

Tilt Rotor Aeroacoustic Model (TRAM): A New Rotorcraft Research Facility

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Abstract-

This paper introduces the Tilt Rotor Aeroacoustic Model (TRAM) project. The TRAM project is a key infrastructure investment for NASA and U.S. Army tiltrotor research. The TRAM project consists of the development and testing of two modular, hardware-compatible, test stands: an isolated rotor configuration and a full-span model (dual rotors with a complete airframe representation). These two test stands are inclusively called the Tilt Rotor Aeroacoustic Model (TRAM). The baseline proprotors and airframe of the TRAM test stands are nominally 1/4-scale representations of the V-22 Osprey aircraft. The research objectives of the project, the TRAM hardware design features and capabilities required to meet those objectives, and the status of the project are discussed in detail in this paper.

Introduction

Tiltrotor aircraft represent a unique opportunity for the civilian aerospace/aviation industry: the potential intro-

duction of a new class of subsonic transport aircraft. The production launch decision of the U.S. Navy's V-22 Osprey, the launch decision for the Bell-Boeing 609 small corporate/utility tiltrotor, and the positive findings of the U.S. Congressional Report of the Civil Tilt Rotor Development Advisory Committee (Ref. 1) as to the market potential of larger commercial airline tiltrotor aircraft all emphasize the importance of development of this technology.

NASA and the U.S. Army have had a long history of successful tiltrotor technology research and development programs. See, for example, references 2 and 3. Initial research into tiltrotor aircraft during these early years focused on aerodynamic performance for highly twisted proprotor blades and aeroelastic (whirl-flutter) stability in high-speed cruise which led to the successful XV-15 Tilt Rotor Research Aircraft development. NASA and U.S. Army research into tiltrotor aircraft continues to this day. The focus of current research is on technology that will result in civilian or dual-use application of tiltrotors.

In 1991, a NASA/FAA-sponsored report (Ref. 4) from Bell-Boeing outlined several technology areas that were either enabling or enhancing technologies for the development of civil tiltrotor aircraft. The Short Haul Civil Tiltrotor (SH(CT)) program -- a sub-element of the NASA

Presented at the AHS
International Meeting on
Advanced Rotorcraft Technology
and Disaster Relief, Gifu, Japan,
April 21-23, 1998

Advanced Subsonic Transport (AST) initiative -- was developed and initiated to address the fundamental research issues underlying the critical enabling technologies for civilian, 40-passenger tiltrotor aircraft. Through both the NASA Short Haul Civil Tiltrotor focused program and the NASA Rotorcraft Base R&T program, NASA sustains fundamental tiltrotor research programs to address the technical challenges for military and civilian tiltrotor aircraft. To accomplish these goals, moderate-to-large scale wind tunnel testing of tiltrotor models is required. This testing provides the data necessary to confirm performance and aeroacoustic prediction methodologies and to investigate and demonstrate advanced civil tiltrotor and high-speed rotorcraft technologies.

Consequently, in 1991 NASA Ames, NASA Langley, and the U.S. Army jointly initiated the development of two modular, hardware-compatible, test stands: an isolated rotor configuration (Fig. 1) and a full-span model (dual rotors with a complete airframe representation; Fig. 2). These two test stands are inclusively called the Tilt Rotor Aeroacoustic Model (TRAM). The isolated rotor configuration is not a permanent stand-alone test stand, instead its modular sub-assemblies will be incorporated into the full-span configuration upon completion of the currently planned isolated rotor testing.



Figure 1 - TRAM Isolated Rotor Configuration



Figure 2 - Full-Span TRAM Test Stand (Assembly In Progress)

TRAM will be used as a test bed for testing moderate-scale tiltrotor models in two different test configurations in different research facilities: (1) isolated rotor testing at the Duits-Nederlandse Windtunnel (DNW) in The Netherlands (through the auspices of the U.S. Army and the Department of Defense); and (2) isolated rotor and full-span testing at the National Full-Scale Aerodynamic Complex (NFAC) at NASA Ames Research Center (Fig. 3). For further details as to the research capabilities of both research facilities, see references 5 and 6. Current plans call for the TRAM test stand to be an advanced technology demonstrator platform for the Short Haul Civil Tiltrotor program, including U.S. industry-developed advanced proprotors being tested on the full-span TRAM test stand in the NFAC 40- by 80-Foot Wind Tunnel.



