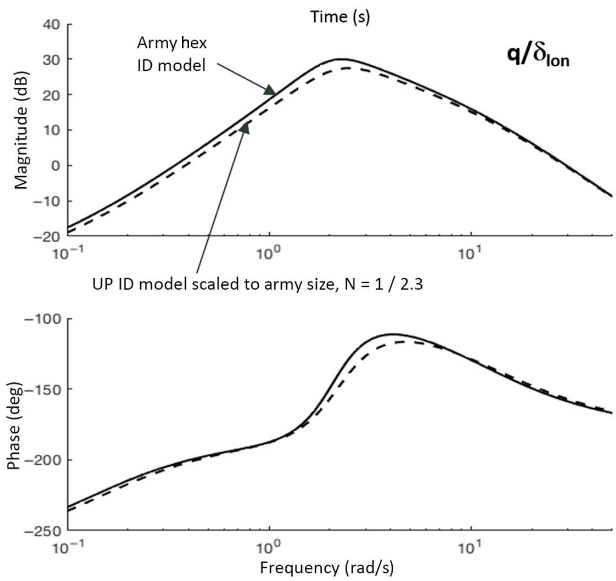
(d) Close correlation of DRB requirements with turbulence performance in flight (Ref. 111)

Fig. 27. Quadrotor flight control development and flight-test results.

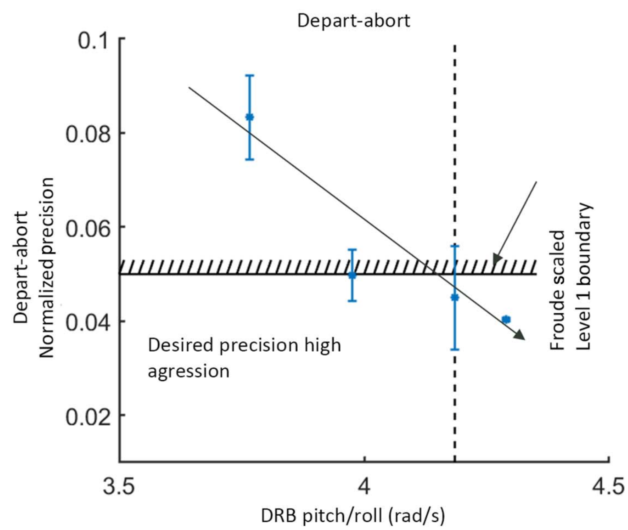
(a) University of Portland hexicopter



(b) Excellent agreement of identified LTI model for large maneuvers



(c) Excellent agreement of froude-scaled dynamics of small-scale and larger-scale hexicopter ID with dynamics based on hub-to-hub scaling



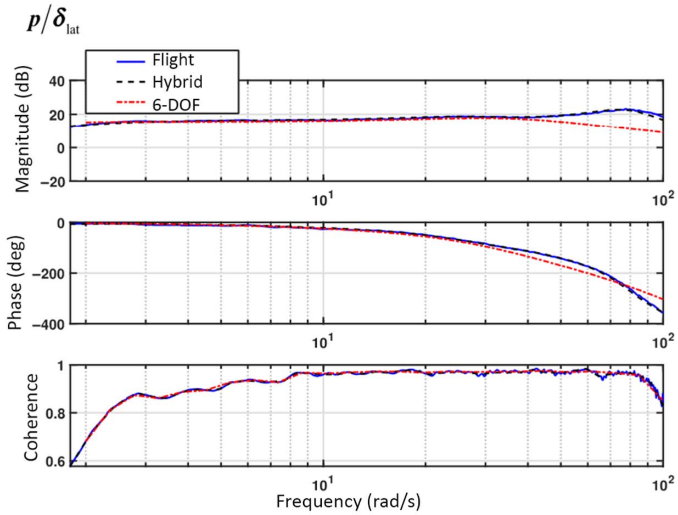
(d) Excellent agreement of froude scale DRB requirement with UAV flight resultst

Fig. 28. Identified LTI model for hexicopter UAV and accuracy of Froude-scaled vehicle dynamics (Ref. 112); flight validation of Froude-scaled DRB specification (Ref. 115).

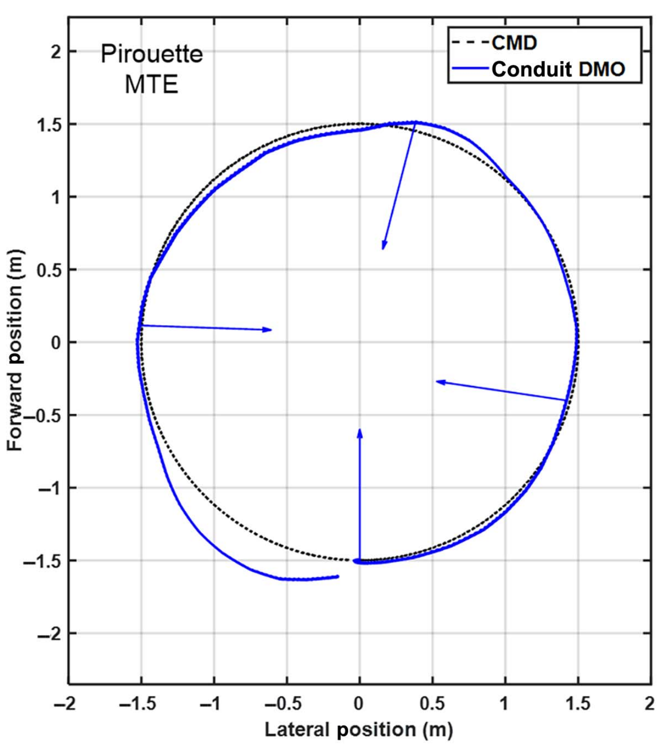
Froude-scaling concept for the *vehicle dynamic response* of UAVs as originally proposed by Cotting (Ref. 114) for fixed-wing UAVs. In Refs. 115 and 116, Ivler and her team proposed and flight-validated a comprehensive UAV handling-qualities evaluation framework that provided MTEs and associated autonomous tracking precision requirements (ε) —analogous to the full-scale ADS-33 HQR methodology. DRB requirements for the hexacopter were proposed based on hub-to-hub Froude-scaling and validated in systematic flight tests for three MTEs. The depart/abort MTE results are shown in Fig. 28(d). Most recently, Ivler et al. (Ref. 117) have proposed UAS-specific maneuvers, attitude bandwidth requirements, and demonstrated the validation of the proposed requirements with the UP hexacopter and the Synergy 626 single main rotor UAV helicopter. Taken together, Ivler's work (Refs. 112, 115–117) provides a "framework" for UAV handling-qualities specification development based on Froude-scaling of the ADS-33 full-scale requirements.

