Design and Development of an F/A-18 Inlet Distortion Rake: A Cost and Time Saving Solution

An innovative inlet total-pressure distortion measurement rake has been designed and developed for the F/A-18 A/B/C/D aircraft inlet. The design was conceived by NASA and General Electric Aircraft Engines (Evendale, Ohio). This rake has been flight qualified and flown in the F-18 High Alpha Research Vehicle (HARV) at NASA Dryden Flight Research Center. The rake's eight-legged, one-piece wagon wheel design was developed at a reduced cost and offers reduced installation time compared with traditional designs. The rake features 40 dual measurement ports for both low- and high-frequency pressure measurements with the high-frequency transducer mounted at the port. The high-frequency transducer offers direct absolute pressure measurements from low frequency to the highest frequency of interest, thereby allowing the rake to be used during highly dynamic aircraft maneuvers. Outstanding structural characteristics are inherent to the design through its construction and use of lightweight materials.

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Design and Development of an F/A-18 Inlet Distortion Rake: a Cost and Time Saving Solution

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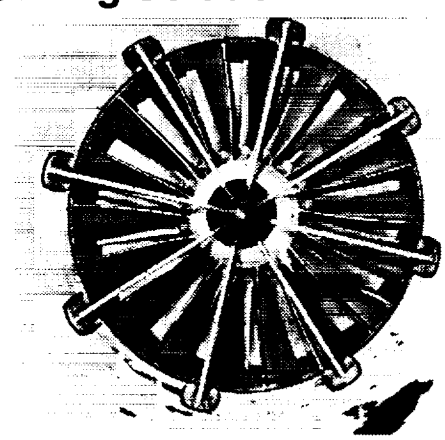

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Outline

This presentation overviews the objective, description, installation, and qualification testing of the HARV inlet rake system. Comparisons of cost and installation time between this design and a previous design are made. The report describes the pressure transducer selection, along with all stages of flight qualification testing, from laboratory testing to flight test. The presentation ends with a summary of concluding remarks.

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Outline

- Objective
- Rake description
- Rake installation
- Pressure transducer selection
- Flight qualification testing
- Concluding remarks

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Objective

The design, development, and installation of an inlet total-pressure distortion rake can be expensive and time consuming. The goal of the F-18 HARV inlet research program is to evaluate the inlet characteristics of high-performance aircraft during both stabilized and highly dynamic maneuvers at high angles of attack. The F-18 HARV inlet research program required a low-cost, quickly installed, low-maintenance solution for a total-pressure inlet distortion measurement system.

Design requirements were established for the rake system. The most important requirement was to provide as much commonality as practical with the planned HARV inlet wind-tunnel test at the NASA Lewis Research Center and with previous F/A-18 inlet testing. Commonality considerations with past and present testing include, but are not limited to, instrumentation setup, rake positioning, and probe configuration. In addition, it was desirable to follow established industry guidelines wherever possible, especially those established by the Society of Automotive Engineers. Meeting aerodynamic and structural requirements was also an important consideration.

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Objective

Design and develop an inlet total-pressure distortion measurement rake

- **Investigate high angle-of-attack inlet flow characteristics during dynamic aircraft maneuvers**
- **Offer reduced cost and installation time**
- **Maintain commonality**
- **Adhere to technical guidelines**
- **Meet aerodynamic and structural considerations**

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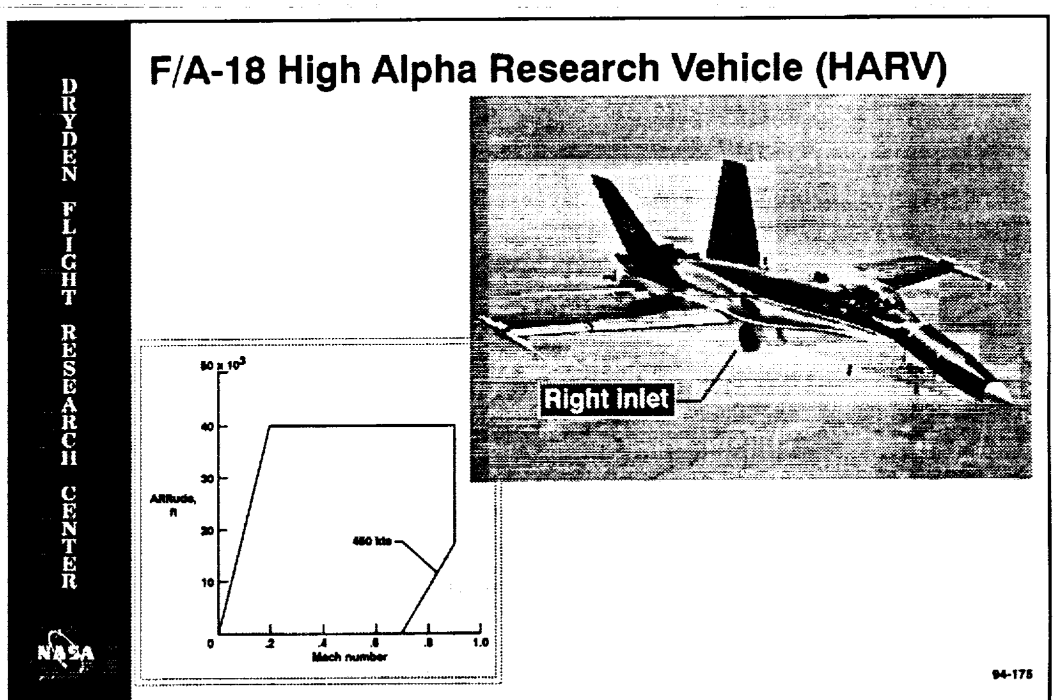
F-18 High Alpha Research Vehicle