Figure 3 - National Full-Scale Aerodynamic Complex

The 1/4-scale TRAM rotors and airframe are based on the V-22 Osprey tiltrotor aircraft. Technical data was acquired through the cooperation and assistance of the U.S. Navy V-22 Joint Project Office, Boeing Helicopter (Philadelphia, PA), and Bell Helicopter Textron (Arlington, TX).

Objectives of TRAM Project

During the early development of the tiltrotor aircraft, wind tunnel and flight testing concentrated on evaluating and addressing aeroelastic stability, hover and cruise performance issues, handling qualities and flight dynamics. Limited acoustic and airloads data were acquired. This situation is changing to where the latter objectives are more important.

Key to the successful launch of the TRAM project was identifying mid- and long-term tiltrotor research objectives that could be uniquely addressed by NASA. In particular, TRAM research objectives had to address critical

milestones for the Short Haul Civil Tiltrotor program.

Therefore, the current scope of TRAM experimental investigations is focused on the following:

1. Acquisition and documentation of a comprehensive isolated prop rotor aeroacoustic database, including rotor airloads.
2. Acquisition and documentation of a comprehensive full-span tiltrotor aeroacoustic database, including rotor airloads, to enable assessment of key interactional aerodynamic and aeroacoustic effects through correlation of data from the isolated rotor and full-span TRAM wind tunnel data sets with advanced analyses.
3. Serve as an advanced technology demonstrator test platform for low-noise prop rotors developed as a part of the Short Haul (Civil Tiltrotor) program and other major research initiatives.

Subsequent discussion in the paper will address some of the proposed long-term research objectives for the TRAM.

TRAM Research Capabilities

Concurrent development of the TRAM isolated rotor configuration and the full-span test stand was planned from the very beginning of the test program. Similarly, the requirement for siting the model in several different wind tunnels was also an early programmatic decision. The final key programmatic decision was to base the TRAM design on a 1/4-scale model of the V-22 aircraft (versus the XV-15 Tilt Rotor Research

Aircraft, or a generic aircraft, representation). These early decisions had an important effect on the TRAM detail design and overall research capability.

A brief summary of the TRAM experimental research capabilities and hardware characteristics are listed below:

Research Objectives and System Requirements

Aerodynamic Performance Measurements

- Rotor & model/fuselage balances required to measure incremental aero loads
- Models to be tested to full V-22 operating envelope
- rotor control system and console designed to minimize re-rigging between different operating regimes
- High fidelity scaling with respect to the V-22 rotor for model blade/airfoil contours
- Interface hardware defined to install and test advanced proprotors on TRAM test stands

Interactional Aerodynamics Assessment

- Both isolated rotor and full-span configurations required (semi-span model determined not to be required but remains an option for a future TRAM upgrade)
- Model wind tunnel support with minimum interference effects
- Fixed-wing control surfaces can be trimmed for model lift and pitching moment
- Good scaling fidelity for model airframe outer mold lines with respect to V-22 aircraft

Acoustic Measurements

- Pressure-instrumented blades to acquire airloads (150 transducers being a nominal target)
- Isolated rotor configuration to be tested in both DNW and NFAC tunnels; full-span TRAM to be tested only in NFAC
- Electric motors and high-speed drive components required for 'quiet' model operation
- Several innovations required in instrumentation, harnesses, signal-conditioning, and data acquisition to acquire large amounts of high-speed dynamic data on a small-scale model with tight packaging constraints
- Acoustic fairings required for isolated rotor configuration
- Emphasis on documentation of TRAM baseline 1/4-scale V-22 model properties/characteristics -- and test conditions -- to enable high-quality correlation of acoustic measurements with new aeroacoustic prediction tools/methodologies

Dynamics/Rotor Loads Data

- Model rotor hub needed to be dynamically similar to V-22
- First elastic modes of model blades dynamically scaled to V-22 frequencies
- Model (both strain-gauged and pressure-instrumented) blades needed to be interchangeable with respect and mass and cg
- Adequate instrumentation to acquire a blade/hub structural load data set for analytical correlation

Isolated Rotor Configuration Hardware Description

- Test stand is wind tunnel sting-mounted.
- Drive train designed for nominal 300 HP and 18,000 RPM

- motor; two transmissions and 11.3:1 gear reduction (Fig. 4)
- Nacelle tilt/incidence angle is ground adjustable
- Six-component rotor balance and instrumented torque coupling
- 300-ring slip ring and rotating amplifier system
- Gimballed hub with constant velocity joint (spherical bearing and elastomeric torque links)
- Three electromechanical actuators and a rise and fall swashplate for each rotor
- 1/4-scale V-22 rotor set (strain-gauged and pressure-instrumented blades; Fig. 5.)

