

A Tribute to Professor René H. Miller

A Pioneer in Aeromechanics and Rotary Wing Flight Transportation

Peretz P. Friedmann
François-Xavier Bagnoud Professor of Aerospace Engineering
University of Michigan
Ann Arbor, Michigan 48109
peretzf@umich.edu

Wayne Johnson
NASA Ames Research Center
Moffett Field, CA 94035-1000
wayne.johnson@nasa.gov

Michael P. Scully
Chief Design Engineer
Aeroflightdynamics Directorate (AMRDEC)
U.S. Army RDECOM
Ames Research Center, Moffett Field, CA 94035-1000
mike.scully@us.army.mil

ABSTRACT

René H. Miller (May 19, 1916 – January 28, 2003), Emeritus H. N. Slater Professor of Flight Transportation at the Massachusetts Institute of Technology, was one of the most influential pioneers in rotary wing aeromechanics as well as a visionary whose dream was the development of a tilt-wing / tilt-rotor based short haul air transportation system. This paper pays a long overdue tribute to his memory and to his extraordinary contributions.

INTRODUCTION - BIOGRAPHICAL SKETCH

René Harcourt Miller (named after a French Godparent) was born in Tenaflly, New Jersey. His father died in 1918, leaving his mother with three small boys of whom René was the youngest. Upon remarriage in 1920, his mother became the Duchesse de Majo Durazzo and moved with her family to a house outside Paris, France.

René's schooling was erratic. An English governess until he was 12, four years at an American School in Paris, followed by three years at Cambridge University in England, where he studied Mechanical Sciences graduating in 1937 with a B.A. degree. He always regretted not being sent to a

French school, which meant, as he said, that his French was "fast, fluent, and incorrect". After graduating from Cambridge he was unable to find a job because of the Depression, so he returned to the USA and joined his family who had previously returned. In his first job as a vibrations and structures test engineer at the Glenn L. Martin Co. in Baltimore, he encountered some "tricky" problems associated with the design and testing of the XPBM-1 Mariner twin-engine flying-boat (XPBM-1 first flight was on 18 February, 1939). Flying in the XPBM-1 as a test engineer was memorable and included measuring the vibratory structural response excited by on-board shakers.

In 1940, René joined the McDonnell Aircraft Corporation that was being set up in St. Louis as chief of aerodynamics and development. He had desperately wanted to join the Armed Forces, however, due to his childhood polio, he had to settle for working long hours for McDonnell. During the next few years, he became involved with the development of several aircraft. The bat-like XP-67 twin-engine fighter (first flight 6 January, 1944) had many

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problems with its low-drag piston-engine installation. This painful lesson emphasized the critical importance of engine inlet and exhaust efficiency. It caused McDonnell to develop engine installation design and test capabilities that gave it a significant advantage in the development of early jet aircraft. These capabilities were important in the rapid and successful development of the FD-1 (later FH-1) Phantom twin-jet fighter (first flight 26 January, 1945) where the engine installation greatly benefitted from the XP-67 experience. The Phantom became the first US Navy jet aircraft to make a carrier take-off and landing on 19 July, 1946. The Phantom was developed into the larger F2H Banshee (first flight 11 January, 1947) with twice the engine thrust. René was also involved in the development of the first ramjet helicopter, the XH-20 "Little Henry" (first flight 29 August, 1947). Ramjet fuel consumption, noise and drag (in autorotation) were issues with the design.

In 1944, René moved to Boston to join the Aeronautics and Astronautics Engineering Department at MIT, an institution with which he was associated for almost 60 years. He continued to work for McDonnell as a consultant during his first few years at MIT. From 1952 to 1954, while on leave from MIT during the Korean War, he was Vice President of Engineering at Kaman Aircraft Co. where he was responsible for completing the development of the HOK-1 (later OH-43D). The piston engine HOK-1 entered service as the USMC observation helicopter in 1956 and was ultimately replaced by the turbine engine UH-1E "Huey". During this period, he also initiated work on several new projects including the first remotely controlled drone helicopter (a drone HTK-1 trainer version of the HOK-1), a helicopter autopilot and a rotorhute for aerial delivery. In 1954, at the end of this period, he obtained his M.A. degree from Cambridge University in England.

In 1955, René returned to MIT where he developed courses in a variety of subjects including Vertical Take-Off Aircraft (16.50 and 16.51), Flight Vehicle Engineering (16.71 and 16.74) and Space Systems Engineering (16.73 and 16.74). In 1962, he was appointed H. Nelson Slater Professor of Flight Transportation. He promptly founded the MIT Flight Transportation Laboratory (FTL). MIT was starting a research planning study for the Northeast Corridor Transportation Project of the U.S. Department of Commerce. The primary focus was on high-speed ground transport but René convinced them to add a Systems Analysis Short Haul Air Transportation as Part III. The product of this effort was the first FTL report [13]. This was a complete air transportation systems analysis including: vehicle design, costs (direct and indirect), system network, ground facilities, management information system and operating characteristics. The multidisciplinary effort resulted in development of a course entitled Flight

Transportation (16.751J), jointly with civil engineering (1.221J), electrical engineering (6.671J), and management (15.483J).

These activities resulted in a substantial FTL research program for the U.S. Department of Transportation on many aspects of flight transportation including the use of vertical take-off airbuses for heavily congested areas. In addition, he was involved with a number of other research projects as described later in the paper. René was the focal point of the rotary-wing activities at MIT and during this time he also served as the third Editor-in-Chief of the Journal of the American Helicopter Society (1958-59).

