F110-GE-129 EFE — Enhanced Power Through Low Risk Derivative Technology

Conference Paper · May 2000

DOI: 10.1115/2000-GT-0578

A. R. Wadia
GE Aviation, Cincinnati, United States

Proceedings of
ASME TURBOEXPO 2000
May 8-11, 2000, Munich Germany

F110-GE-129 EFE – ENHANCED POWER THROUGH LOW RISK DERIVATIVE TECHNOLOGY

2000-GT-0578

A.R. Wadia and F.D. James
Large Military Engine Systems Design and Integration
GE Aircraft Engines
Cincinnati, Ohio 45215

ABSTRACT

The F110-GE-129 EFE (Enhanced Fighter Engine), presently undergoing qualification testing, is being offered at two different thrust/inspection levels with a maximum augmented thrust of 34,000 pounds. The EFE has been developed using low risk derivative engine technology. It features a new increased airflow, high efficiency, three-stage long chord blisk fan and an advanced radial augmentor that reduces complexity, improves maintainability and provides increased parts life. The paper first provides a historical background of the F110 engines to relate the heritage of the F110-GE-129 EFE. The F110 engine model development roadmap is shown to illustrate the incremental low risk approach used to provide thrust growth with improved product reliability. A detailed description of the unique power management features of the EFE engine to meet individual customer thrust and life requirements is outlined. The long chord blisk fan design, development and test results are presented followed by a description of the radial augmentor and the exhaust nozzle. The EFE engine has successfully completed sea level static and altitude development testing and fan aero mechanical qualification at the AEDC in Tullahoma, Tennessee.

NOMENCLATURE

A/B	=	Afterburner
AEDC	=	Arnold Engineering Development Center
CIP	=	Component Improvement Program
EFE	=	Enhanced Fighter Engine
ENSIP	=	Engine Structural Integrity Program
F/H	=	Flame Holder
FOD	=	Foreign Object Damage
IHPTET	=	Integrated High Performance Turbine Engine Technology
IPE	=	Improved Performance Engine
IRP	=	Intermediate Rated Power (Dry Thrust)
LSP	=	Laser Shock Peen
Mach	=	Mach Number
Max A/B	=	Maximum Augmentation
OLGA	=	On Line Gas Analysis
TAC	=	Total Accumulated Cycles
LRU	=	Line Replaceable Unit

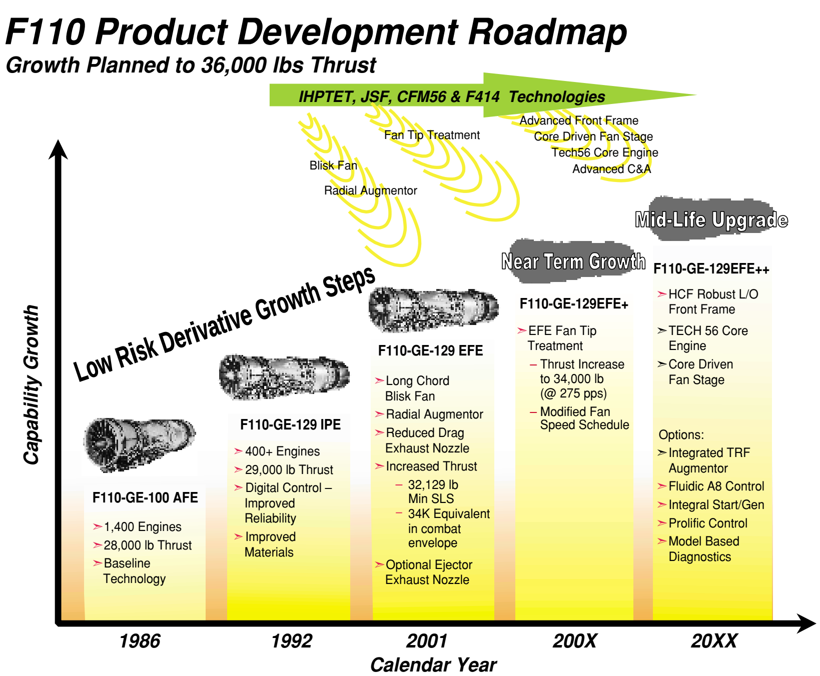

Figure 1: F110 Engine Model Product Development Roadmap

HISTORICAL BACKGROUND

The development of the F110 engine family has paralleled the dynamic growth of Lockheed Martin's F-16 fighter aircraft. The F110 engine product development roadmap is presented in Figure 1. The increase in thrust (pounds) with improvement in life (TACs), shown in Figure 2, illustrates the deliberate path taken by GE Aircraft Engines to use a low risk derivative engine approach to grow the F110 engine model over the last fifteen years without sacrificing reliability. Figures 1 and 2 are valuable for establishing the current industry standards and state-of-the-art and for identifying future priorities.