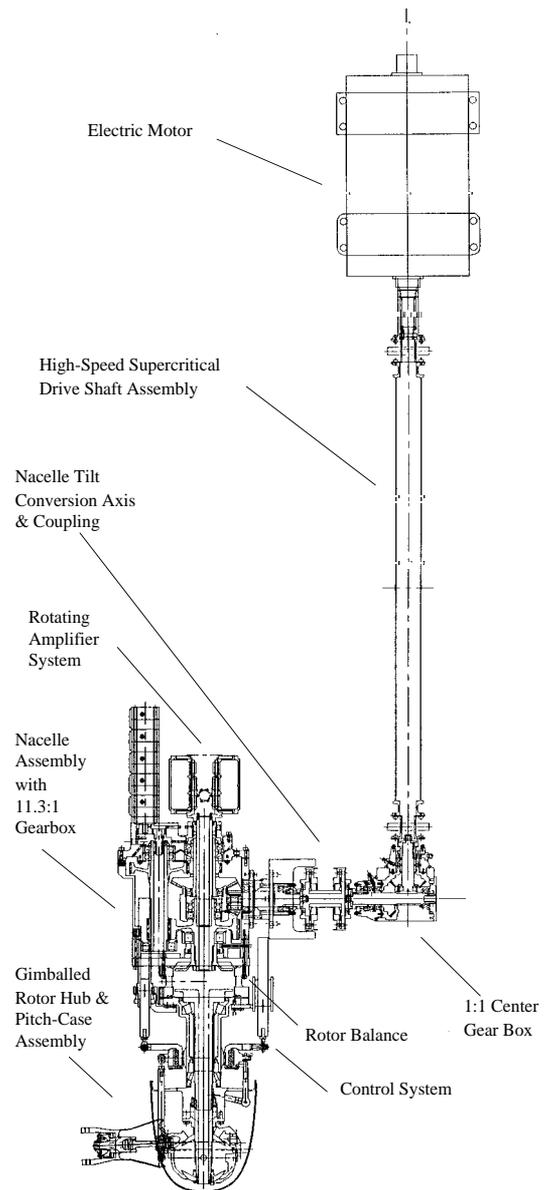


Figure 4 -- Isolated Rotor Configuration Schematic (Top/Planform View; nacelle assembly positioned in airplane-mode)

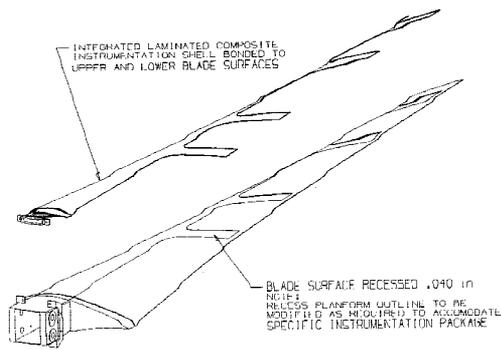


Figure 5 -- Pressure-Instrumented Rotor Blade Design Approach

Full-Span Configuration Hardware Description

- 1/4-Scale representation of V-22 aircraft (Fig. 6)
- Two rotor balances (one for each rotor) and a model balance
- Drive train designed to deliver 300 HP to each rotor
- Model designed for testing up to 300 Knots (maximum speed of NFAC)
- Wing flaperons (total of 4) and the elevator are remote-controlled; rudders are ground-adjustable
- Nacelle tilt/incidence angle is ground-adjustable
- Model support designed for minimum interference and maximum load capacity
- Model designed to accommodate pressure-instrumented rotor
- Model capable of accommodating modular transmission upgrades to test advanced proprotors with lower tip speeds for noise reduction
- Over 700 data, health monitoring, and 'Safety-of-Flight' (SOF) instrumentation channels
- Health and real-time safety-of-flight (SOF) monitoring systems, utility, and fixed-wing control console workstations to support efficient and safe rotorcraft testing.