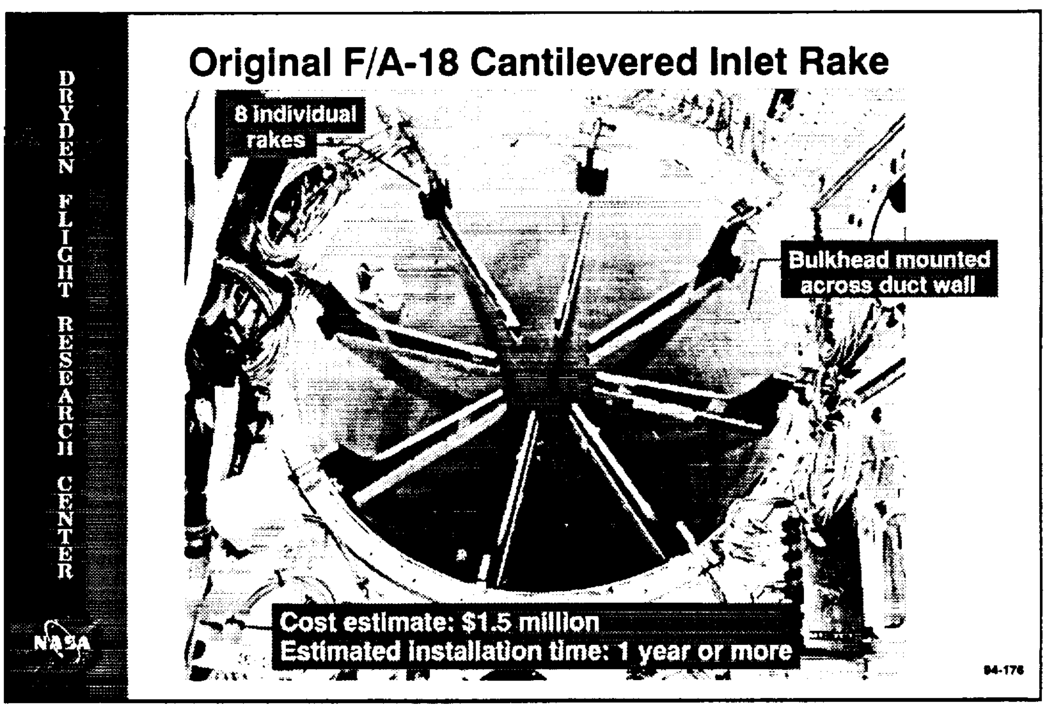
The F-18 HARV is a one-of-a-kind research aircraft located at NASA Dryden Flight Research Center. This preproduction, single-seat fighter-attack aircraft has been uniquely modified to perform extensive flight testing in the high-angle-of-attack region. These modifications include a thrust-vectoring control system that uses three paddles per engine nozzle to deflect the jet exhaust. The aircraft has two General Electric F404-GE-400 turbofan engines. The inlet rake was installed in the right inlet (aft looking forward).

The aerodynamic design flight envelope coincides with the normal operating envelope of the HARV aircraft and was chosen to allow unrestricted flight with the inlet rake installed. Inlet research test points are primarily focused at the low-speed portion of the envelope between Mach numbers (M) 0.3 to 0.4. The worst-case dynamic pressure condition is $M = 0.7$ at sea level conditions in which the free-stream total pressure is 20.4 psia and the hot day total temperature is 618 °R.