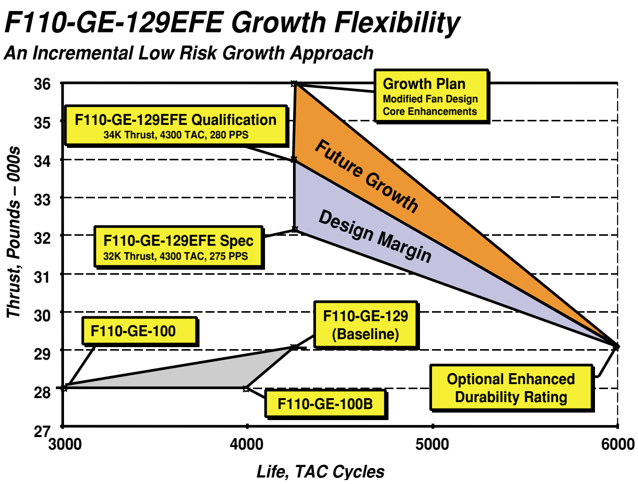

Figure 2: Reliability and thrust growth provide flexibility to satisfy a wide range of future customer requirements.

The F110-GE-100, rated at 28,000 pound thrust was deployed on the first United States Air Force F110 powered F16-C/D in October 1986. The F110-GE-100 was introduced to the Air National Guard in June 1991 and to the USAF Reserve in August 1992 and has accumulated nearly 2 million engine flight hours with an unscheduled, engine caused shop visit rate of 3.45 visits per 1000 flight hours. It currently powers the U.S. Air Force's F-16C/Ds throughout Europe and the Pacific; and has served as the "Fighting Falcon" adversary aircraft for the United States Navy's Top Gun program. Since its inception in 1986, the governments of Bahrain, Egypt, Greece, Israel and Turkey have also chosen the F110-GE-100 to power their front-line fighters. In follow on purchases, these governments have continued to select the F110 as the engine of choice for the F-16 due to its performance characterized by unrestricted throttle operation throughout the flight envelope and an improved rate of climb. The F110-GE-400, a derivative of the F110-GE-100, powers the U.S. Navy's F-14B and F-14D Tomcat.

The focus on reliability of the F110 fighter engine has continued into the current production F110-GE-129 Increased Performance Engine (IPE). The IPE is a 29,000 pound thrust class engine that has extended a strong fundamental heritage of stall free operability and unrestricted throttle movement which allows the pilots to concentrate on the mission instead of the machine. The IPE's high cycle durability, mature reliability — because of extensive parts commonality (81%) with the F110-GE-100 — and full thrust retention, has translated into highly desirable in-commission rates and safety records for single engine applications. A good match between the aircraft inlet airflow and engine combination has provided pilots better penetration performance for strike missions. Engine maintenance was designed to be conducted at the base level to provide maximum self sufficiency and significant cost savings for the military. Since its deployment in the field in 1992, the IPE has logged over a quarter of a million engine flight hours with an unscheduled engine caused shop visit rate of less than one visit per 1000 flight hours.

Other F110 engine developments (Anderson, 1992) include a highly successful demonstration in the AVEN® thrust vectoring initiative, a rigorous flight test demonstration program utilizing the U.S. Air Force NF-16D VISTA platform. During this effort, the F110 endured extreme levels of airflow distortion and operated flawlessly in performing super-maneuvers such as the Cobra and the J-Turn.

In 1999, the F110-GE-129 successfully completed flight testing on the McDonnell Douglas F-15E Strike Eagle and is now qualified for new installations or re-engining of the F-15E fleet. The robust F110-GE-129's 275 lbs/sec inlet airflow capability is another good match with the F-15 inlet, paying off in significant range advantages on low-altitude strike scenarios and other combat missions.

Other applications of the F110-GE-129 IPE include powering Japan Air Self Defense Force's (JASDF) F-2, and a derivative of the F110, the F118, powers the B-2 bomber and the U-2 reconnaissance aircraft.