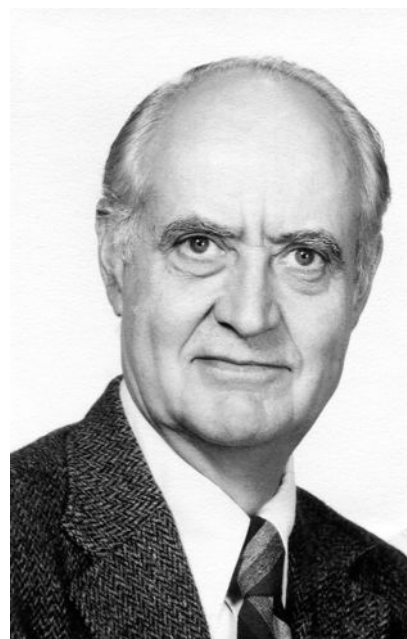


Figure 1. René's picture from the period when he was Department Head at MIT.

In fall of 1968, René was appointed Head of the MIT Aeronautics and Astronautics Department serving in this position for ten years. A picture from this period, Fig. 1, only partially conveys his presence and personal charm. His ten-year term came at a time of great unrest in the universities, but, despite the drop in the number of aero students, the department weathered the storm well. During this period, his innovative approach was again evident. He started the Space Systems Laboratory, which eventually became one of the focal points in the department. His strong interest in Systems Engineering continued and he emphasized this area. It is interesting to note that currently in the Aeronautics and Astronautics Department, systems engineering has become an important pillar of activity

replacing more traditional areas such as the rotary-wing engineering.

After completing his tour as Department Head, René continued his activities in research and teaching on both rotorcraft and spacecraft. During his distinguished career, he belonged to many engineering bodies and served on numerous committees such as: the FAA Technical Advisory Board, Air Force Scientific Advisory Board, Army Scientific Advisory Panel, Chairman of the Aviation Scientific Advisory Panel of the Army Aviation Command, NASA Advisory Committee on Aircraft Aerodynamics, Aircraft Panel of the President's Scientific Advisory Committee, NAE Supersonic Research, and Technology Committee.

René was also very active in AIAA, where he served on the Publications Committee, the Board of Directors, and as the President of AIAA in 1977-78. He also enjoyed travelling and attended many conferences. He even managed to get a pre-service flight on the Concorde from Boston to Paris and back.

During his long career, René guided many students who went on to fill some of the top positions in the US aerospace industry. One of his delights in the summer was taking groups of students to the Scrag Island in Maine where they worked enthusiastically on the many projects that he devised to help make life there somewhat less primitive than it had been when he first acquired the island. Even after moving to England, he still managed to spend part of each summer on the island.

René became Professor Emeritus in 1986 and moved to Penzance, England where his wife Maureen owned a lovely house close to the beach. After retiring, he continued with his research on wake models, in particular the fast free wake methods. He continued presenting his research at conferences and published several journal papers.

René's exceptional accomplishments have been recognized by numerous awards, the most important were: election to the National Academy of Engineering, AHS Alexander Klemin Award and Honorary Nikolsky Lectureship, AIAA Sylvanus A. Reed Award, US Army Decoration for Meritorious Civilian Service, and the I.B. Laskowitz Award (N.Y. Academy of Sciences). He was an Honorary Fellow of AIAA and AHS.

RESEARCH CONTRIBUTIONS

Professor Miller's research contributions covered a broad range of topics, as evident from References 1 - 33, which are representative of his rotary wing related work. The principal topics covered were: (a) jet propulsion applied

to helicopters [1,4], (b) helicopter stability and control [2,3 and 29], (c) vibration and flutter [5, 25], (d) helicopter design and operations [4, 12, 13], (e) helicopter airloading in hover and forward flight [6-11], (f) free wake modeling and fast free wake analysis in hover and forward flight [18-24, 26-28, and 30-33] and (g) wind turbine aerodynamics and dynamics [15-17]. Miller's article in Progress of Aerospace Sciences of 1985 summarized his work in many of these disciplines [25].

Helicopter Design and Operations

René's interest in the design of unusual configurations is evident from an early paper written for McDonnell Aircraft on jet propulsion applied to helicopter rotors during his Assistant Professor period [1]. In this paper, he carried out a detailed comparison between two jet driven rotor configurations: (a) a rotor driven by a ramjet located at the blade tip and (b) a jet driven rotor where the pressure to the tip jet combustion chamber is produced by centrifugal compression in a hollow blade augmented by additional compression generated by a compressor.

The justification for these tip jet configurations was the weight saving associated with the elimination of anti-torque devices and weight saving due to mechanical simplicity. The configurations were compared using relatively simple expressions for the aerodynamic efficiency of the rotor in both hover and forward flight. Assuming a constant speed rotor, he obtained expressions for vertical rate of climb, range, and maximum range. The maximum range was evaluated for various tip speeds, disc loading and solidity, assuming a fuel fraction equal to 7.5% of gross weight.

Arguing that the case of a ramjet driven rotor is straightforward, the paper focused on detailed examination of the case where air is pumped through the rotor blade(s) to the tip jet. Pumping losses due to friction inside the rotor blade(s) drive large rotor solidity and minimum number of blades. Ignoring compressibility effects, ideal cycle efficiencies were considered as a function of the pressure ratio, defined as the ratio of combustion chamber pressure to atmospheric pressure. After introducing several assumptions, the performance of a conventional helicopter was compared to a helicopter using a jet driven rotor and it was concluded that, "It will be probably possible in every case to exceed the performance of a conventional helicopter, provided that a single-blade rotor could be built and made to operate in a satisfactory manner. If a two-bladed rotor is used, the performance will still be better, except for the case of a light helicopter with a jet driven rotor."