Recent research by Walker and Tischler (Refs. 118, 119) has flight-validated the integrated use of full-scale flight control technologies and Froude-scaling to achieve precise vehicle control in turbulence for a subscale highly-agile single main rotor eVTOL configuration. This research work has been comprised of subscale system ID using CIFER®, explicit model-following (EMF) control laws, flight control optimization for a comprehensive set of Froude-scaled ADS-33 requirements and DMO using CONDUIT®, Froude-scaled MTEs, and the autonomous tracking precision metric (ε). The research vehicle is the *flybarless* (highly-agile and mechanically simple) 360CFX UAV (Fig. 29(a)). Figure 29(b) shows very high flight-test coherence for the bare-airframe roll rate response p/δ_{lat} over the broad frequency range of interest for flight control development, and essentially perfect agreement $J = 10.1$ of the hybrid rotor-flap/fuselage model for the roll rate response. The low MIMO cost function $J_{\text{ave}} = 58$ reflects excellent identified state-space model accuracy for the subscale flybarless helicopter as earlier shown for multicopters. The quasi-steady (6-DOF) identification model structure cannot adequately capture the tightly coupled flapping/fuselage response as shown in Fig. 29(b). The flight-test results for the Froude-scaled Pirouette MTE are

(a) 360CFX flybarless helicopter UAV (rotor diameter = 0.81 m)



(b) Hybrid higher-order and quasi-steady (6DOF) identified LTI models



(c) Flight-test results of optimized design (solid line) vs. commanded ground track (dotted line) for Pirouette maneuver

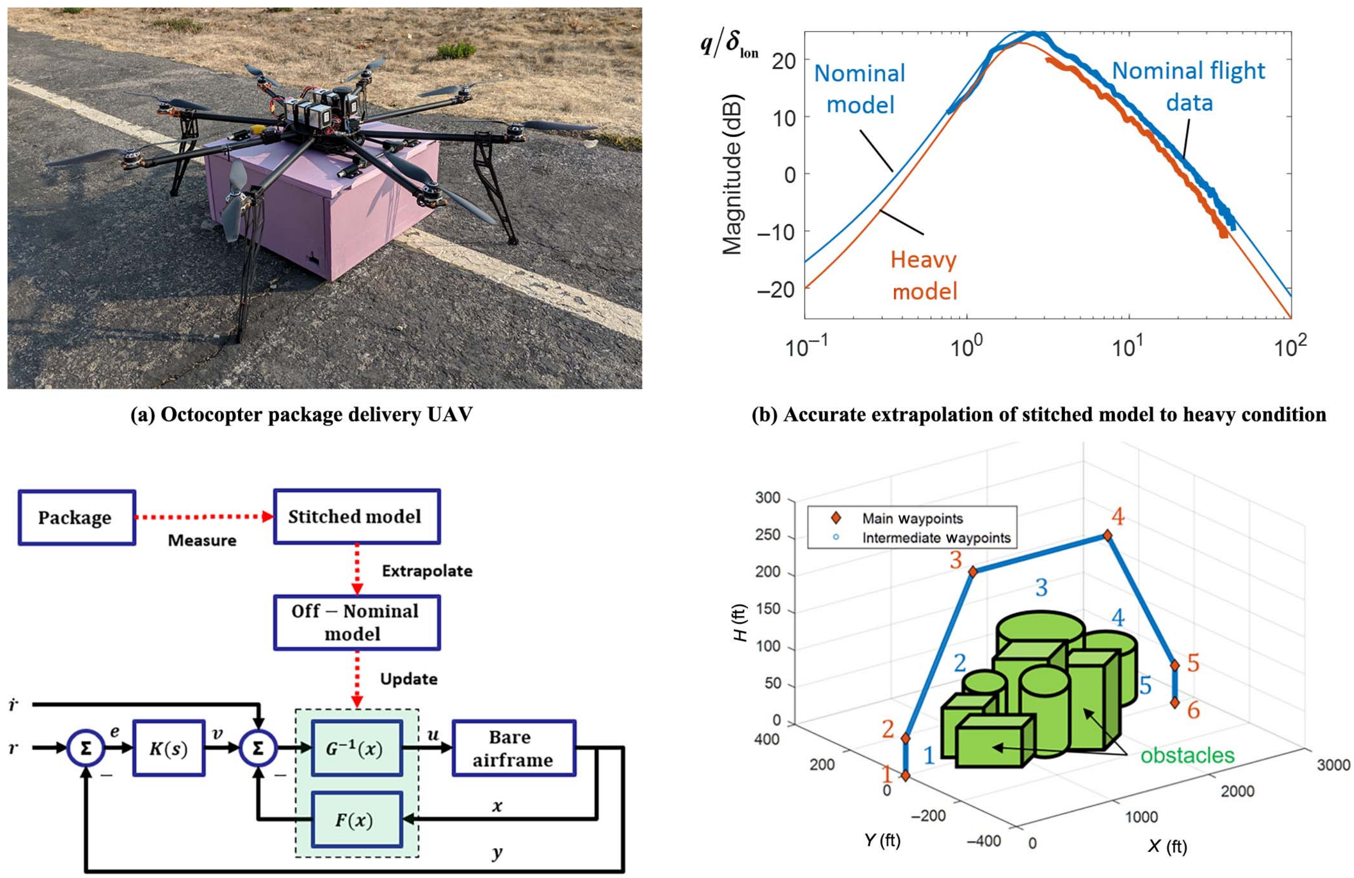
Fig. 29. System identification and flight control evaluation results for flybarless UAV helicopter (Ref. 118).

shown in Fig. 29(c). The flight-test agility score of $\varepsilon = 0.1013$ for nondimensional precision accuracy meets the UP proposed requirement for desired performance in highly aggressive maneuvering (Ref. 116). Similarly, accurate system ID results of an advanced winged-single main rotor eVTOL configuration with a vectored thrust tail duct were obtained by Nadell et al. (Ref. 47) for multiple flight conditions spanning the flight envelope and combined to achieve a continuous stitched simulation model.