F110-GE-129 EFE NEW FEATURES AND THRUST REQUIREMENTS

Based on the F110 product growth plan (see Figures 1 and 2) that utilizes a low risk derivative approach, GE Aircraft Engines has developed the F110-GE-129 Enhanced Fighter Engine (EFE) to meet future operational requirements and market opportunities. Technological advances in the EFE, as illustrated in Figure 3, include a three-stage long chord blisk fan and an advanced radial augmentor. Other changes include a lightweight filament wound composite fan duct, and control system enhancements to power manage the engine up to 34,000 pounds thrust. Durability improvements from current production engine component improvement programs (CIP) for the turbine hot section and exhaust nozzle divergent flaps and seals, form an integral part of the F110-GE-129 EFE. The F110-GE-129 EFE has an option to use an ejector nozzle which results in a significant improvement in exhaust nozzle parts life while at the same time lowering exhaust system weight.

The F110-GE-129 EFE is being offered at two different thrust/inspection levels as shown in Figure 4. On a standard day with full afterburner augmentation these two power ratings are 29,600 pounds of thrust (average, statically) with a 6,000 TAC ENSIP overhaul inspection interval (Kandebo, 1996) or the 33,000 pounds thrust (average) with 4300 TAC ENSIP overhaul inspection interval.

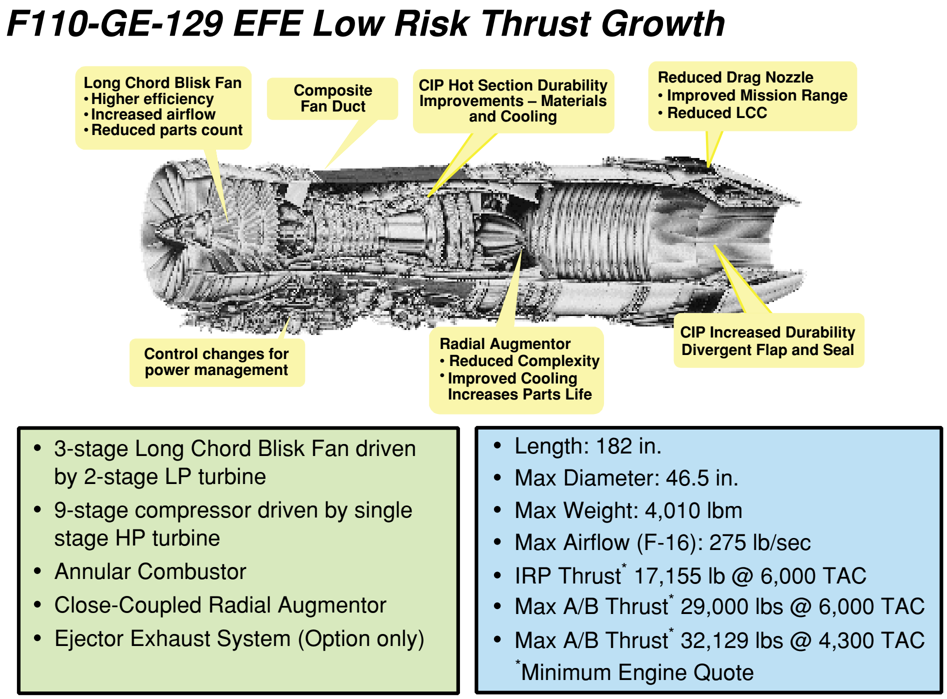

Figure 3: F110-GE-129 EFE New Features

The EFE control system currently provides 34,000 pounds maximum augmented thrust on an average engine basis with a 0.9 Mach number signal when operating in the higher thrust mode. An increasing Mach number signal into the engine control raises fan operating line schedules to automatically increase airflow and available thrust. This increased performance is delivered in the heart of the operational flight envelope where it is tactically useful. As the 34,000 pound thrust option is already automated within the control schedules, no interaction by the pilot is required to achieve this performance and the EFE operating in this mode has the full 4300 TAC durability without any time limitations. At Intermediate Rated Power (IRP), the EFE in the higher thrust mode is capable of producing 19,000 pounds average SLS equivalent thrust. This performance is also achieved at the full 4,300 TAC rating without any time limitations or pilot interaction.