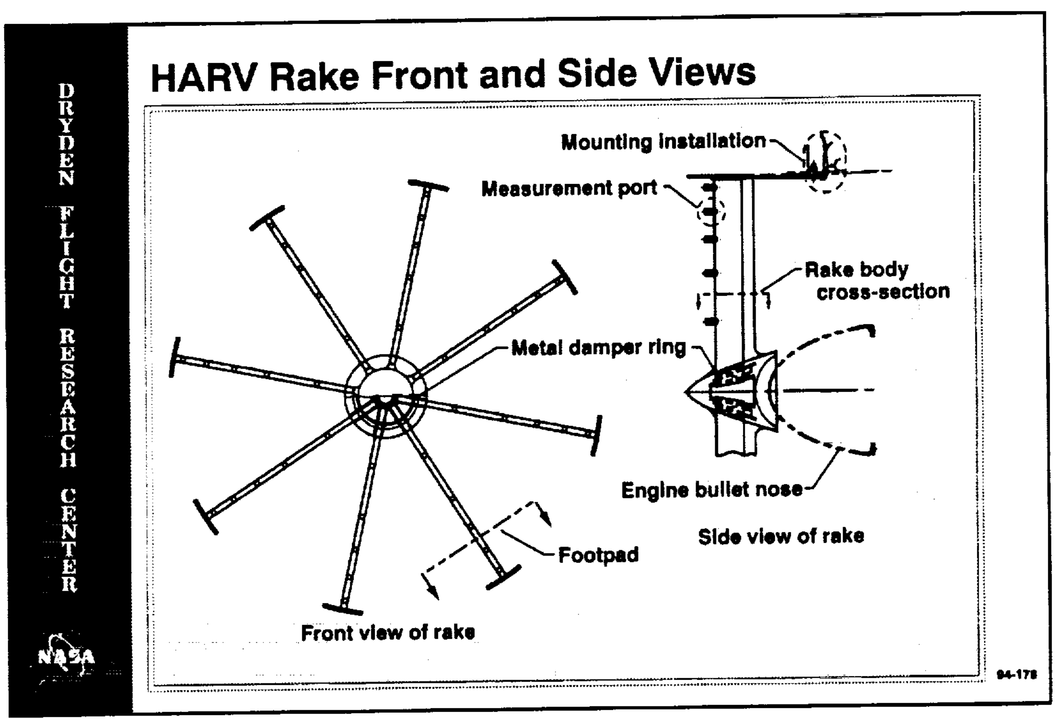
Original F/A-18 Cantilevered Inlet Rake

An evaluation of the rake used in the original F/A-18 inlet compatibility program, flown in the mid-1970's on the second preproduction F/A-18A, indicated current costs more than $1.5 million and installation time of a year or more. Driving both these factors was the complexity of using eight individual cantilever rakes. Those designs had to be developed, tested, and installed independently. Installation in the HARV would require the aft portion of the inlet duct to be extensively reinforced. To meet the complex inlet rake structural requirements, the bulkhead on aircraft #2 was specifically designed to accommodate the inlet rake mounting requirements. It was quickly apparent that this was not a viable approach for the HARV project. During an early design conception meeting NASA and General Electric personnel conceived an alternative approach in which all eight rake legs would be joined at the center of the inlet with a hub similar to that of a wagon wheel to simplify design.



HARV Rake Front and Side Views

The HARV rake is much like a wagon wheel, with the streamlined centerbody acting as the hub, the eight aerodynamic rake bodies as the spokes, and the inlet duct as the rim. The load-bearing structure is a welded steel unit that joins the rake bodies and the central hub into a single piece, which is supported by integral foot pads and bolted to the aircraft inlet duct flange. Each of the eight rake legs contains five probes located on the centroids of five equal areas of the flow area. The body comprises a steel frame with a bonded elastomer. The elastomer, which acts as an excellent damping material, allowed the overall weight to be reduced and the rake struts to be aerodynamically shaped easily (in comparison with an all-metal body). The weight of the entire rake assembly is approximately 15 lb. No physical contact is made between the engine and the rake system. A detailed description of the rake hub, rake body cross-section, measurement port, footpad, and mounting installation follows.