Figure 30 shows work led by Gong et al. (Refs. 120, 121) to develop a package delivery system using *deterministic reconfiguration,* based on weighing the package and then storing it inside a fixed payload bay of an octocopter (Fig. 30(a)). LTI models were identified at three airspeeds from flight tests for the *unloaded cargo bay* and then combined in a full flight-envelope stitched model (Ref. 120). Weighing the package provides updated overall vehicle weight, inertias, and CG with little change in the aerodynamics due to the fixed payload bay. Then, the stitched model accurately extrapolates the nominal model to provide loaded vehicle LTI models. This extrapolation was checked with frequency response comparison to separate flight data for the loaded configuration not used in the stitched model development. As seen in Fig. 30(b), the stitched model extrapolation for the loaded pitch rate response q/δ_{lon} is quite accurate. The overall operational concept is shown in Fig. 30(c) (Ref. 121). The package to be delivered is weighed and the stability and control derivatives for the loaded configuration are determined from the stitched model. Then, the dynamic inversion control system can be immediately updated with the LTI matrices for the loaded configuration. This approach allows for *deterministic reconfiguration* in which the flight control system characteristics are known and repeatable based on a simple measurement of the package weight. A simulation analysis of the full mission scenario of Fig. 30(d) is given by Gong et al. (Ref. 121) and shows excellent tracking accuracy of the commanded flight path.

There are additional significant flight control technology progress highlights for the eVTOL multicopter configuration. Lopez et al. (Ref 113) conducted flight tests and system identification of several multicopter configurations of the same scale and quantified as much as a 10% loss in the aerodynamic control power of the *individual rotors* due to the rotor-on-rotor interference when the rotors are in close proximity. Considering the overall configuration, this resulted in a 15% loss in the *dimensional pitch control power* $M_{\delta_{\mathrm{lon}}}$. These significant interference effects also have important implications for the design of full-scale UAM configurations. The ability to extract the aerodynamic control power from this overactuated configuration (i.e., with highly correlated control effectors) was made possible with the development in system identification technology of the *joint input–output (JIO) method* for highly-correlated inputs by Berger et al. (Ref. 122). The JIO method is a postprocessing step to the conventional or *direct* frequency response system identification method as presented earlier. Berger et al. (Ref. 123), Berrigan et al. (Refs. 84, 85), and Nadell et al. (Ref. 47) further demonstrated the broad flight-test applicability of the JIO method for a wide range of rotorcraft: modern high-speed rotorcraft, subscale UAVs, and fixed-wing aircraft which are often over-actuated for increased controllability and damage reconfiguration. The JIO method is an important advancement in system ID technology and has recently been incorporated into the CIFER® software suite.

STI led a multiyear broad team effort to define a handling-qualities specification for unmanned aerial systems (2017–2022; Ref. 124). Flight tests by team members were conducted to define UAS handling-qualities metrics, criteria boundaries, suitable MTEs, and rating methodologies. Finally, there is an ongoing collaboration under the U.S. Army Joint Tactical Area Resupply Vehicle program (JTARV) based on the SURVICE-Malloy TRV-80 coaxial quadrotor with an 80-lb payload capability. This



(a) Octocopter package delivery UAV

(b) Accurate extrapolation of stitched model to heavy condition

(c) Deterministic reconfiguration concept

(d) Nominal package delivery mission

Fig. 30. Deterministic reconfiguration of flight control system based on preflight package inertial measurements (Refs. 120, 121).

collaborative research program involves physics-based modeling using the HeliUM simulation code, system ID flight tests to validate and improve the physics-based model, and optimized flight control performance for military and commercially applicable eVTOL UAS package delivery systems.

The research experience to date has demonstrated the significant progress, efficacy, and general applicability of the full-scale flight control technologies to subscale eVTOL aircraft: system ID, flight dynamics model validation/update methods and metrics, full flight envelope stitched modeling, EMF control system architecture and optimization methods, and Froude-scaling for handling-qualities requirements and MTE definition.

There remain important challenges for the wide range of configurations and missions of small eVTOL UAVs. One common aspect of the multicopter configurations, as seen in the system identification results of several flight-test studies referenced above, has been the importance of the speed-stability derivatives L_v and M_u; the (relatively) large speed-stability derivatives make the bare airframe *highly unstable and especially sensitive to turbulence*. This represents a significant challenge to flight control design and optimization for all-weather operations, especially for roof-top and ship-board landings. Another challenge is that while physics-based blade element simulation models of UAV flight dynamics are progressing, the models are at the early stage of development and do not exhibit adequate fidelity for flight control design as seen in comparison with system identification flight-test data (Ref. 125). A key issue is that the needed values of the basic parameters, such as rotor airfoil characteristics and vehicle inertias, are not measured accurately or known. Also, aerodynamic modeling assumptions are advancing but do not yet capture the many unique aspects of small eVTOLs such as multirotor shrouding and mutual interference as compared to the state-of-the-art, well-developed aerodynamic modeling theory of legacy full-scale rotorcraft. Another challenge is the rapidly changing configuration during flight-test development resulting in a "fly-crash-fix-fly" development process. Physics-based modeling cannot keep up with this vehicle development approach which often sees new configurations on a daily basis. A final challenge to eVTOL flight control technology is the need for a complete set of flight-validated flying quality specifications and appropriate automated MTEs.