A fascinating systems analysis, completed 20 years later, dealt with the short haul air transportation in the

Northeast Corridor consisting of Boston - New York - Washington, DC. The study represented the culmination of a ten-year effort funded by the Department of Commerce on transportation issues in the Northeast Corridor [13]. It is a marvelous illustration of the dangers and pitfalls associated with making assumptions that about future developments.

As a starting point, the automobile was identified as the dominant and most popular mode of transportation despite its shortcomings in speed, accident rate, and overall cost. René concluded that the reason for this situation was due to the door-to-door convenience combined with the fact that once the initial fixed costs have been paid, additional mileage is accumulated at less than one cent per available seat mile. Therefore, to compete with the door-to-door convenience of the automobile, the terminal areas of the air transportation system have to be moved much closer to the individual passenger's point of origin, which implies locating a substantial number of transportation collection and distribution points, i.e. terminal areas, in highly populated areas. This requirement logically directed the study into consideration of VTOL and STOL configurations since such vehicles have, "terminal requirements equal or less than ground transportation systems, and in addition, need no right of the way. Short haul VTOL transportation can thus achieve a higher degree of flexibility in routing than any other public transportation system while retaining the accessibility to densely populated areas of ground transportation." It was also noted that for such a system, no costly fixed installations are required and the air transportation system can readily adjust to cyclic variations in travel demand. Finally, it was noted that aircraft can operate efficiently with relatively small passenger capacities, of the order of 80, and frequent service based on demand is feasible.

Block time vs. stage length and trip cost per passenger vs. trip distance were both modeled as a zero distance value plus a linear slope vs. distance. The short trip distances of interest (100 statute miles or less) drove a requirement to minimize both block time and trip cost for zero distance. This resulted in optimized flight profiles with no maneuvering for air traffic control and minimized indirect costs comparable to bus operators rather than airlines. Boeing noticed this study result and suggested an airport design with a double length runway and a passenger terminal in the middle to minimize taxi time.

With these assumptions a comprehensive study was conducted comparing the characteristics of five different vehicle configurations: (a) a conventional short haul jet, (b) a STOL vehicle, (c) a tilt-wing, (d) a jet lift and (e) a helicopter. Five aircraft design (sizing) computer codes were

created, one for each configuration. These design codes were used to develop "optimum" designs for each configuration. Gross weights of 47,000-62,000 lbs were obtained for five configurations sized to carry 80 passengers over a 200 mile design range. Parametric design studies were also performed, including aircraft sized for both 40 passengers and 120 passengers to validate the 80 passenger design point. The technical characteristics of the vehicles were based on specific 1970 technology assumptions documented in the report. Using these assumptions, the direct operating costs for typical short haul aircraft based on 1970 technology are shown in Fig. 2.

Subsequently, a set of fairly optimistic assumptions were introduced and similar vehicles were sized based on 1980 technology. The principal benefits of the more advanced technology were: reduction in structural weight through the use of composites, increase of engine horsepower (or thrust) to weight ratio combined with a reduction in engine cost, and also increase in utilization due to increase in operational experience. The difference due to these more optimistic assumptions is illustrated in Fig. 3. While Ref. 12 admits that such assumptions are speculative, the results show the superiority of the tilt-wing vehicle compared to its competitors.

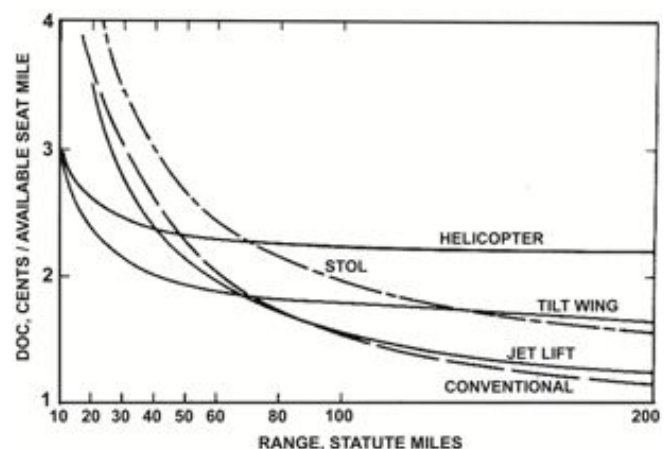


Figure 2. Direct operating cost for typical short haul aircraft – 1970 time period.

Finally additional predictions regarding cost reduction were introduced to estimate the potential total cost per trip for the short haul air transportation system operating in the 1980 time frame, shown in Fig. 4. These predictions were fascinating in view of our current knowledge. For example, it was postulated that a reservation system could be eliminated and passenger would use a credit card inserted in a suitable reader when boarding and again at the

destination. Thus, “the need for several agents at the terminal gates would be reduced.” This was based on an automated fare collection system planned for the Bay Area Rapid Transit (BART) rail system in the San Francisco Bay Area. A similar fare collection system is used by the Washington Metro Rail System.

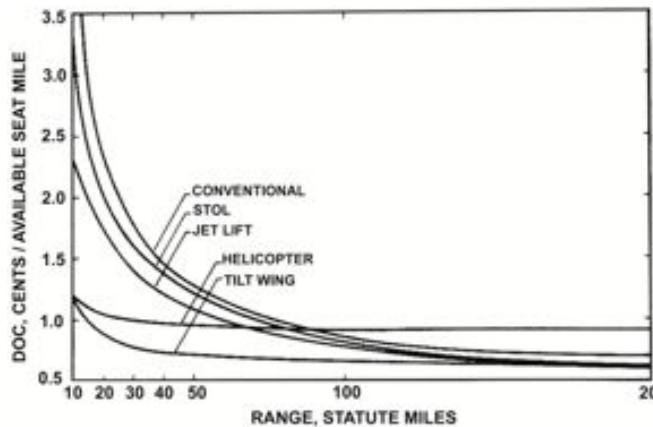


Figure 3. Direct operating cost for typical short haul aircraft – 1980 time period.