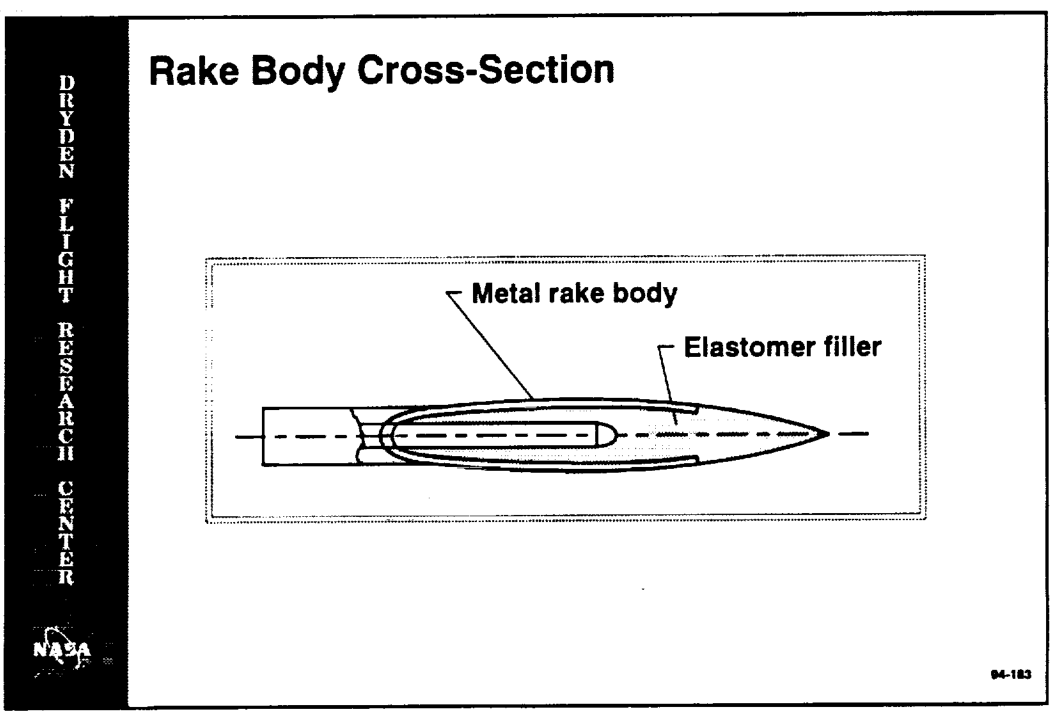


Rake Hub

All of the rake bodies are gathered in a central hub and welded to an inner ring. The hub also contains an isolated metal damper ring potted in the polyurethane centerbody. This allows the damping material to dissipate vibration energy more effectively than an all-metal body would. The same polyurethane material forms the streamlining of centerbody.

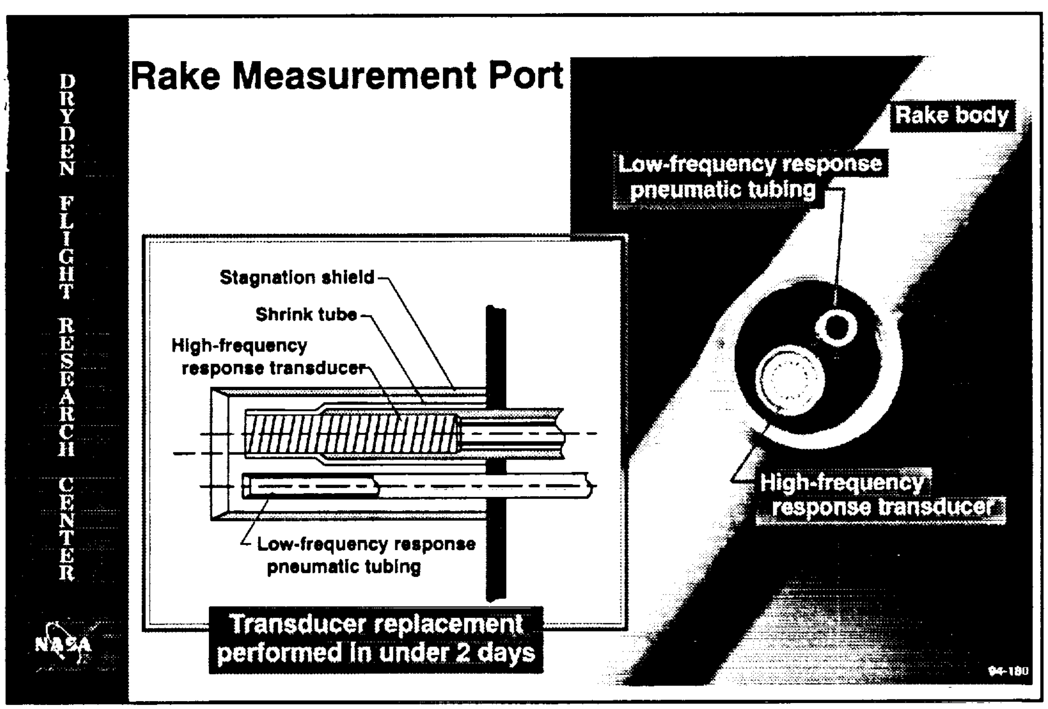
Rake Body Cross-Section

The rake bodies (or spokes) are made by forming sheet metal into the leading edge and sides of the airfoil shape. The sheet metal is left open at the trailing edge. This allows the installation of the sensor and lead-out tubes. The rake bodies are filled the elastomer, and the trailing edges of the rake bodies are aerodynamically formed with the elastomer. The rake body is 2.5-in. long with maximum thickness of about 0.39 in.