Full-scale eVTOL for urban air mobility

A NASA presentation by Patterson (Ref. 126) defines the *urban air mobility* (UAM) mission as constituting: "Local" missions up to 75 miles around metropolitan areas, largely novel "vertiport" infrastructure, eVTOL, potentially eSTOL or eCTOL aircraft, and 1 to 6 passengers or equivalent cargo to address ground traffic congestion. This section focuses on advancements and key remaining challenges of flight control for the full-scale eVTOL UAM passenger service applications. As seen in the aviation press and vehicle developer websites, the range of UAM configurations is very broad, each with specific/unique flight control technology considerations and challenges. One developer is Joby Aviation which has conducted extensive flight testing of "air-taxi" demonstrators starting with a *subscale* prototype in 2016, the *full-scale* "Generation 1" prototype in 2018 (Ref. 127) and actively since then. Some configurations of the many UAM developers utilize tilting rotor nacelles with full-flapping rotor controls to provide both vertical lift and forward propulsion, while others utilize overactuated fixed lifting and forward propulsion multicopters (propellers with only RPM control) for mechanical simplicity and failure reconfiguration. Together, there are an estimated 300 UAM developers worldwide, and over 630 unique eVTOL configuration concepts (Ref. 128), as compared to a much fewer number of legacy rotorcraft developers and configurations. Finally, UAM is a subset of *advanced air mobility* (AAM), the latter also including commercial inter-city, cargo delivery, public services, and private/recreational vehicles.

Though specific details in the open literature are very limited, significant overall progress in flight control technology has been achieved for eVTOL UAM aircraft as witnessed by the many flight videos on YouTube and the developer websites. Additional flight control advancements have been presented in special technical sessions and dedicated symposia on eVTOL-UAM by the Vertical Flight Society (VFS). Physics-based simulation models with higher order aerodynamic computations are coupled to account for the many "unconventional" rotorcraft aspects that differ significantly from the classical rotorcraft aerodynamic assumptions. State-of-the-art rotorcraft flight control technologies and software tools developed for full-scale conventional rotorcraft, as discussed above, are being routinely used in the UAM research and commercial development communities.

There are several research efforts working to advance and document best practices in eVTOL handling qualities and flight testing. A key effort is the NASA Revolutionary Vertical Lift Technologies (RVLT) Project—under the Aeronautics Research Mission Directorate's Advanced Air Vehicles Program. In the flight control technology domain, research is focused on developing guidelines and tools for vehicle design and operations that result in acceptable handling and ride qualities of UAM vehicles. The project seeks to assess classical handling-qualities metrics for applicability to UAM mission requirements and the *effect of meeting these HQ metrics on ride quality for passenger comfort*. The NASA RVLT research project thrusts parallel the key thrusts of this paper:

1) Physics-based simulation modeling of increasing fidelity and development of flight control tools for conceptual design,

2) Flight control design (for normal and failure states, optimal control allocation, robust control),

3) Human subject testing (including piloted handling qualities and passenger ride quality testing), and

4) Subscale flight testing.

A new capability under development by NASA is the FlightCODE tool chain (Ref. 129) that enables the flight dynamics and control assessment of rotorcraft vehicle (including eVTOL UAM) design concepts as synthesized by the NASA rotorcraft preliminary design tool NDARC. The approach uses a suite of tools including MATLAB®/Simulink®, CONDUIT®, and X-Plane® to generate flight dynamics models, analyze and optimize EMF control systems, and enable real-time piloted simulation of the combined flight dynamic and control models. The coupling of the handling-qualities assessment to the NASA UAM design concepts will demonstrate in particular where a design concept has adequate control power or needs to be enhanced to meet the UAM HQ requirements. Some goals that NASA hopes to achieve in the near term horizon: complete pilot-in-the-loop hover assessments of RPM-controlled multi-rotor eVTOL configurations, consideration of various levels of control augmentation (ACAH and TRC), varying agility requirements (e.g., comparing ADS-33 versus proposed UAM requirements), and assess normal states and failures.

The *E-VTOL Flight-test Council* is a multinational independent, informal group that works jointly with professional societies such as the VFS and the Society of Flight-test Engineers (SFTE) to establish best practices for flight testing the peculiarities of electric aircraft. An open collaboration venue with 250 members from a dozen countries, the council does not publish its own technical papers or standards; instead, it encourages members to do so through their associated standards and development organizations or joint sponsors (e.g., SFTE symposia).

So, to the extent that information is available in the popular media and given the reported significant level of financial investment and UAM preorders by major airline companies!, this relatively new rotorcraft sector is garnering rapidly growing attention. Flight control technology has a *pivotal role* in ongoing UAM advancing development, especially in the areas of handling qualities (perhaps better termed as flying qualities in recognition of the long-term autonomous operations goal), physics-based simulation modeling, flight control system design/optimization, and flight testing to validate flight dynamics performance/ride quality, reliability, and safe failure recovery.

There are several key flight control technology challenges for eVTOL UAM concepts. An overarching challenge is that, due to proprietary and competitive concerns, very few technical details and flight-test results have been published by the UAM developers in the open literature (beyond promotional videos). This creates a significant challenge to compile flight control technology guidance documents and compendia of lesson-learned as resources to be shared and discussed among the community as was commonplace in the legacy rotorcraft and fixed-wing fleet, for example, by Tischler (editor) (Ref. 60), Moorhouse (editor) (Ref. 61), and Tischler et al. (Ref. 48). The correlation of quantitative flight control characteristics and qualitative performance is central to the development/validation of handling-qualities requirements tailored to the UAM mission and would benefit the entire community.

Government-operated ground simulators such as the NASA Ames Vertical Motion Simulator, with their excellent perceptual fidelity and ability to simulate a wide range of rotorcraft, can be a significant asset in developing open literature research for UAM flight control. Highly capable in-flight simulators and FBW testbeds (e.g., U.S. Army CH-47B and JUH-60A RASCAL, NRC B205/B412, and DLR Bo-105/EC-135) were mainstays of flight control technology research of the past 50 years. Parametric experiments conducted using these aircraft contributed significantly to the development of ADS-33 standards and advanced flight control concepts (e.g., rotor-state feedback, active stick cueing, sling-load stabilization, CETI model determination/validation), but all of these testbeds are conventional single-main rotor configurations and so have limited capability for parametric flight control studies of UAM flight control technology concepts. There is a strong role for government-operated, reconfigurable Froude-scaled demonstrators as effective platforms for flight control test beds. My expectation is that such government testbeds will be developed out of necessity to support generic publishable research in the development of FAA and EASA civilian standards of certification, regulation, and procurement. In my view, relevant CONOPS and the associated need for flying qualities requirements for a military eVTOL UAM will follow. In the interim, given the UAM configuration size and personnel transport missions that are comparable to the legacy rotorcraft and fixed-wing fleet, the quantitative requirements of ADS-33 and MIL-STD-1797 are a valid starting point for control system design/optimization.