- Rotor control console designed to control -- independently or linked-together -- the two rotors

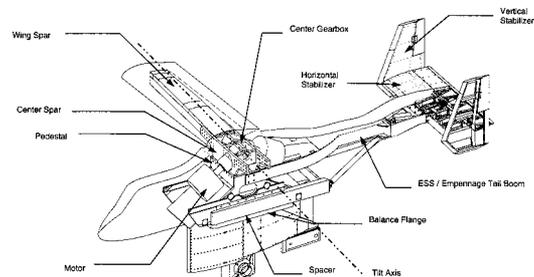


Figure 6 -- Full-Span TRAM Schematic

During the course of the TRAM development, many new technologies needed to be developed/refined for application to the TRAM test stands. Some of these unique, non-rotorcraft-specific, technologies are:

- High-speed/high-performance (permanent earth) electric motor and power electronics (Fig. 7)
- Supercritical drive shafts and advanced drive train technology
- New model balance technology (Fig.8)
- Rotating Amplifier System (RAS) technology. (developed by the Nationaal Lucht-en Ruimtevaartlaboratorium (NLR) -- see Ref. 7 and Fig. 9.)
- Programmable, high frequency, high channel-capacity, amplifier/signal conditioning systems
- Real-time, digital, wind tunnel SOF monitoring systems -- see Ref. 8
- Commercial-platform health monitoring system software
- Digital, multi-actuator, control console electronics and software
- High load-capacity, high positioning-fidelity, electro-

mechanical actuator technology



Figure 7 -- High-Speed & Power Electric Motors & Power Electronics

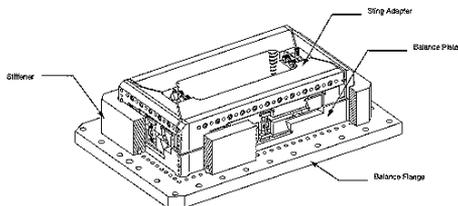


Figure 8 -- Model Balance



Figure 9 -- Rotating Amplifier System

TRAM is more than a set of test models. It is, instead, a complete rotorcraft research facility. A whole host of support systems had to be developed in conjunction with the wind tunnel models in order to meet the project research objectives (Fig. 10).

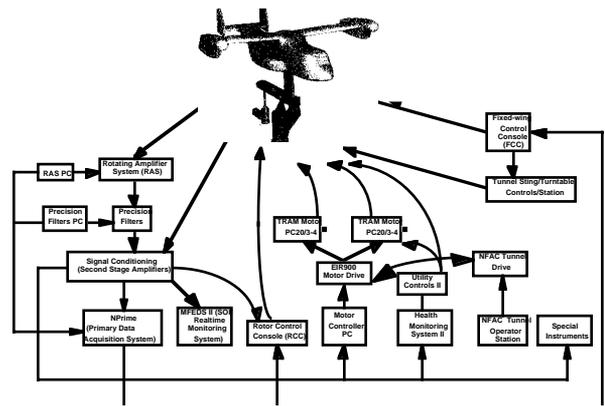


Figure 10 -- Full-Span TRAM System Flow Chart

Project Status

Two risk-reduction tests have been completed with the TRAM isolated rotor test stand: hover testing at NASA Ames and a phase I, wind-on, helicopter-mode, checkout test in the DNW Wind Tunnel (December 1997; Fig. 11). The TRAM isolated rotor configuration is currently in the final preparatory stages for phase II research testing in the DNW Wind Tunnel. The DNW phase II research test entry is scheduled for April 1998.



Figure 11 -- TRAM Isolated Rotor Configuration at DNW

The test preparation and risk reduction activities at NASA Ames included the acquisition of hover data -- including rotor airloads --

for the 1/4-scale set of proprotor blades using the NFAC NPRIME data acquisition system (Ref. 9). As a valuable aid to evaluating the TRAM 1/4-scale V-22 isolated rotor hover performance data and loads, TRAM data is being correlated against data from references 10-12.