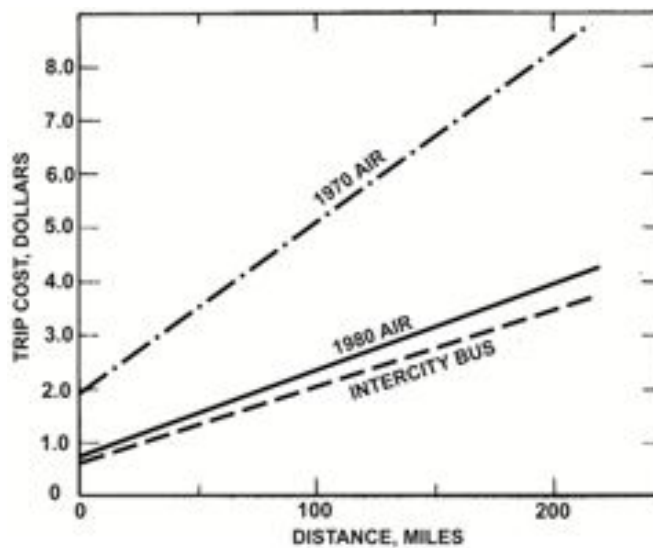


Figure 4. Potential total trip cost for short haul air transportation system operating in the 1980 time period.

Figure 4, from Ref. 12 shows clearly that the final cost per trip for the tilt-wing based air transportation system is comparable to an intercity bus. Thus, the principal conclusion of Ref. 12 was concisely summarized as, “A reliable, all weather, high speed, short haul air transportation system operating directly from urban

centers at costs approaching present bus system costs could be developed for the 1980 period. No new technologies which are not already in development stage are needed in order to achieve this goal.”

Vibration and Flutter

Reference 5 was an interesting contribution to aeromechanics which addressed two connected problems. One problem was the reduction of vertical vibrations due to vertical forces at the hub by adjusting the blade torsion-bending coupling and torsional stiffness. Since the method requires the manipulation of the blade torsional stiffness, a second problem - coupled bending torsion flutter and divergence in hover - was also addressed.

This comprehensive study, for the case of hover, was substantially ahead of its time in recognizing and identifying several important parameters that started to appear routinely in aeroelastic analyses a decade later. From a historical perspective, it is well known that the importance of nonlinear terms due to moderate blade deflections and the role of the lag degree of freedom were only understood later based on the research conducted in rotary-wing aeroelasticity in the 1970-80 time frame [34]. The first part of the paper focused on the aeroelastic stability of a rotor blade in hover by examining the effects of several parameters and assumptions in a systematic manner. The principal effects examined were: blade flexibility in bending and torsion, steady state deflection including steady state coning, offsets between blade center of gravity (CG) elastic or feathering axis (EA) and aerodynamic center (AC), aerodynamic assumptions, the lag degree of freedom and the role of higher order terms in the lag equation, steady in-plane of rotation bending, control system stiffness, distributed torsional flexibility, and tip masses.

For aeroelastic stability, comprehensive equations modeling the effects mentioned above were derived. The derivations represent a combination of careful analysis and Miller’s extraordinary intuition and insight as to the essential terms that have to be included and which may be neglected. This was one of his trademarks. The equations had additional coupling terms associated with finite deflection, bending-torsion coupling terms, and steady state deflections. The unsteady aerodynamic loads were obtained either by using a slightly modified version of Theodorsen theory, or using Loewy’s modification of Theodorsen theory which incorporates the returning wakes in hover [35]. A series of problems with increasing complexity were examined.

Using these equations several problems were considered. First a rigid blade in flap, combined with torsional flexibility as represented by control system stiffness at zero pitch, was considered. In this case steady

elastic deflections and coning angle were both zero. The parameter varied was the CG offset from the EA, which was assumed to be coincident with the AC.

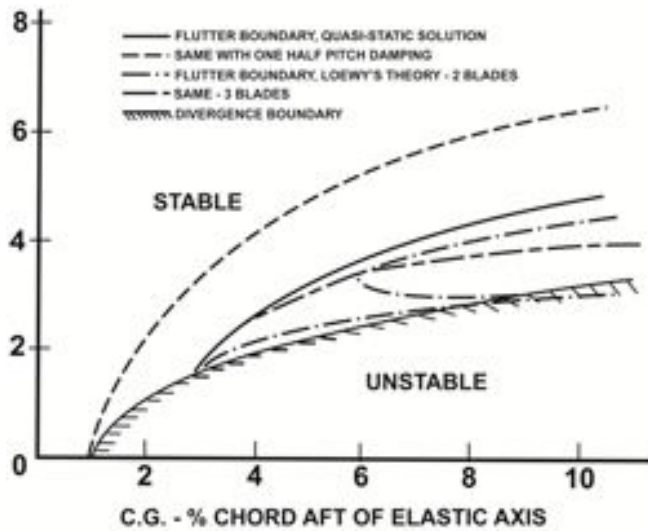


Figure 5. Flap-pitch stability boundary.