The next key challenge is that many of the proposed eVTOL-UAM configurations do not correspond to the conventional rotorcraft simulation assumptions or rotorcraft configuration categories. Therefore, the "textbook" assumptions/methods for aerodynamics, flight dynamics, and control modeling methods are often not applicable to the UAM configurations. Further, the needed input parameter values (e.g., airfoil characteristics, interference effects, mass properties) are often not known accurately. Advanced configurations will require the use of higher order aerodynamic model methods (see Future Vertical Lift section; e.g., VPM (Fig. 24), CFD, free wake), coupled with sophisticated system ID methods (e.g., Refs. 92, 93) to extract lower order real-time LTI representations for flight dynamics models. Stitched models are most likely the best source for the development of accurate flight dynamics and control simulations of unconventional configurations in the near term, but this requires flight testing of the full-scale designs or subscale prototypes, and the results will not extrapolate to different aerodynamic and configuration properties.

UAM missions, as depicted on government and developer websites, envision heliports on the roofs of tall urban buildings. Given characteristically strong winds aloft, even for nearly calm winds at street level, and the close proximity of urban skyscrapers, there is an urgent need for *flight-validated CETI turbulence models* applicable to rooftop takeoff and landing for use in the flight control design process and mission representative simulation to assess the control power and configuration trade-offs for precision roof-top operations. A start to achieving a generic CETI model for multicopters is the work by Truong et al. (Ref. 130).

The next flight control technology challenge is that many of the UAM concepts use RPM-based flight control for mechanical simplicity. Simulation studies, by Walter et al. (Ref. 131) and Malpica and Withrow-Maser (Ref. 129), raise credible concerns about whether RPM-controlled UAM configurations have adequate control power to meet ADS-33 handling-qualities requirements.

Another significant challenge for UAM flight control technology occurs for the configurations in which the rotors and rotor/aerodynamic surfaces are in close proximity, resulting in significant mutual interference and associated reduction in control power, as discussed earlier with results by Lopez et al. (Ref. 113). Interference effects obtained from higher order aerodynamics computations must be flight-validated with wind-tunnel and flight-test experiments, as was done in the development of the GenHel UH-60 simulation model (Ref. 24).

A final key challenge for UAM flight control technology arises from the highly overactuated configuration concepts. Real-time flight validated algorithms must ensure optimal control power distribution to the rotors across the flight envelope. Also, a deterministic approach to damage tolerance control is needed to ensure reliable UAM operations in the civil airspace.

Summary of future rotorcraft challenges and relevant technology solutions

The key rotorcraft flight control challenges for future configurations and the relevant technology solutions, as discussed in this Nikolsky Lecture journal paper, are summarized in this section:

1) Challenge: Release and continually update the rotorcraft handling-qualities specification to provide quantitative requirements and specialized MTEs for the modern missions of future military and civilian manned rotorcraft and extend the specification guidance to subscale autonomous rotorcraft.

Proposed solutions:

a) Implement the proposed changes of Blanken et al. (Ref. 101) in an update to ADS-33 to be redesignated as MIL-DTL-32703. This update is expected to be published by the end of CY2022. These requirements based on *legacy fleet flight experience* will continue to be needed for flight control evaluation of "conventional" rotorcraft configurations and as the basis for future versions of MIL-DTL-32703.

b) Analyze and publish (in the open literature) handling qualities and flight control flight-test data from JMR and FVL flight trials to support an update to MIL-DTL-32703 for modern high-speed rotorcraft.

c) Continue to conduct parametric handling-qualities studies in ground-based and in-flight simulators to set quantitative requirements boundaries and MTEs appropriate to modern rotorcraft configurations and missions.

d) Continue the flight validation of Froude-scaling as the basis for the development of quantitative requirements and MTEs in a complete flying qualities specification for subscale UAV rotorcraft.

2) Challenge: Validated flight dynamics and control system simulation models for a broad range of new configurations and missions.

Proposed solutions:

a) Augment traditional physics-based blade-element models with high-fidelity aerodynamic computations. Lower order models extracted using system identification from these high-fidelity computations are necessary for real-time simulation and linearized flight dynamics and control (LTI) applications.

b) Use system identification as the basis to flight-validate and update physics-based nonlinear and LTI vehicle simulation and control models of new rotorcraft concepts.

c) Key sources of higher order dynamics and effective time delays (e.g., rotor and structural modes, inflow dynamics, control system filters, and actuator rate saturation) must be carefully determined using system identification and included in flight dynamics simulation and control models. Fifty years of experience has shown that excessive equivalent time delays are a key risk to handling qualities and flight control performance of modern highly augmented flight vehicles.

d) Develop CETI models from flight-test data for highly challenging shipboard and rooftop operations. The CETI realistic turbulence models are critical for flight control design and real-time mission-representative simulation in these critical operations.

3) Challenge: Highly-compressed development schedules and limited budgets for UAM rotorcraft configuration concepts and autonomous flight control.

Proposed Solutions:

a) Subscale demonstrators based on Froude-scaling can provide accurate stability and flight control measurements at a fraction of the time/cost of full-scale vehicle flight tests. The use of subscale demonstrators allows for effective design iteration, especially in the early phase of vehicle and control evolution. Subscale demonstrators have already been used at the early stages of development where configuration changes occur rapidly.

b) System identification is already being used early and routinely in flight-test programs to assess and update control system performance and dynamic models and to reduce flight control tuning and costs. This practice must be built into future rotorcraft programs and further developed.

c) Stitched models can provide accurate higher order, real-time, full flight envelope simulations from LTI point models as obtained using perturbation methods and system ID from non-real-time physics-based simulations and flight tests.

4) Challenge: The multitude of proposed future rotorcraft configurations and operational concepts present a challenge to legacy flight control architectures and traditional design processes.