After completing the test preparation activity at NASA Ames, the TRAM isolated rotor test stand and associated support and data acquisition equipment were shipped to the DNW Wind Tunnel. A six-week build-up/checkout effort was conducted in one of the DNW test hall model preparation work areas. Upon completion of the build-up effort, the TRAM isolated rotor test stand was installed in the DNW open-jet test section where a two-week, wind-on, checkout test was conducted. The DNW Phase I checkout test focused on low-speed helicopter-mode test conditions. The rotor tip Mach number for the phase I testing was 0.63. Figure 12 shows the test conditions achieved. Values of C_T/σ (uncorrected for aerodynamic or weight tares) up to 0.12 and 0.14 were reached. Limited blade airload data was acquired during phase I as well as limited acoustic survey data with the DNW acoustic traverse. Initial blade-off, wind-off, runs were also conducted to assess whether higher tip speeds could be achieved during the phase II entry. The insights gained from phase I test will be used to optimize the test plan for the phase II entry. The phase II entry will seek to obtain a comprehensive data set for the complete tiltrotor operating envelope up to 160 knots in airplane-mode.

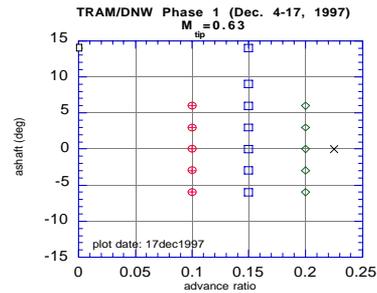


Figure 12 -- Test Conditions Achieved in DNW Phase I Checkout Test

The full-span version of the TRAM test stand has been concurrently developed in conjunction with the isolated rotor configuration. The full-span TRAM configuration is beginning system integration and functional testing at NASA Ames. The first wind tunnel test of the full-span TRAM is planned in July 1999 in the NASA Ames NFAC 40-by-80 Foot Wind Tunnel.

The full-span TRAM development effort will benefit considerably from the risk-reduction activity performed for the isolated rotor TRAM test stand configuration. However, the full-span TRAM test stand will undoubtedly present several new challenges before it becomes fully operational.

In addition to acquiring baseline 1/4-scale V-22 aeroacoustic data, the full-span TRAM will also be used to test advanced proprotor designs from Boeing Helicopter and Sikorsky Aircraft for the Short Haul Civil Tiltrotor program. However, only the 1/4-scale V-22 rotors will be pressure-instrumented. This proprotor airloads data set will be an invaluable asset for refining tiltrotor performance and aeroacoustic prediction methodologies. Only one other airload data set exists (static pressures for a hovering proprotor) in the

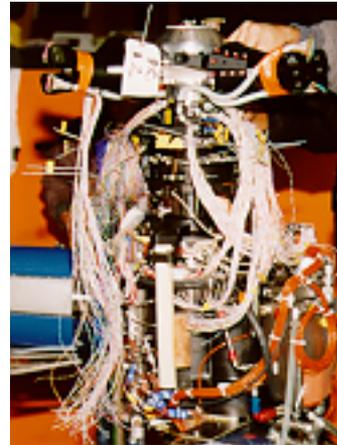
public domain for proprotors -- see Ref. 13.

With the introduction and use of the TRAM isolated rotor and full-span TRAM test stands, NASA will be well-positioned to fulfill a cornerstone role in experimental tiltrotor aeromechanics research. But, in addition to the TRAM, two other rotorcraft research test platforms that can support helicopter-mode tiltrotor investigations have been or are in the process of being upgraded by the Aeromechanics Branch: the Rotor Test Apparatus (RTA) upgraded to support ~25 foot diameter proprotors, and the Large Rotor Test Apparatus (LRTA) which will be able to test ~38 foot diameter proprotors. However, the use of these two large-scale test stands are limited to hover and helicopter-mode testing. Use of all three test platforms (TRAM, RTA, and LRTA) will enable the testing of a broad spectrum of tiltrotor aircraft proprotors and provide new insights into aerodynamic performance and acoustic scaling laws.