The F110-GE-129 EFE offers the user flexibility in trading performance for life as shown in Figures 2, 3, and 4. However, applying these options requires consideration of all components within the engine. A balance between the advantages gained from the thermodynamic cycle and the mechanical structure's ability to sustain these benefits is required. In selecting the increased performance option, the turbine is the area within the engine that shoulders the maximum life penalty due to increased temperatures. The current production F110-GE-129 has demonstrated

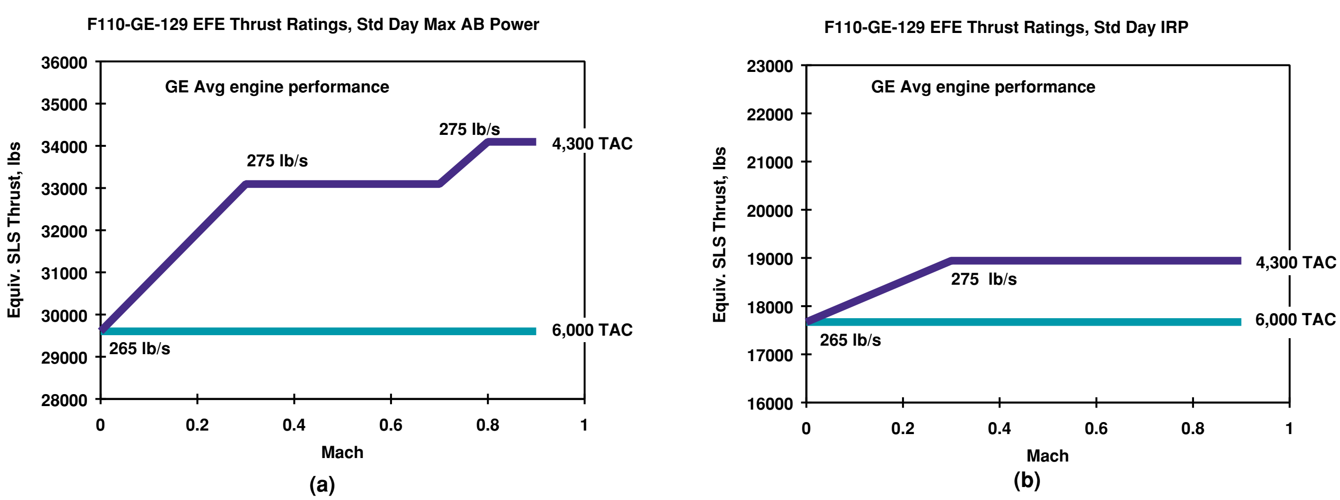

Figure 4: F110-GE-129 EFE Average Thrust Ratings on a Standard Day, (a) Max A/B Power and (b) Intermediate Rated Power (Dry).

more than adequate temperature margin in field service as seen by the absence of hot section failures, no related in flight shutdowns or power losses, and zero performance related removals. An additional method of evaluating the mechanical robustness of an engine is through weight growth required for the other components to adapt to the increase in thrust with the new fan. In the case of the F110-GE-129 EFE, the small weight increase is associated with the new fan module. This weight increase is a direct consequence of applying long chord fan aerodynamics technology to achieve thermodynamic improvements.

EFE FAN DESIGN AND TEST RESULTS

The cornerstone of the EFE is a higher airflow long chord blisk fan, adapted from the F118-GE-100 engine used on the B-2 bomber. The blisk design used technology leveraged off the F118 and other IHPTET fans, and incorporated practical lessons learned from F110 field experience to obtain high fan efficiency and improve durability, performance and thrust. Figure 5 shows the technology trends in fan efficiency between the current production F110-GE-129 fan and some highly loaded, advanced technology IHPTET fans. In engine tests, the F110-GE-129 EFE blisk fan exceeded these IHPTET goals while providing significant improvements in maintainability, reliability and safety.

A comparison of the fan aerodynamic design point parameters between the current production F110-GE-129 IPE and the F110-GE-129 EFE is shown in Table 1. The significant improvement in fan efficiency at cruise relative to the current production fan translates into lower turbine temperatures that results in increased hot parts life.