Proposed solutions:

a) The EMF architecture provides for a transparent and well-vetted flight control development. This 2-DOF architecture is ideal for task tailoring and is used on most current FBW piloted rotorcraft. It is also well suited to new UAS/UAM concepts at full-scale and subscale.

b) Optimum control allocation and deterministic damage reconfiguration concepts need to be further developed and flight-validated for the many new configurations that feature highly over-actuated control systems. This can be accomplished efficiently with ground-based simulation tests and subscale flight demonstrators, especially in the early development phases.

c) Multi-objective parametric optimization provides a family of optimized flight control designs that meet the wide array of design specifications, with varying levels of response aggressiveness and minimum overdesign. This approach is "specification-driven," putting the design emphasis on the proper selection of requirements and Level 1 boundaries.

5) Challenge: Flight control technology data for advanced configurations (FVL, UAV, eVTOL) must be collected under military and civil *government S&T programs* to build an open-literature database for advancing the state of the art.

a) As they have been for decades for the legacy fleet, government programs must be initiated with continuity of funding to ensure that the government labs are the focal point and repository of experience/data for future rotorcraft.

b) Next-generation government-owned in-flight simulators and FBW testbeds must be maintained to conduct objective handling qualities and flight control studies and the research results published in the open literature. Government-owned facilities are needed that emulate the flight dynamics and control characteristics specific to FVL and eVTOL UAMs.

c) Concerted multinational efforts using government-owned high-fidelity facilities are needed to coordinate research efforts and pool available resources, as was done very successfully in the development of ADS-33.

The methods, tools, and lessons learned over the last 50 years of flight control technology development, and highlighted in this Nikolsky Lecture journal paper*, are the keys to the successful development of the next generation of rotorcraft.*

Lessons-Learned and Key Takeaways as a Career-Long Flight Control Engineer/Researcher, Group Leader, and Senior Technologist

1) A broad range of experience and collaborations is essential to advance multidisciplinary flight control technology:
My career experience spanning the past 40+ years of widespread collaborations with industry, government, and international research organizations has shown that flight control engineers must have a wide range of experience and exposure to spark new ideas for the evolving rotorcraft flight control challenges. These collaborations may involve applications that may not have an obvious application to the vehicle configurations at hand; however, working on a broad range of applications *always provides cross-fertilization and new ideas*. Some examples of fixed-wing, rotary-wing, and UAV projects that the U.S. Army TDD Flight Control Technology Group and I have worked on during my research career and group leadership are shown in Fig. 31. This broad range of experience, national/international collaboration, and attending national/international professional conferences are all essential to encourage engineers to "think outside of the box" and to advance the state-of-the-art in the highly multidisciplinary field of rotorcraft flight control. Flight control technology advancement *cannot be achieved by engineers working only within their office space or in a remote environment*. As Professor Peter Hamel called them, many "aha moments" occur when technical and social exchanges occur away from the laboratory. In my experience, some of the greatest new ideas and insights occurred during international collaborative work away from the home laboratory environment and perhaps over a beer at a pub.
2) Frequency-domain system identification is likely the single most important integrative and cost-saving flight control technology:
System identification provides important quantitative data for assessing the accuracy of physics-based flight vehicle simulation and flight control models, and a methodical basis for updating the models. System identification models obtained from simulation and flight-test data provide a source for accurate LTI design models and for rapidly developed real-time stitched models. Since rotorcraft flight control design and quantitative handling qualities/flight control specification metrics are based in the frequency domain, the use of frequency response system identification methods will ensure an accurate transition from simulation to HIL system testing and finally to flight with a minimum amount of flight-test tuning/cost.
3) Flight-validated tools, best practices, and guidelines based on years of diverse applications must be instantiated in software tools. Companion comprehensive documentation and repeated offerings of engineering courses on the tools and the underlying theory are central to technology transfer and impact on the community:
An important lesson learned is that it is no longer sufficient to publish key equations and results in a journal paper and assume that this provides for adequate technology transfer. *True technology transfer that changes established practice takes a lot of determined and multifaceted effort*. This demands that new methods are flight-validated for a wider range of rotorcraft configurations. Then the methods must be instantiated in reliable and user-friendly software tools that are put into the hands of working engineers and taught in training courses. These are all necessary to have a lasting impact on the flight control community. Comprehensive reports, books, and compendia of research results, lessons learned, and key practices (e.g., AGARD and NATO documents) provide critical resources for working-level engineers. Some of the milestone software tools and publications that have emerged from decades of research and development, applications to rotorcraft and fixed-wing projects, and national and international collaborations are shown in Fig. 32; Refs. 40–43, 56, 57, 60; and in collaborative references cited earlier.
4) Flight control technology is multidisciplinary and model based:
Advancements in simulation and control methods require validation for a wide range of applications including fixed-wing and rotary-wing aircraft. Ground-based and in-flight simulation, as well as full-scale and subscale flight testing, are all crucial to validate that the new methods are robust, accurate, and broadly applicable. Exposure and interaction of flight control engineers at national/international technical conferences and symposia, and multilateral collaborations are critical to technology and research advancement and workforce development (e.g., under the aegis of bilateral "project agreements" and NATO Science and Technology Organization research technical groups). Career advancement in flight control engineering requires that subject matter experts have exposure/command of a wide range of subdisciplines: rotorcraft first principles, physics-based flight dynamics, system identification, flight control fundamentals, design, and optimization.
5) Fielded application of new flight control concepts/methods can be as much as 20 years out from the foundational research and development effort, requiring a sustained effort, continuity of subject matter experts and funding:
For example, the development of the ADS-33 rotorcraft handling-qualities specification from the project start until the final "E" version took 20 years of research, flight testing, applications, and refinement to become the breakthrough and invaluable tool it is recognized for today in flight control design and aircraft acquisition. It has been 20 more years since the release of ADS-33E, and it is well overdue to be updated as the forthcoming MIL-DTL-32703. Yet even this revision will be outdated with the lack of handling-qualities requirements for advanced configurations and high-speed flight. CIFER® and CONDUIT® have changed the way flight simulation models and control systems are developed in the rotorcraft and fixed-wing communities. Each took about 20 years of research and development effort to develop and flight-validate the ideas and algorithms, and instantiate them in user-friendly and reliable software tools, together with comprehensive textbooks and training materials. As a

Fig. 31. A broad range of experience and collaborations was essential in the advancement of multidisciplinary flight control technologies.