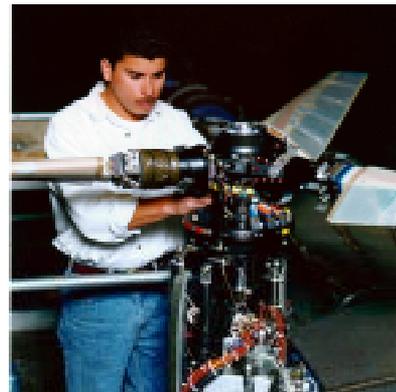
Technical Challenges

Several major technical challenges had to be addressed in order to make the isolated rotor and full-span TRAM test stands operational. The selection of the TRAM model-scale size was an important issue to address early in the development program. The proprotor size (1/4-scale) was chosen as the largest diameter (given the required disk-loading) compatible with the DNW open-jet wind tunnel test section. This rotor size (9.5 feet in diameter) presents packaging problems for drive train, instrumentation, and utility installation/routing in both the isolated rotor and full-span test stands (see Fig. 13a-b). Among the other anticipated challenges for the full-span TRAM

test stand is the appropriate handling of a significant increase in data volume/bandwidth that will result from its usage. Nonetheless, major tiltrotor milestones will be achieved with TRAM.



(a)



(b)

Figure 13 -- Example of the Challenges of Test Stand Development: Instrumentation Routing & Packaging (a. before, b. after)

Future Directions

It is anticipated that TRAM will be a nationally critical tiltrotor test stand/research facility for NASA and the U.S. Army for many years.

In addition to meeting its primary aeroacoustic research objectives for the Short Haul Civil Tiltrotor program, there are many additional areas of tiltrotor aeromechanics research that will be investigated with TRAM. Among these additional areas of investigation are:

- Efficient, high-speed cruise proprotor performance.
- Expanded interactional aerodynamic studies including hover download, tiltrotor ground effect and low-speed cross-flow, comprehensive rotor wake studies, assessment of rotor-on-rotor interactions, image effects through TRAM semi-span testing, and assessment of aerodynamics of alternate fuselage and empennages.
- Development/validation testing of new experimental test techniques for rotary wing problems for the unique operating conditions and aeromechanics phenomena of tiltrotors.
- Scale effects & wind tunnel versus flight test assessments.

Conclusions

The research capabilities of -- and the innovations underlying -- the Tilt Rotor Aeroacoustic Model (TRAM) have been briefly summarized. The TRAM project promises to provide NASA and the U.S. Army a new and unique rotorcraft research facility for technology investigations in tiltrotor aeromechanics.

Acknowledgments

A project as complex as TRAM is easily indebted to dozens of dedicated professionals working

over several years to achieve success (some of whom are shown in Fig. 14). The efforts of Paul Loschke (NASA-retired), Martin Galinski, Dr. Gloria Yamauchi (NASA Ames), Earl R. Booth, Jr. (NASA Langley), Jon Lautenschlager (U.S. Army), Mike Derby, Jeff Johnson, Alexandra Swanson, Stephen Swanson (Sterling Software), Ken Sullivan, Scott Ralston, Joe Piazza (Micro Craft), Gerry Shockey, Seth Dawson, Dave Domzalski, Dennis Kennedy (Boeing-Mesa) -- and many other individuals and companies -- must be acknowledged. The TRAM team has made tremendous technical contributions: to tiltrotor technology; to the next wave of rotorcraft research, in general; and to the development of leading-edge technology in many areas in addition to those of rotorcraft technology. Finally, this paper is dedicated in memorial to two very important individuals -- George Unger (NASA) and H. Andrew Morse (U.S. Army) -- without whose efforts the TRAM project would not exist.

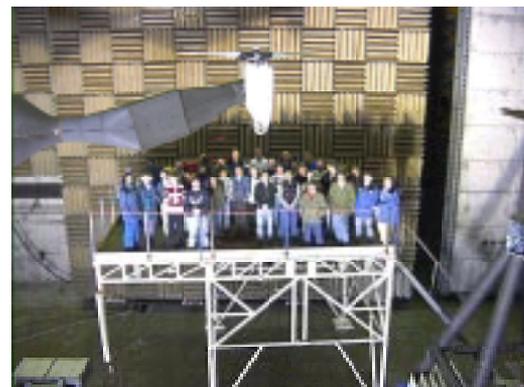


Figure 14 -- TRAM/DNW Test Team

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