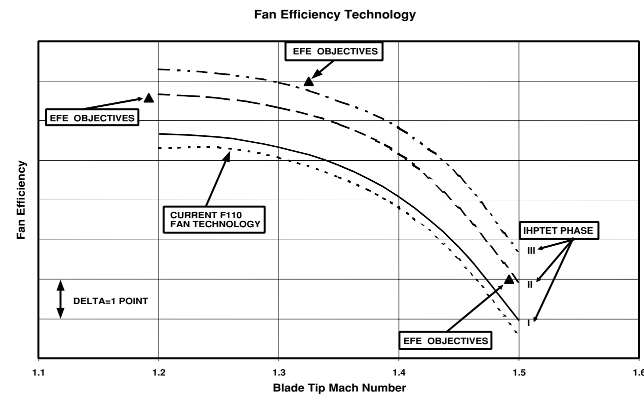

Figure 5: Fan Efficiency Technology Comparison

Table I: Fan Aerodynamic Design Point Comparison

Parameters	F110-GE-129	F110-GE-129 EFE
Inlet Corrected Flow (lbs/sec)	269	294
Inlet Corrected Tip Speed (ft/sec)	1400	1483
Pressure Ratio	3.4	4.2

Figure 6 shows the comparison of the F110-GE-129 current production fan with the EFE blisk. Significant design, development, repair and field experience has been accumulated with

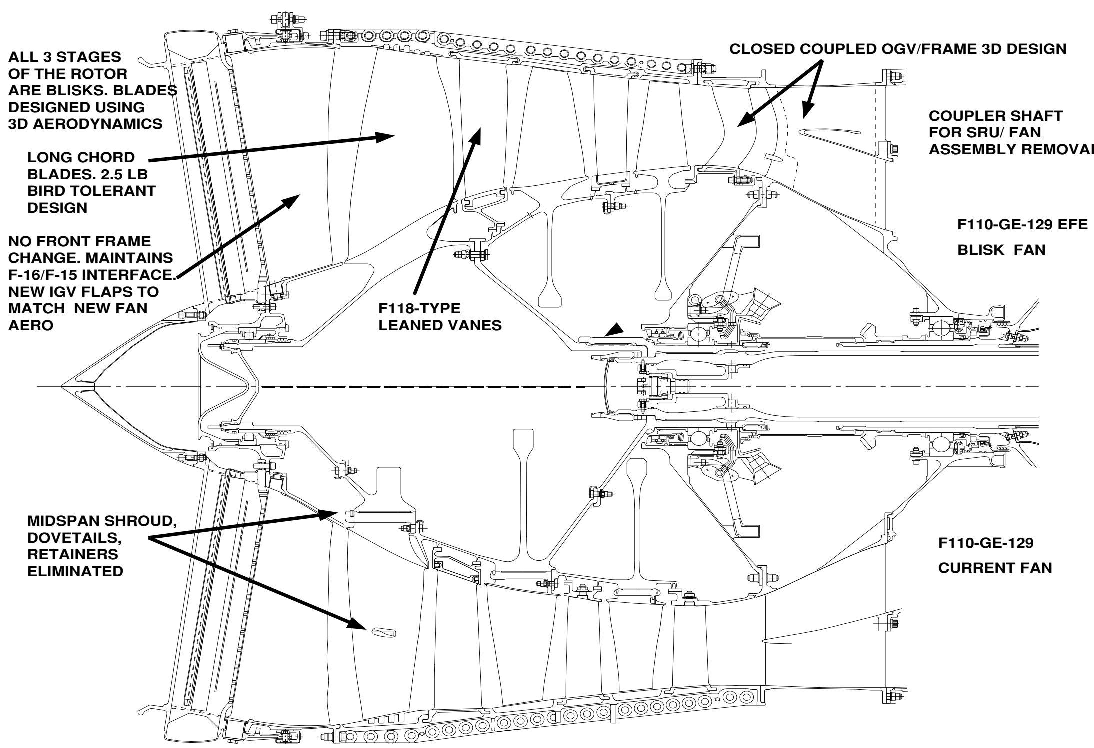

Figure 6: F110-GE-129 EFE Fan Design Features – EFE Fan is physically interchangeable with current production IPE Fan. No change in airframe/engine interface is required as the inlet diameter is identical between the two fans.

blisks on the T700 helicopter engines, the LM2500+ Marine and Industrial engines, the F120 ATF/JSF engines and the F414 engines for the Navy F-18E/F. All three stages of the F110-GE-129 EFE fan are of blisk construction. The assembled fan rotor is shown in Figure 7. The blisk configuration produces a reliability improvement over the current system by eliminating potential sources of high stress regions such as blade dovetails and mid span shrouds (Kandebo, 1996). This simplified configuration also reduced the fan module part count by over 65%.

Figure 7: F110-GE-129 EFE assembled blisk fan rotor. The blisk fan produces reliability improvements over the current system by eliminating potential sources of high stress regions such as blade dovetails and mid span shrouds.