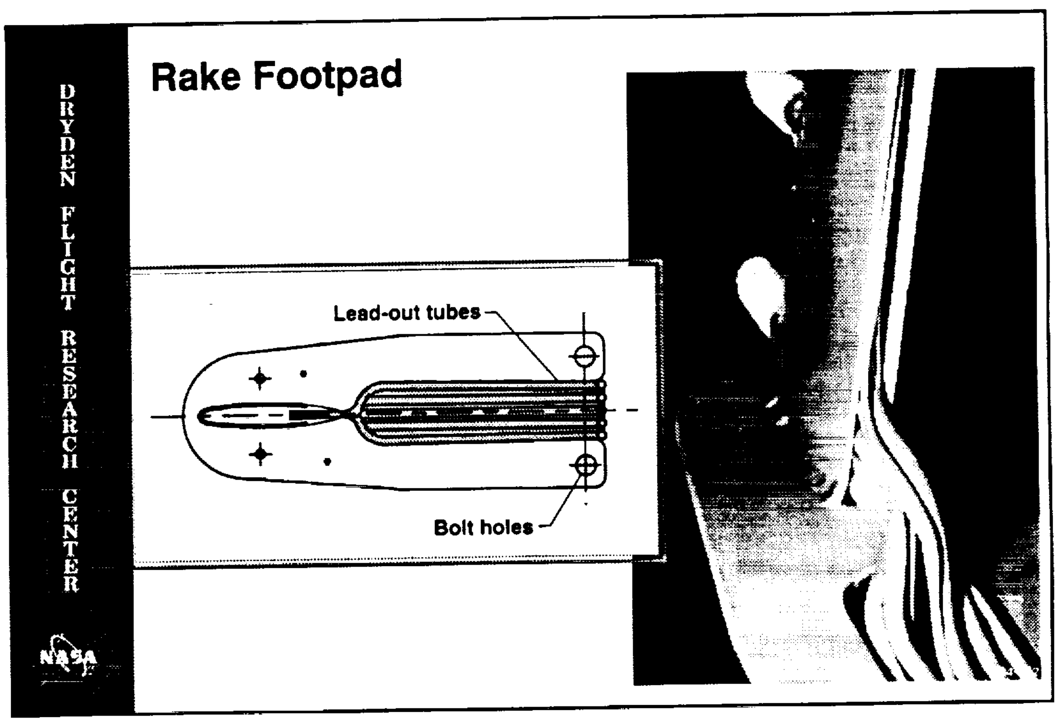
Rake Measurement Port

The rake sensors are shielded total-pressure measuring sensors consisting of a high-frequency response pressure transducer and a 1/16-in. diameter low-frequency response pressure tube. The stagnation shield configuration was tested to show its ability to measure the true total input pressure at flow angles of ±25° in yaw and +15° and –25° in pitch (positive angle is toward engine centerline). The probes are aligned within 2° of the anticipated steady-flow streamlines. The innermost probe is the only one that had to be angled (5.5°) with respect to the rake body. The high-response transducers are installed in carrier tubes. The tubes have a counterbore to receive the transducers. Installation is accomplished by feeding the electrical leads through the carrier tube from the sensor end, coating the back of the transducer with an adhesive, and inserting the transducer into the counterbore. Next, the transducer is covered with heat-shrinkable tubing. This arrangement gives a secure mounting for the transducers but allows replacement while the rake is still in the aircraft. Transducer replacement was demonstrated with the replacement of seven transducers requiring less than 2 days once the engine was removed.



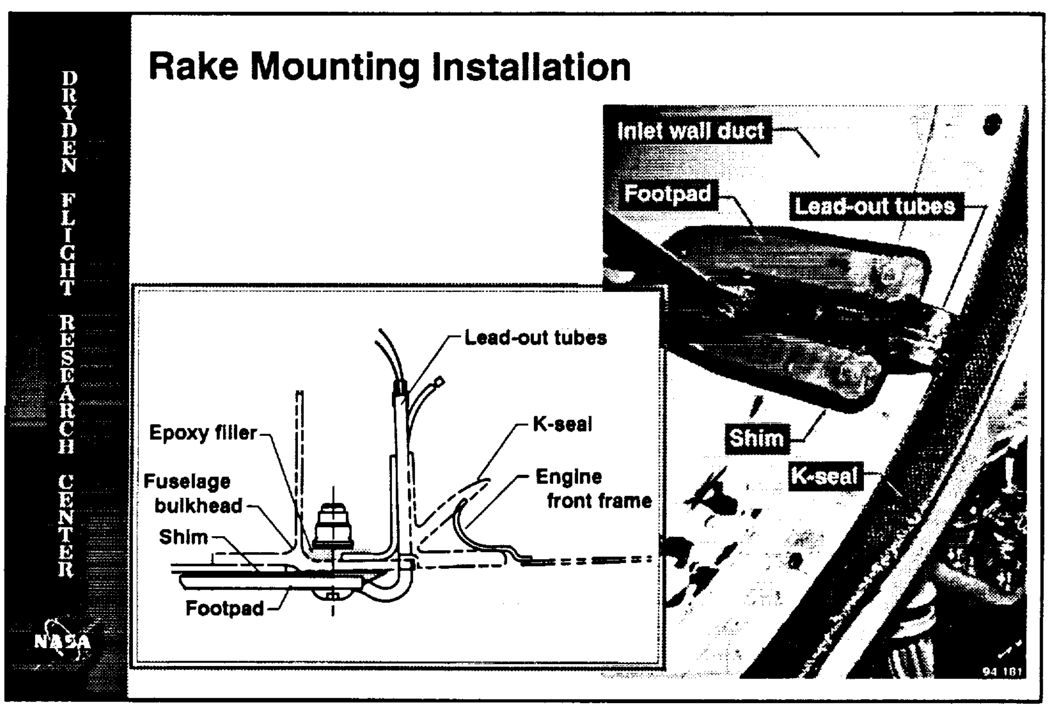
Rake Footpad

The rake bodies are welded to the foot pads. The footpads allow the duct flange to support the rake without inducing any bending load in the sheet metal wall of the duct. The lead-out tubes are carried between the toes of the footpad.