Typical results for divergence and flutter boundaries are shown in Fig. 5. Positive offsets are aft of the EA and they are plotted on the horizontal axis of Fig. 5. The vertical axis is the nonrotating natural frequency in torsion about the feathering axis nondimensionalized with respect to the speed of rotation. The results correspond to a 3-bladed rotor with a solidity of 0.04. The lower boundary (cross hatched) is the divergence boundary and the lines above the divergence boundary represent several flutter boundaries. The upper dashed line represent the flutter boundary with quasi-steady Theodorsen theory, with apparent mass terms neglected and damping in pitch reduced by 50%. Below this curve the full line represents the flap-pitch flutter boundary with quasisteady Theodorsen theory. The two additional lines between the flutter and divergence boundaries represent flutter boundaries using Loewy type of aerodynamics. The broken type lines represent flutter boundaries based on Loewy's theory for two and three bladed rotors, assumed to oscillate in phase, with an assumed wake spacing $h=2$. The most important conclusion obtained was that the quasisteady assumption is a reasonable assumption for the coupled flap-torsion problem of rotor blades in hover and it has been widely used since then. Next the effect of steady in-plane bending was examined using the geometry shown in Fig. 5. The blade was assumed to have its torsion axis outboard of the flap and lag hinges and the deflection of the quarter chord line was denoted by ϕ shown in Fig. 5. The resulting aerodynamic twist due to sweep back or sweep forward was included using an equivalent CG – EA offset, and the effect was found to be negligible. It is

important to note that this was the first study to examine in detail the effect of the lag degree of freedom. Next, blade flexibility in bending was introduced by incorporating the first blade elastic bending mode. All the torsional stiffness was represented by the control system stiffness; i.e. blade was torsionally rigid along its span. It was concluded that the elastic bending mode had a negligible effect on the flap pitch flutter boundary shown in Fig. 4, when the CG location of the blade is the primary variable. Subsequently, the effect of distributed torsional stiffness was considered and Miller concluded that the added computational effort due to this effect is not justified. Next, the effects of initial elastic deflection and steady coning were also examined and found to be negligible.

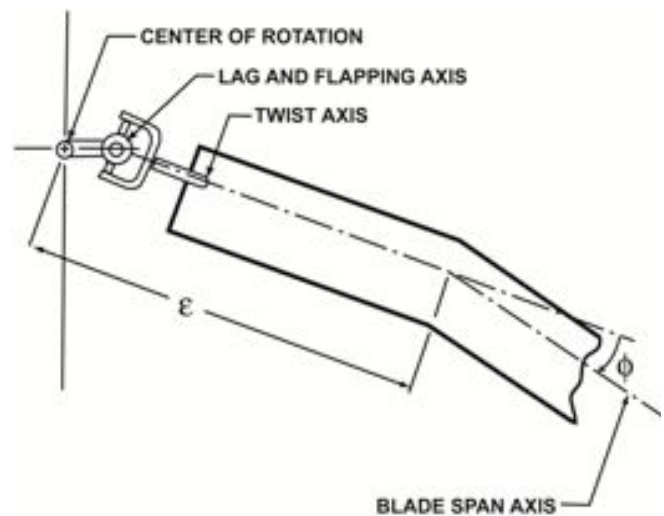


Figure 6. Planview of blade with in-plane deflection.

In the second part of the paper, a detailed parametric study of the vibration problem was conducted by examining the vertical oscillatory shear at the root of the blade. Since the equations were limited to hover and the vibratory loads due to forward flight were not modeled, a harmonic excitation was introduced by assuming harmonic variations in the pitch input as a result of an external source such as a servo flap or harmonic variations in inflow. Shear at the root was modeled by considering the response of a uniform beam and the following ratio was examined:

$$\frac{s}{s_o} = \frac{\text{flexible in torsion with torsion bending coupling}}{\text{stiff in torsion without torsion bending coupling}}$$

This ratio was evaluated for a large range of parameters using an analog computer. The quantities varied were frequencies, blade CG offsets from EA, torsional flexibility, and concentrated masses. The effect of these variations on the control loads and the bending moments were also considered. This portion of the paper presents a novel

approach of dealing with the vibration problem by using the hover equations; however its conclusions were less fundamental than those obtained in the first part.

Airloads and Wakes

Miller described the problem of computing the harmonic airloading on a helicopter rotor blade in forward flight [6, 10]:

“The determination of the air loads acting on rotor blades in forward flight presents an interesting and challenging problem in applied aerodynamics. Of particular importance for design purposes are the oscillatory components of this loading occurring at harmonics of the rotor speed. Unlike a wing, the trailing and shed vortex system of the blade generates a spiral wake that returns close to the blade. Because of its close proximity to the blade, the wake cannot be considered as rigid. Also, since the resulting loads are highly time-dependent, unsteady aerodynamic effects become important.”

“The oscillatory air loads occurring at harmonics of the rotor speed are the primary source of the blade stresses that establish the fatigue life of the structure and of the periodic hub loads that determine the fuselage vibration level.”

The work was the extension of non-rotating wing and two-dimensional airfoil unsteady aerodynamic theory to the complicated wake of the helicopter rotor in forward flight, made possible by the digital computer. Developing wake models for rotor non-uniform inflow calculations continues today, but the work started with Miller.

Miller relates that experimental work at MIT in the 1950s, such as Refs. 36–37, made clear the importance of unsteady aerodynamics for rotor blades [8]:

“The tests ... clearly indicated the need for an analytical tool for computing blade downwash velocities which would take into account the individual blade wake geometry and also introduce the effects of unsteady aerodynamics. Attempts to obtain a closed form solution to this problem, or one based on tabulated integrals, were not successful and it was evident that extensive computer facilities would be required to explore this problem and, hopefully, to provide a basis for obtaining simplified solutions suitable for engineering applications. In 1960 the availability of an IBM 709 computer at the MIT Computation

Center and funds from a Carnegie grant permitted initiation of such a program.”

Miller’s first publication of this work was a 102-page IAS paper presented in January 1962 [6] later published as Ref. 10. The work was supported primarily by the Department of the Navy. In October 1963, Miller delivered the Cierva Memorial Lecture to the Royal Aeronautical Society; this lecture was the basis for Ref. 9.