The first stage of the F110-GE-129 EFE fan incorporates long chord fan aerodynamic technology while eliminating the mid-span shroud and dovetails using blisk technology. The airfoils are robust and have thicker blade leading edges relative to its IPE predecessor (shown in Figure 8) with on-wing blend limits increased twofold. Recently developed Laser Shock Peen (LSP) technology is also applied to the stage 1 fan blade, reducing crack propagation and further enhancing FOD tolerance capabilities. In engine tests, intentionally damaged LSP fan blades have passed full AMT endurance testing without cracking and the LSP process has been qualified for the current production F110-GE-129.

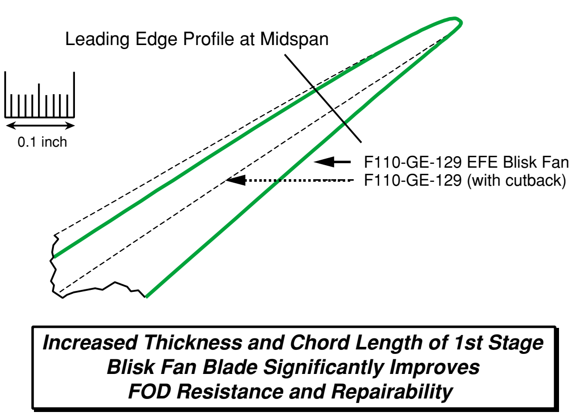

Figure 8: EFE stage 1 fan blade has a thicker blade leading edge.

The F110-GE-129 EFE fan airfoil aerodynamic design uses the latest 3D viscous design codes to increase efficiency (Kandebo, 1996) and minimize the performance impact of the above mentioned thickness increases. Blade mean camber line shapes were custom tailored (Wadia and Law, 1993) to reduce the shock losses associated with the larger blade wedge angle as a result of an increase in the leading edge thickness. The EFE fan hub end wall contours were also customized to reduce the impact of airfoil maximum thickness increase required to eliminate the mid-span shroud. Fan stage 1 vane was leaned, similar to that in the F118-GE-100, to reduce hub inlet Mach numbers and have shock free diffusion along the stator surface for increased performance.

An example of aerodynamic development for the EFE unique closely coupled fan frame and outlet guide vanes is described below. In cutting the engine length to make the long chord blisk fan adaptable for the F-16, the outlet guide vanes were packaged closer to the fan frame, as illustrated in Figure 6. Although only 1.4 inches shorter in length to the fan frame struts, this reduction could not only create an undesired back pressure, with potential to hurt performance and aerodynamic stability, but it could also adversely impact the fan distortion transfer to the compressor. The 3D design of the closely coupled OGV-Fan Frame system described below eliminated this risk. The length and inlet diameter constraints applied to the long chord blisk fan design are significant as they provide the customer with the flexibility to either use the EFE in new aircraft purchases or to retrofit the current production F110-GE-129 IPE fleet with the more efficient blisk fan during the IPE engine's 8,000 TAC depot inspection visit.

Commercial aircraft engine applications have for a long time relied on the principle of using non-axisymmetric stator configurations ahead of pylons/struts to achieve a uniform flow field upstream of the stators. This approach is described in the papers by Hemsworth (1969) for the General Electric TF-39 engine and by Rubbert et. al. (1972) for an alternative engine installation on the Boeing 747 aircraft. As a practical alternative to building stator cascades with different camber angles, the F110-GE-129 EFE design started by first considering a slightly more attractive option that lowered the cost of implementation by using circumferentially re-staggered stator vanes to aerodynamically guide the exit flow from the stator trailing edge smoothly around the strut leading edge. To reduce maintenance costs even further, the design evolved into a unique set of swept and leaned fan outlet guide vanes that eliminate the complexity of local tailoring (i.e. the need to use different "vane-types" or "vane re-stagger"). Figure 9 shows a 3D pictorial view of the closely coupled fan frame/outlet guide vane system.