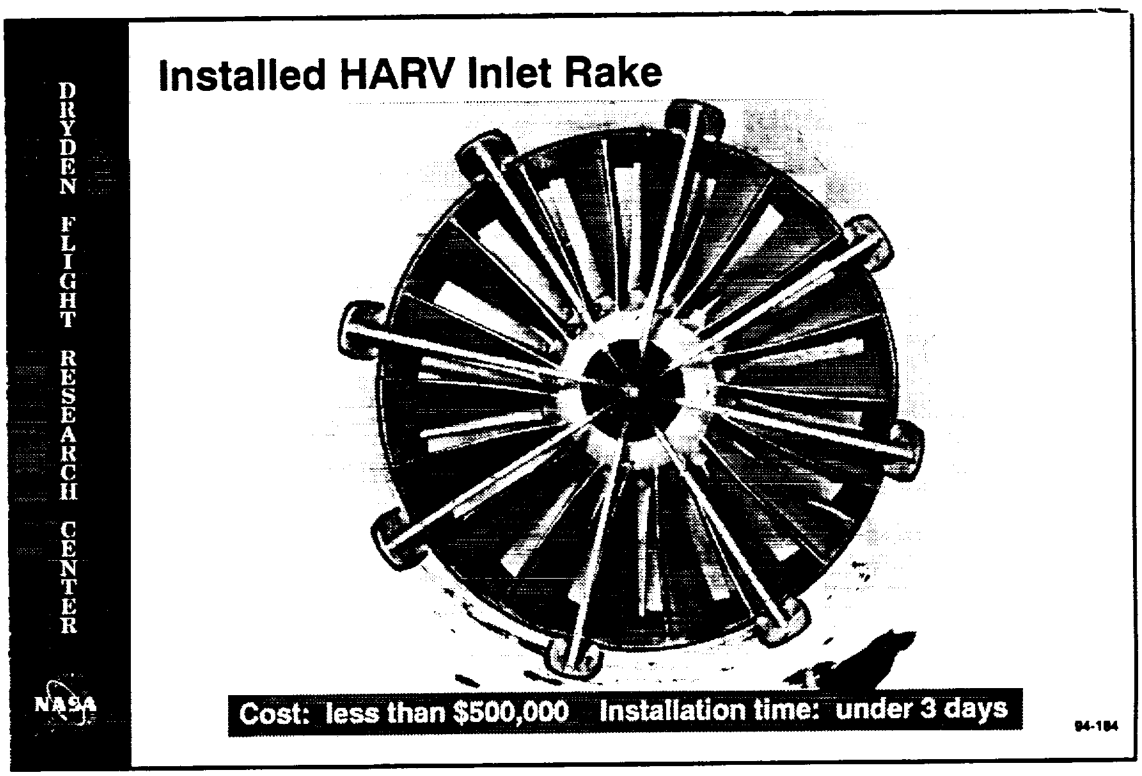
Rake Mounting Installation

Installation of the rake was accomplished after the right engine and K-seal had been removed. The minimal modifications that were required on the airframe consisted of 16 bolt holes drilled in the inlet duct flange aft of the rear bulkhead. Backup washers were placed at each hole on the outside of the duct and epoxied in place to provide a solid and flat surface for seating the nuts of the rake mounting bolts. The rake was placed in the duct, and an even fit for each rake strut was achieved by placing shims between the metal footpad and the inlet duct wall. The rake was then installed with an adhesive injected between the foot pads and the shims. The foot pads were bolted in place and the adhesive cured giving the assembly a firm, elastomer-damped mounting. The K-seal was contoured to allow the rake tubes to pass freely under it. The seal was then bolted in place on the aft duct flange, and the electrical leads and the pneumatic tubes were routed to their respective connector locations.



Installed HARV Inlet Rake

The NASA/General Electric design greatly simplifies installation and aircraft modifications required for an inlet rake system. General Electric has designed, developed, and built one prototype and two flight-worthy rakes for less than $500,000. One flight-worthy rake had an entire set of high-response transducers included in the cost. The rework to the airframe, installation of the rake assembly, modification to the K-seal, and installation of the seal ready for lead routing was accomplished in two and a half 8-hour shifts. This installation time shows a significant reduction in aircraft down time compared with more traditional designs.



Pressure Transducer Selection

The pressure transducer requirement was to develop an instrumentation setup that would allow for accurately measuring the pressure level and the time-dependent component of the pressure during highly dynamic maneuvers. Minimization of two known uncertainties that affect the ability to measure an accurate pressure level during a dynamic maneuver were addressed: (1) pneumatic lag and (2) thermal zero shift. The pneumatic lag describes the condition in which the pressure signal is delayed, in reference to time, to the transducer at the end of the tubing and, therefore, affects low-response accuracy. The thermal zero shift affects the ability of the transducer to accurately measure the pressure level at varying inlet temperature conditions. Thermal zero shift describes the calibration shift of the zero voltage condition experienced as a pressure transducer sensing element varies with temperature.