The rotor model consisted of a sheet of distributed vorticity for the blade, and a wake of shed and trailed vorticity shown in Fig. 7. The Biot-Savart law gave the induced velocity increment caused by trailed vorticity (from radial change in bound circulation), simplified to the case of a lifting line in which the variation over the chord is neglected. It was necessary to integrate from the blade to infinity down the spiral, initially accomplished with numerical integration. From Ref. 9:

“Computations of air loads is complicated by the existence of singularities in the solution. These occur as the shed wake approaches the trailing edge of the rotor and whenever the blade passes through a trailing vortex line generated by itself or another blade. The treatment of the singularities and of the non-uniform flow field presents no basic problem providing lifting surface theory is used. However, this requires the numerical evaluation of the downwash at several chordwise as well as spanwise stations and hence, usually involves a prohibitive amount of machine computation time. Approximate methods have therefore been used to evaluate the unsteady aerodynamic effects.”

The initial approach was to develop a combined analytical and numerical procedure [6]. In Ref. 7 a simpler method was developed, in which the induced velocity was calculated at a single point on the airfoil chord, but only using the shed wake up to a finite distance behind the collocation point.

Miller’s results included analytical work to support the assumptions and simplifications [10]. A two-dimensional solution for a hovering rotor was developed, to obtain Loewy’s results using a lifting line approximation for the far wake. A three-dimensional solution for vertical flight was developed, from vortex theory for an unsteady actuator disk.

Three-dimensional solutions for forward flight were obtained by numerical integration on a high speed digital computer. In Ref. 10, the calculated inflow was compared with the measured airloads of Falabella and Meyer [36] interpreted as a measured downwash. In Ref. 9,

comparisons were made with the measured airloads of Rabbott and Churchill [38] and the flight test data of Scheiman [39].

Prof. Miller acknowledged the assistance of his student Michael P. Scully in preparing Ref. 9. Scully, who started working for Miller in September 1963, carried the research forward, dealing with the efficiency of the wake model [40]. This work resulted in a finite straight-line model for the trailed wake shown in Fig. 8. Then their attention turned to free wake geometry calculations [41–42].

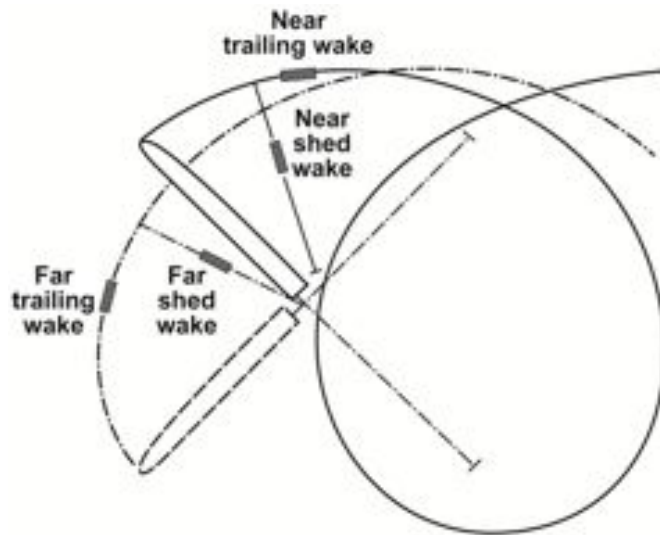


Fig. 7. Wake geometry showing trailing tip vortex and element of shed wake [9].

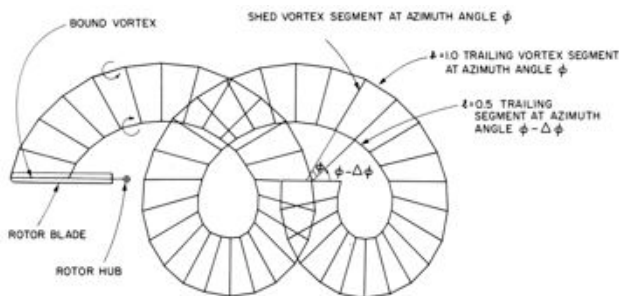


Fig. 8. Finite straight-line approximation [40-41].

Motivated by the high computational costs of free wake geometry calculations, Miller developed a simplified approach [18–23] intended to “help obtain a better understanding of the physics of the problem of wake structure and as a guide for more elaborate aerodynamic modeling” [19]. Two-dimensional models, and elementary

extensions to three dimensions, were used for the hover free wake analysis — called fast free wake. The wake directly behind the blade is composed of a series of straight semi-infinite vortex filaments. It was assumed that this distributed wake rolls almost immediately, according to Betz’s theory of conservation of momentum. The wake from the tip to the bound circulation peak rolls up to form the tip vortex. “A second roll up will most likely occur between this point of maximum circulation and the point where the circulation gradient again starts changing abruptly. The remaining circulation to the root must then roll up into a third vortex.” The root and mid vortices are thus a simple model of the inboard wake sheet. “The far wake is represented by semi-infinite vortex sheets in the case of the two dimensional model and by semi-infinite vortex cylinders for the three dimensional case.” The wake geometry is calculated by an iterative method, by integrating the induced velocities at points on the wake. For both the two-dimensional and three-dimensional models the induced velocity was required at only a small number of points in the wake. Combined with the simplifications of the wake structure, the result was a very fast method. Good comparison was shown with measured hover airloads and wake geometry.