Fig. 32. Integrated tools, training, and documentation were central to achieving technology transfer and impact on the community.

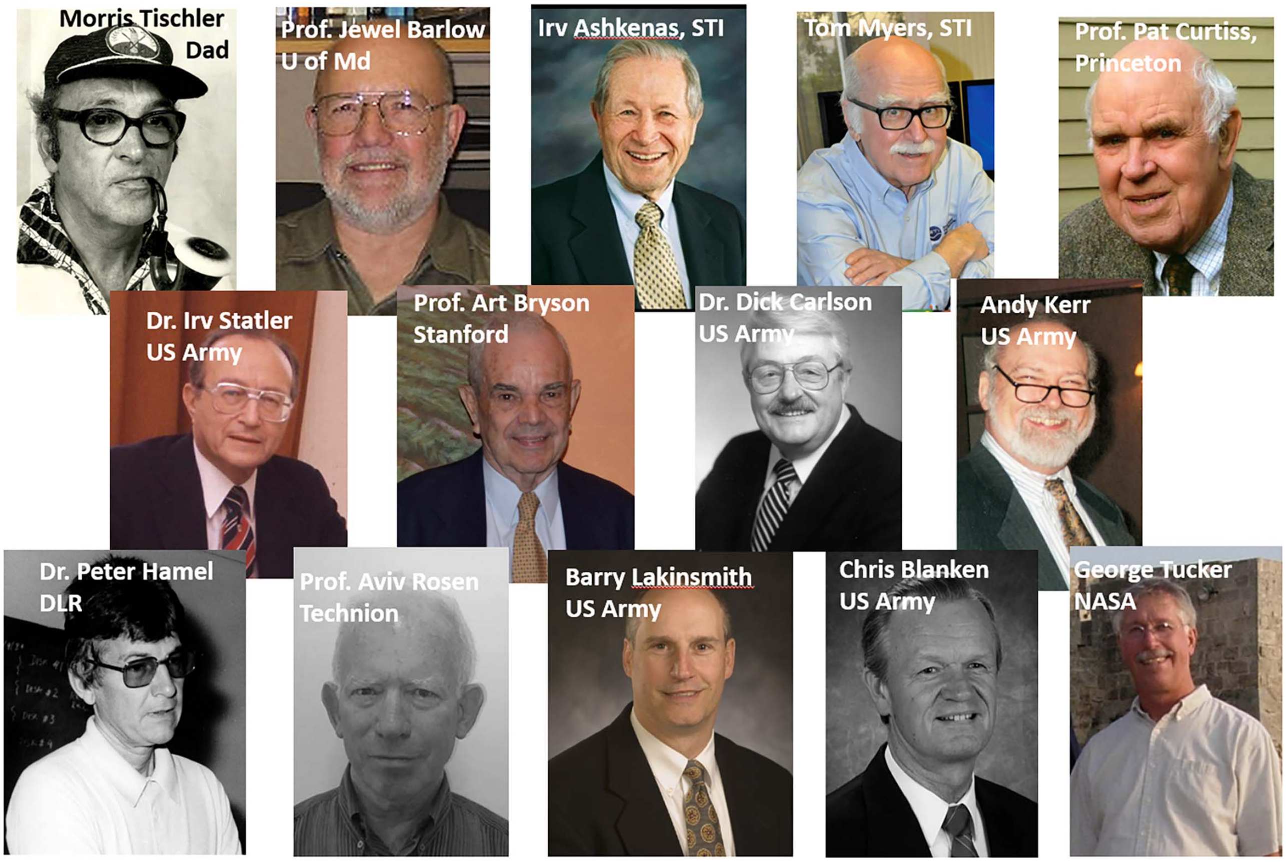


Fig. 33. Thanks to my many wonderful mentors.

result of these decades-long efforts, these tools are now worldwide standards.

6) The flight control technology advancement process is highly nonlinear:
It is essential that rotorcraft research engineers work on a broad range of applications. For example, lessons learned and "cross-fertilization" from working on fixed-wing problems have been the key to advancement in the rotorcraft community. Also, research is quite often ahead of its time and new algorithms and methodologies must wait for the proper application (e.g., the JIO method was initially developed in 1968 for an entirely different application than highly correlated control effectors!). Yet, great innovations and breakthroughs are achieved by applying older ideas to new applications. This requires researchers to have more flexibility in their work assignments. Flight control research must be *less schedule-driven and more technology-driven* in order to have a long-term and lasting impact on the rotorcraft community.

7) As has been demonstrated in this paper, there are many evolving new rotorcraft configurations and missions:
The past 50 years have seen comparably less configuration change in the legacy fleet of single main rotor and tandem rotor configurations. Legacy configurations generally conformed well with the common simulation assumptions. Hardware advancement (e.g., eVTOL), new concepts of operations (e.g., high speed and UAM), and associated new rotorcraft configurations (e.g., FVL and UAM multicopters) are driving a much-increased pace of rotorcraft flight control technology evolution. While many existing technologies developed over the past 50 years are highly applicable to today's challenges, this Nikolsky Lecture journal paper has also highlighted the many new rotorcraft configurations and associated flight control technology challenges for the new military and civilian missions. Taken in total, I believe we are in a "*golden age*" of flight control. There are many opportunities for young engineers with a strong background and passion in rotorcraft flight dynamics and control—as witnessed by the many position openings for flight control engineers within the industry community.

Acknowledgments

It is critically important for engineers, both in their early careers, but also throughout their careers to have *mentors that can guide them*, help them with critical technical and career decisions, and be a sounding board for new ideas. In so many cases, these more experienced mentors have seen the technical problems and career issues that young engineers face and may have insights that they would be delighted to share based on their lifetime of experience. In Fig. 33, I have shown just a few of the mentors throughout my career. Some of these mentors were academic advisors, and others were industry and government managers/collaborators who had many years of perspective to balance the exuberance of this engineer. Some of their advice was career related, while other guidance provided technical perspectives. In all cases, these peers, researchers, and managers had wisdom and experience well beyond my own years, helping and guiding me with the many difficult decisions and choices throughout my career.