The high-response probe used a temperature-compensated pressure transducer with an absolute pressure range of 0 to 20 psia. The transducer was selected because of its ability to minimize thermal zero drift through passive temperature compensation. To further increase the accuracy of the transducer measurement, a series of pressure calibrations were performed over the entire required pressure and temperature range, up to 20 psia and at –65, –30, 0, 75, and 150 °F. These calibrations, along with the measured engine inlet temperature, would allow for any remaining zero thermal drift to be removed during postflight data processing. The low-response measurements will be used to verify the pressure levels of the high-response measurements at stabilized conditions. This high-response transducer setup will allow for the accurate measurement of high-frequency pressure levels during highly dynamic maneuvers and also meets the system accuracy requirements.

The low-frequency response probe uses a differential transducer with a reference pressure. This transducer unit was thermally stabilized to increase accuracy by minimizing thermal zero drift. This was accomplished by wrapping the transducer unit in temperature-controlled thermal blanket. Another transducer feature that was used to increase accuracy was its ability to perform in-flight calibrations. This allows for any calibration bias error to be removed during postflight data processing. The in-flight calibration is accomplished by applying the reference pressure to both sides of the differential transducer.

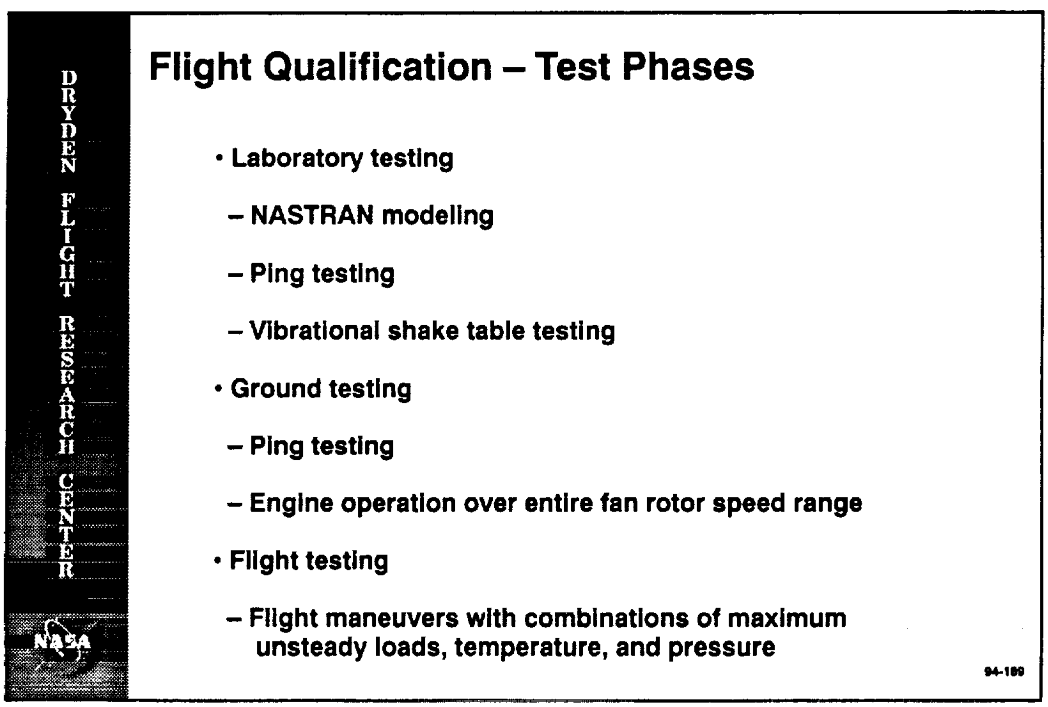
Pressure Transducer Selection

Challenge: Measure inlet pressures during highly dynamic aircraft maneuvers by minimizing pneumatic lag and thermal zero shift

- High-frequency response instrumentation
  - Absolute pressure range of 0–20 psia
  - Passive temperature compensation
  - Laboratory calibrations at temperatures from −65 to 150 °F
- Low-frequency response instrumentation
  - Differential transducers with reference pressure
  - Thermal blanked transducers
  - In-flight calibration capability