Both configurations (i.e., the "vane constant-stagger" and "vane re-stagger") were analyzed and tested in the full engine environment, including inlet distortion. The tests demonstrated that no reduction in the fan's performance and stability resulted from this reduced length design. Test results showed that the more expensive "re-stagger" option with the swept and leaned fan exit guide vanes was not required. The aerodynamic design of the closely coupled fan frame system, highly complex 3D analyses and engine test results have been reported by Wadia, Szucs and

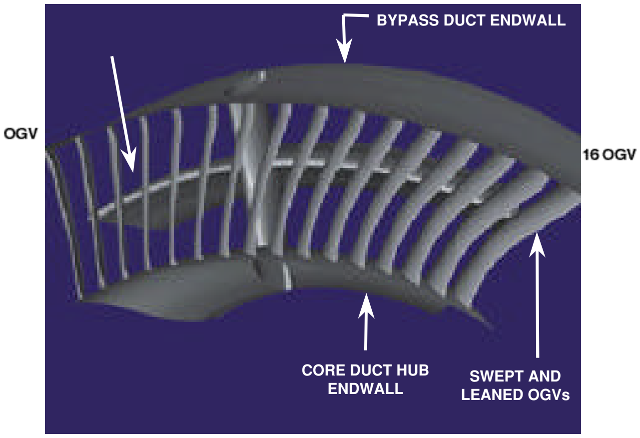

Figure 9: 3D pictorial view of the closely coupled fan frame and exit guide vane system.

Gundy-Burlet (1999). Figure 10 illustrates an example of the calculated entropy (loss) contours showing the stator wake streaks along both the upper and lower splitter surfaces and also along the inner and outer flowpath surfaces. The splitter, which has to accommodate a significant swing in its leading edge incidence with changes in bypass ratio, is well behaved as represented by the very low loss level shown in “blue.” The highest loss levels near the outer wall of the bypass stream are shown in “red.” The exit guide vane wakes show up as distinct “dark blue” and “red” entropy contours along the splitter and endwall surfaces.

ENTROPY CONTOURS (Side View)

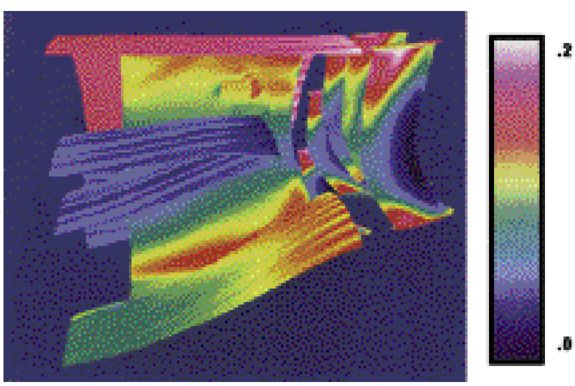

Figure 10: Entropy contours along the fan frame strut, splitter, and exit guide vanes showing stator wake streaks along the splitter surfaces and outer and inner endwall surfaces.

General Electric’s company wide quality initiatives (Velocci, 1998) entitled Design for Six Sigma (DFSS) and Design for Reliability (DFR) were used to produce the fan blisks. These processes established six sigma capable tolerance levels for a new size range of production titanium blisk airfoils, particularly stage 1, for the critical to quality (CTQ) characteristics such as leading edge thickness, leading edge profile and blade twist angle. The long chord blisk fan demonstrated excellent structural capabilities in two aero-mechanical design and test iterations. The instrumented blisk to qualify the fan to meet the U.S. Air Force requirements is shown in Figure 11.

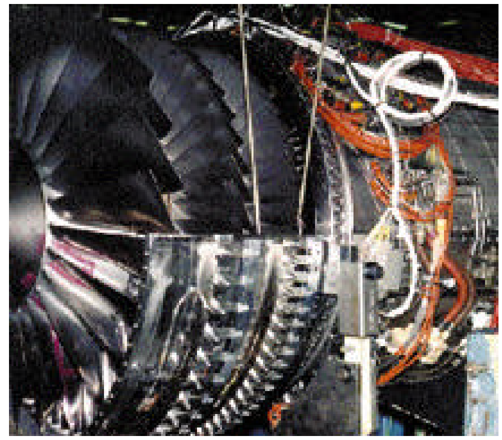

Figure 11: Instrumented EFE Blisk installed in the F110 engine for aeromechanical qualification.

The long chord blisk fan accumulated over 700 hours of test time including over 500 hours of testing at altitude conditions. Testing covered a wide range of flight conditions and power settings from sea level to 40,000 feet/Mach 2.0, idle to 34,000 pounds thrust at standard and hot day operations. Aero-mechanical test data acquired in General Electric’s test facilities in Evendale and in the altitude test facilities at Arnold Engineering Development Center (AEDC) in Tullahoma, Tennessee resulted in resonant responses for all the blades and vanes below GE’s design practices and the U.S. Air Force HCF criterion. In addition to the optimized aero-mechanical design, the fan exceeded the EFE efficiency objectives shown in Figure 5 by an additional 1.5% while meeting all its operability requirements.