Always close to my heart are my parents. My mother, Ruth Judith Tischler (z"l), always made sure that our home was filled with tradition and the love of learning. My father, Morris Tischler (z"l), provided lifelong encouragement and mentorship. Starting from age 12, I expressed an interest in aeronautics. Yet my dad was interested in electronics and

Fig. 34. Aeronautics has always been my greatest passion (author, 16 years old).

the new transistors that were coming on to the scene. My father had large shoes to fill, being the inventor of the first transistorized pacemaker that he provided to President Eisenhower's physician for the President's heart problems. And yet, my dad was always a great supporter of my interests in building all manner of flying machines. He was my greatest fan and supporter throughout my life, and I could not have achieved what I did without his constant encouragement to push me further than I thought possible. In my youth, he always demanded: "100% effort even when it did not always bring 100% results." That was the key to his career, and it proved to be a key to mine as well.

Aeronautics has always been my greatest passion. At first, I was interested in Estes kit model rockets and was mesmerized by the landing on the moon. By high school, I was designing novel swing-wing rocket gliders (Fig. 34) with a rudimentary computer code for configuration design and to ensure basic static stability. In college at the University of Maryland, I was drawn to flight dynamics and control since that seemed to me to provide a view of the entire aircraft's response characteristics. I advanced my work in model rocket gliders with ever-sophisticated configurations, wind tunnel experiments, and analytical models to finally flight-demonstrate a successful two-stage, radio-controlled model rocket boost swing-wing glider design for the AIAA student competition in 1979 (Ref. 132). My regular advice to youngsters trying to decide on an engineering discipline and concerned that aeronautics might be too limiting was that "if you were born with an airplane in your mouth, then study aeronautical engineering!" During the 1970s slump in aeronautical engineering, when I was in high school and expressed concern about the job market if I chose this as my path, my Dad's advice was "if you excel and have a passion in your field, there will always be opportunities for you." He was right about that too!

I want to express my special thanks to two very important colleagues. Dr. Thomas L. Thompson (U.S. Army DEVCOM) for nominating me for this wonderful Nikolsky Honorary Lecture recognition. Throughout my Army career, Tom always believed in me and my methods. He advocated tirelessly for the Army to apply the new system ID, handling qualities, and flight control methods and tools that my research group and I developed. He encouraged his researchers to attend my short courses and apply our methods to ongoing rotorcraft programs. Special thanks also go to Ms. Olivia H. Lee (San Jose State University Research Foundation) for her outstanding support in transcription, organization, preparation of figures, technical editing, and final draft preparation of this journal paper. *I simply could not have completed this without her steadfast help*!

Finally, I want to thank the Vertical Flight Society and the vertical flight community for the wonderful honor to present this 40th Alexander A. Nikolsky Honorary Lecture and journal paper on the 20th anniversary of Pat Curtiss' outstanding Nikolsky Lecture and share this wonderful honor with a long list of my role models in aircraft and rotorcraft flight dynamics and control.

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Dr. Mark B. Tischler retired in January 2021, as an Army Senior Technologist (now Emeritus) and Senior Scientist with the U.S. Army Technology Development Directorate—Moffett Field, CA. He earned B.S and M.S. degrees in aerospace engineering from the University of Maryland and a Ph.D. in aeronautics and astronautics from Stanford University. His over 40-year professional career includes extensive technical and leadership experience in the aerospace industry and government. For over 25 years, he led the U.S. Army Flight Control Technology Group at Moffett Field, CA, which conducts research on handling qualities, flight dynamics, and control on a wide range of rotorcraft, fixed-wing aircraft, and unmanned air vehicle (UAV) applications. He has mentored an entire generation of flight control researchers. Dr. Tischler headed the development and broad application of two widely used commercial tools for aircraft and rotorcraft system identification and control system design (CIFER® and CONDUIT®) and pioneered the concept and implementation of model stitching for continuous full-flight envelope simulation from system ID point models. He initiated and was the U.S. Army lead of the U.S.–Israel Memorandum of Understanding (MOU) on Rotorcraft Aeromechanics and Man/Machine Integration for 30 years (1986–2016).

Over his career, Dr. Tischler authored and co-authored over 200 research publications and authored four textbooks: *Aircraft and Rotorcraft System Identification* (AIAA, 2006, 2012), *Practical Methods for Aircraft and Rotorcraft Flight Control Design* (AIAA, 2017), and *Advances in Aircraft Flight Control* (Taylor & Francis, 1996; Organizing Editor and co-author). Dr. Tischler has served as a primarily technical and thesis co-advisor for many M. S. and Ph. D. students who have conducted their thesis research within the Flight Control Technology Group. For over 30 years, he has taught short courses on flight control technologies in various professional forums and industrial facilities and has widely mentored industry researchers. From 2018 to 2020, he initiated and led the NATO international research technical group of 20 leading researchers on “Rotorcraft Flight Simulation Model Fidelity Improvement and Assessment” and co-led the follow-up international Research Lecture Series (2021).

Dr. Tischler has received many major awards for his work over the years, including AIAA Associate Fellow (2001), being named to the University of Maryland Academy of Distinguished Alumni (2007), four times awarded the Department of the Army Research and Development Achievement (RDA) Award (1989, 1997, 2002, 2007), American Helicopter Society (AHS) Technical Fellow (2007), the Department of the Army International Collaboration Award (2010), and the U.S. Army RDECOM Director’s Decoration for Superior Civilian Service (2017). He has the rare distinction of twice receiving the Presidential Rank Award for Distinguished Senior Professional (2009, 2018). The Vertical Flight Society awarded Dr. Tischler the 2020 Nikolsky Honorary Lectureship. He received the Department of the Army Distinguished Civilian Service Medal in 2020 for extraordinary contributions as a senior research scientist.

Dr. Tischler recently launched “Tischler Aeronautics,” with a focus on providing Engineering Support in Rotorcraft and Aircraft Flight Dynamics and Control.