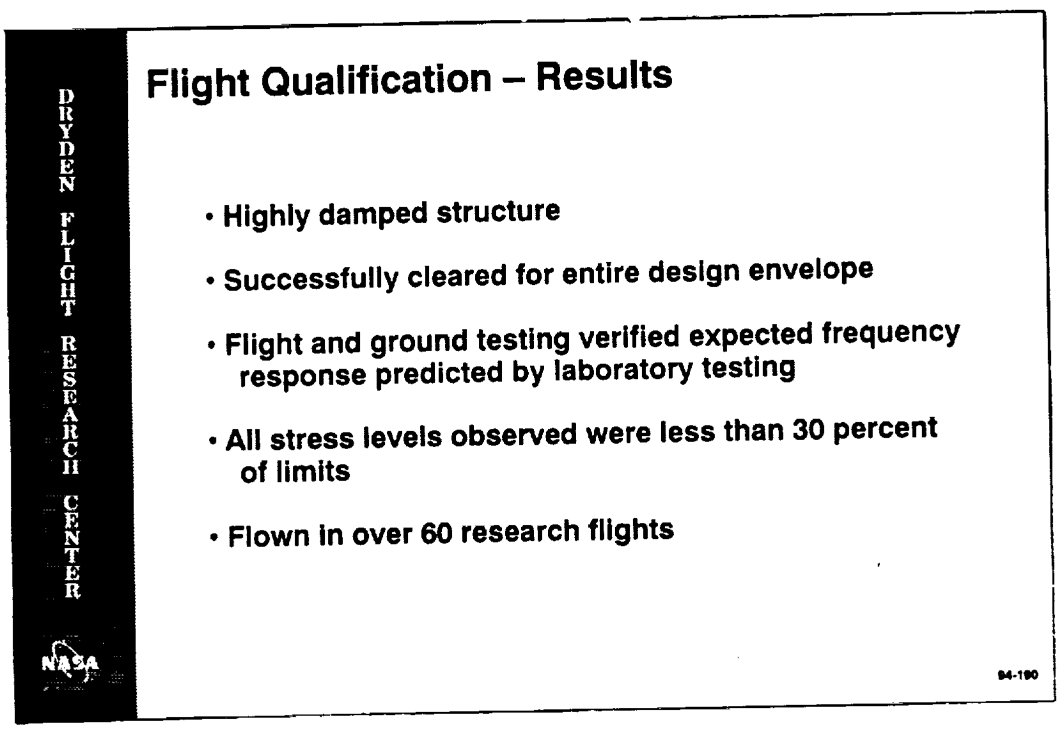
Flight Qualification—Test Phases

The flight qualification testing was broken into three phases: (1) laboratory, (2) ground, and (3) flight. The laboratory phase determines the baseline structural and vibrational characteristics of the rake. This phase consists of NASTRAN computer modeling of the rake structure, along with ping testing and vibrational shake table testing of a prototype rake. The baseline results from the laboratory tests were used for comparison with the results from the remaining phases: installed ground and flight testing. Ground testing consisted of a ping test being performed on the inlet rake installed in the HARV. Then, the installed rake was ground tested on the HARV with the aircraft tied down. The right engine was operated through its full range with a slow acceleration from idle power to full maximum afterburning and a slow acceleration back to idle power. This procedure allows predominant frequencies to be identified over the entire fan rotor speed range. Flight testing for the rake consisted of flight maneuvers to give maximum unsteady loads ($\alpha = 60°$ at 20,000 ft), maximum temperature, and pressure ($M = 0.7$ on the deck), and maximum combination of temperature, pressure, and unsteady loads ($M = 0.9$ at 18,000 ft) within the HARV flight envelope. The latter two points were at the limits of the HARV flight envelope. The first point was flown to a high-angle-of-attack condition, while the latter two obtained maximum g-limit loading.



Flight Qualification—Results

The rake structure was demonstrated to be highly damped and was successfully flight qualified for the entire HARV flight envelope. The spectra of the rake vibrations experienced during laboratory testing remained consistent with the ground and flight test results. The maximum stress levels observed were less the 30 percent of limits (30,000 lbf/in^2, peak to peak). The stress levels observed during high-α flight were 26 percent of limits and less than 10 percent of limits during maximum-g flight. The highest stress limits observed were 30 percent of limits during aircraft takeoff. Based on the laboratory, ground, and flight test results, the rake is now fully cleared for conducting flight research within the entire HARV flight envelope with no restrictions. The inlet rake system has flown over 60 successful research flights.



Concluding Remarks

An improved cost- and installation-time-saving inlet distortion pressure rake was successfully designed, built, and validated for flight testing on the F/A-18 HARV research aircraft. The cost for one prototype and two flight-worthy rakes along with required development testing was under $500,000. The innovative design consists of a one-piece, wagon wheel approach that resulted in ease of installation with minimal aircraft modifications. The demonstrated installation time was under 3 days. Design features include lightweight, high-strength, low structural resonance, low flow blockage, and easy transducer removal and replacement. Instrumentation selection allowed for direct pressure measurement during highly dynamic aircraft maneuvers. A prototype of the new rake was environmentally tested in a laboratory where it passed all vibration structural requirements. Ground test verified the expected frequency response predicted from laboratory test. Flight qualification was completed and the rake is now cleared for flight testing on the HARV aircraft with over 60 flights performed. All stress levels observed during ground and flight qualification were less then 30 percent of limits.

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Concluding Remarks

- NASA/GEAE inlet rake design demonstrated improved cost and installation-time savings
- Cost for entire design and development of two flight-worthy rakes was under $500K
- Rake installation in under 3 days
- Direct pressure measurements during dynamic aircraft maneuvers
- Flight qualification successfully completed (60+ flights)
- Structural stress levels were less than 30 percent of limits
- Ease of transducer replacement demonstrated

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