A cloud-in-cell CFD method was developed to generate a more accurate rollup of the trailed filaments in the near wake [27]. The fast free wake geometry method was also developed for applications to wind turbines [15-17, 23]. Miller also revisited the issues of forward flight wake models [24, 27]. It is common for a helicopter rotor in high-speed forward flight to encounter negative lift on the advancing tip. Hooper [43] used blade airloads measurements from the wind tunnel test of the H-34 rotor to examine the blade vibratory aerodynamic loading, focusing on cases with negative tip loading. The vortex-induced loading on following blades shows that this negative loading produces substantial negative trailed vorticity in the wake. Miller [24] developed a wake model in which entrainment of trailed vorticity into the tip vortex occurs from the outboard (negative) peak bound circulation, not from the inboard (large positive) peak. Figure 9 illustrates Miller’s concept for the wake model. References 26, 30 and 31 dealt with the issues of wake rollup in hover and forward flight; they also are notable for Miller’s work with two generations of Ellis’s, the first generation being Ref. 5.

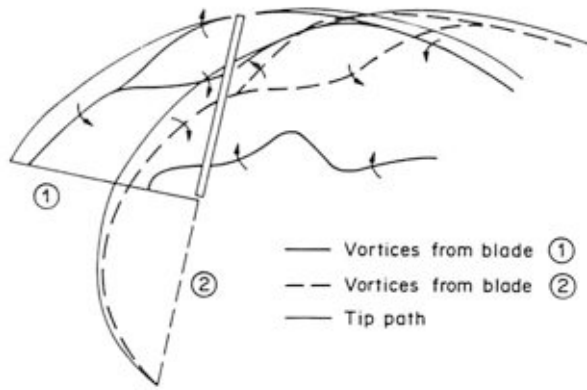


Fig. 9. Sketch of wake geometries at critical intersections [24].

CONCLUDING REMARKS

The authors had the good fortune to spend a number of years at MIT working under René Miller's guidance: Scully from 1960 to 1975, Johnson from 1964 to 1970, Friedmann from 1969 to 1972. That this time was productive and enjoyable was in large part due to both his personal attention and the impact he had on the MIT Aero Department. He introduced us to rotorcraft, and you can still see his influence in our work. In the decades to follow we became colleagues and remained friends. A few individual notes follow.

Mike Scully

During the dozen years that I worked with René, he taught many things including: aviation and space systems design, systems analysis and rotary wing aeromechanical analysis. Above all he taught how to be a real engineer using many tools to develop, substantiate and sanity check the product. Students who turned in obviously wrong answers straight from the computer got a lesson in real engineering. He inspired a career in vertical take-off aircraft (instead of space) that continues to be exciting and fulfilling.

Peretz Friedmann

My involvement with rotary wing vehicles started in early 1970 when René asked me whether I would like to work on nonlinear rotary-wing aeroelasticity for my doctoral thesis. In retrospect it is amazing how an affirmative answer turned into a lifelong activity. René provided exceptional guidance based on his understanding of the problem and his intuition that allowed him to identify invariably the most important issues. He was always generous with his time. The two and a half years that I spent doing research with him were among the most enjoyable years in my life. At the end of this period he provided the advice and mentoring needed for starting an

academic career and continued to mentor me throughout the years. He had a major influence on my life and was a role model that I tried to emulate during my career.

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REFERENCES

1. Miller, R. H., "Jet Propulsion Applied to Helicopter Rotors," *Journal of the Aeronautical Sciences*, Vol. 13, No. 12, December 1946.
2. Miller, R. H., "Helicopter Control and Stability in Hovering Flight," *Journal of the Aeronautical Sciences*, Vol. 15, No. 8, August 1948.
3. Miller, R. H., "A Method for Improving the Inherent Stability and Control Characteristics of Helicopters," *Journal of the Aeronautical Sciences*, Vol. 17, No. 6, June 1950.
4. Miller, R. H., "Some Factors Affecting Helicopter Design and Future Operations," *Fourth Anglo-American Aeronautical Conference*, London, September 1953.
5. Miller, R. H., and Ellis, C. W., "Helicopter Blade Vibration and Flutter," *Journal of the American Helicopter Society*, Vol. 1, No. 3, July 1956.
6. Miller, R. H., "Rotor Blade Harmonic Air Loading," *IAS*, Vol. 62, No. 82, January 1962.
7. Miller, R. H., "On the Computation of Airloads Acting on Rotor Blades in Forward Flight," *Journal of the American Helicopter Society*, Vol. 7, No. 2, April 1962, pp. 56-66.
8. Miller, R. H., "A Discussion of Rotor Blade Harmonic Airloading," *CAL/ TRECOM Symposium on Dynamic Load Problems Associated with Helicopters and V/STOL Aircraft*, Buffalo, NY, June 1963.
9. Miller, R. H., "Unsteady Air Loads on Helicopter Rotor Blades," *Journal of the Royal Aeronautical Society*, Vol. 68, No. 640, April 1964, pp. 217-229.
10. Miller, R. H., "Rotor Blade Harmonic Air Loading," *AIAA Journal*, Vol. 2, No. 7, July 1964, pp. 1254-1269.
11. Miller, R. H., "Theoretical Determination of Rotor Blade Harmonic Airloads," *MIT ASRL TR 107-2*, August 1964.
12. Miller, R. H., "Air Transportation in the Eastern Corridor," SAE Paper No. 660332, *National Aeronautic Meeting*, New York, NY, April 1966.

13. Miller, R. H., and Simpson, R. W., "A Systems Analysis of Short Haul Air Transportation," *MIT FTL TR 65-1*, August 1965.
14. Miller, R. H., "Notes on Cost of Noise Reduction in Rotor/Prop Aircraft," *MIT FTL M68-9*, August 1968.
15. Miller, R. H., Dugundji, J., Chopra, I., Sheu, D., and Wendell, J., "Wind Energy Conversion. Volume III: Dynamics of Horizontal Axis Wind turbines," *ASRL TR 184-9*, September 1978.
16. Miller, R. H., Dugundji, J., Martinez-Sanchez, M., Gohard, J., Chung, S., and Humes, T., "Wind Energy Conversion. Volume II: Aerodynamics of Horizontal Axis Wind Turbines," *MIT ASRL TR 184-8*, September 1978.
17. Miller, R. H., Dugundji, J., Martinez-Sanchez, M., Gohard, J., Chung, S., and Wendell, J., "Wind Energy Conversion. Volume I: Methods for Design Analysis of Horizontal Axis Wind Turbines," *MIT ASRL TR 184-7*, September 1978.
18. Miller, R. H., "Simplified Free Wake Analysis for Rotors," *MIT ASRL TR 194-3*, August 1981.
19. Miller, R. H., "A Simplified Approach to the Free Wake Analysis of a Hovering Rotor," *Vertica*, Vol. 6, No. 2, 1982.
20. Miller, R. H., "Vortex Theory for Hovering Rotors," *AIAA Journal*, Vol. 20, No. 12, December 1982.
21. Miller, R. H., Tanuwidjaja, A., and Brower, M., "Free Wake Techniques for Rotor Aerodynamic Analysis," *NASA CR 166434*, *CR 166435*, *CR 166436*, December 1982.
22. Miller, R. H., "Rotor Hovering Performance Using the Method of Fast Free Wake Analysis," *Journal of Aircraft*, Vol. 20, No. 3, March 1983.
23. Miller, R. H., "Application of Fast Free Wake Analysis Techniques to Rotors," *Vertica*, Vol. 8, No. 3, 1984.
24. Miller, R. H., "Factors Influencing Rotor Aerodynamics in Hover and Forward Flight," *Vertica*, Vol. 9, No. 2, 1985.
25. Miller, R. H., "Methods for Rotor Aerodynamic and Dynamic Analysis," *Progress in Aerospace Sciences*, Vol. 22, 1985.
26. Miller, R. H., and Ellis, S. C., "Prediction of Blade Airloads in Hovering and Forward Flight Using Free Wakes," *Twelfth European Rotorcraft Forum*, Garmisch-Partenkirchen, Germany, September 1986.
27. Miller, R. H., Roberts, T. W., and Murman, E. M., "Computational Methods for Wake Modeling and Blade Airload Determination in Hover and Forward Flight," *Computers and Mathematics with Applications*, Vol. 12A, No. 1, 1986.
28. Miller, R. H., "The Prediction of the Vibratory Airloads of Helicopter Rotors in Forward Flight," *Journal of Fluids and Structures*, Vol. 1, No. 1, January 1987.
29. Miller, R. H., "Improving Handling Qualities in Low Speed and Hover with Velocity Feed Back Systems," *Royal Aeronautical Society International Conference on Helicopter Handling Qualities and Control*, London, UK, November 1988.
30. Miller, R. H., Ellis, S. C., and Dadone, L., "The Effects of Wake Migration During Roll-Up on Blade Air Loads," *Vertica*, Vol. 13, No. 1, 1989.
31. Miller, R. H., Ellis, S. C., and Dadone, L., "The Effects of Inner Wake Modelling on Blade Airloads," *Sixteenth European Rotorcraft Forum*, Glasgow, UK, September 1990.
32. Miller, R. H., "Fast Free Wake Analyses in Hovering and Forward Flight," *Nineteenth European Rotorcraft Forum*, Cernobbio, Italy, September 1993.
33. Miller, R. H., "The Development and Applications of the Fast Free Wake Technique," *Sixth International Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems*, University of California, Los Angeles, Los Angeles, CA, November 1995.
34. Friedmann, P. P. and Hodges, D. H., "Rotary Wing Aeroelasticity a Historical Perspective", *Journal of Aircraft*, Vol. 40, No. 6, November-December, 2003, pp. 1019-1046.
35. Loewy, R. G., "A Two-Dimensional Approximation to the Unsteady Aerodynamics of Rotary-Wings," *Journal of Aeronautical Sciences*, Vol. 24, No. 1, 1957.
36. Falabella, G., Jr., and Meyer, J.R., Jr., "Determination of Inflow Distributions From Experimental Aerodynamic Loading and Blade-Motion Data on a Model Helicopter Rotor in Hovering and Forward Flight," *NACA TN 3492*, November 1955.
37. Ham, N.D., and Zvara, J., "Experimental and Theoretical Analysis of Helicopter Rotor Hub Vibratory Forces," *WADC TR 59-522*, October 1959.
38. Rabbott, J.P., Jr., and Churchill, G.B., "Experimental Investigation of the Aerodynamic Loading on a Helicopter Rotor Blade in Forward Flight," *NACA RM L56I07*, October 1956.
39. Scheiman, J., and Ludi, L.H., "Qualitative Evaluation of Effect of Helicopter Rotor-Blade Tip Vortex on Blade Airloads," *NASA TN D-1637*, May 1963.
40. Scully, M.P., "Approximate Solutions for Computing Helicopter Harmonic Airloads," *MIT ASRL TR 123-2*, December 1965.

41. Scully, M.P., "A Method of Computing Helicopter Vortex Wake Distortion," MIT ASRL TR 138-1, June 1967.
42. Scully, M.P., "Computation of Helicopter Rotor Wake Geometry and Its Influence on Rotor Harmonic Airloads," MIT ASRL TR 178-1, March 1975.
43. Hooper, W.E. "The Vibratory Airloading of Helicopter Rotors." *Vertica*, Vol. 8, No. 2 (1984).