RADIAL AUGMENTOR DESIGN AND TEST RESULTS

The F110-GE-129 EFE features a radial augmentor derived from concepts embodied in the F120 and F414 programs. It provides reduced complexity, improved maintainability and reliability with over 50% improvement in parts life due to advanced cooling of the augmentor parts. Figure 12 shows the comparison between the current production IPE and the EFE augmentor. Some of the unique features of the EFE augmentor are also summarized in the attached table in Figure 12. The centerbody in the F110-GE-129 EFE is truncated for heatshield (LRU) removals resulting in a significant (90%) reduction in maintenance man hours. The radial augmentor not only lowers LRU removal and shop visit rates, but also reduces the augmentor weight by about 3% relative to the current production augmentor. The radial augmentor also has a 50% reduction in part numbers and a 15% reduction in parts count relative to the current production augmentor.

Like the blisk fan, the radial augmentor was also developed using highly complex 3D CFD analyses. Each element that constitutes the augmentor shown in Figure 12, was modeled in the analysis. The model started at the turbine rear frame exit and ended at a predetermined distance aft of the exhaust duct liner. The model spanned 22.5 degrees from a fan chute centerline to the adjacent

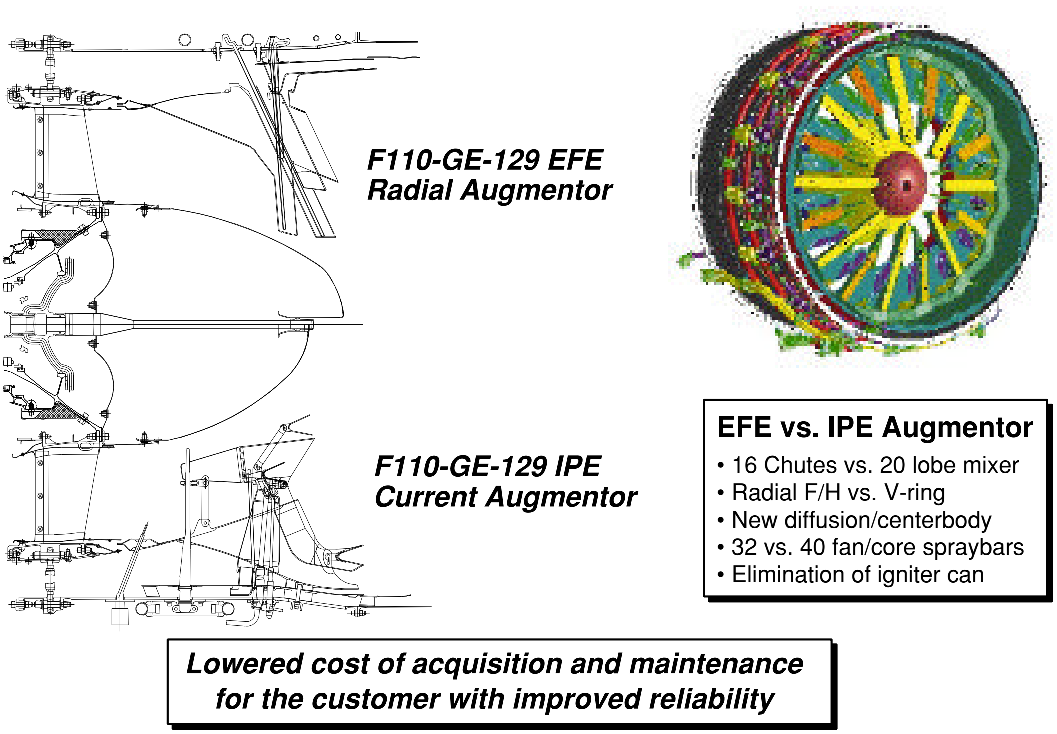

Figure 12: F110-GE-129 EFE Radial Augmentor Features

fan chute centerline with periodic boundary conditions imposed on the sidewalls. The model included mixer chutes, wall flameholders, radial heatshield / flameholder, centerbody, spraybars, liners and blockages due to struts and hangers. Liner screech and cooling holes were treated as porous media flow cells in the analysis. The geometric complexity of the augmentor was accurately modeled with a grid system that exceeded two million grid points.

The analysis was first validated with extensive on-line gas analysis (OLGA) data from the current production augmentor to develop a sound understanding of the inner workings of the 3D

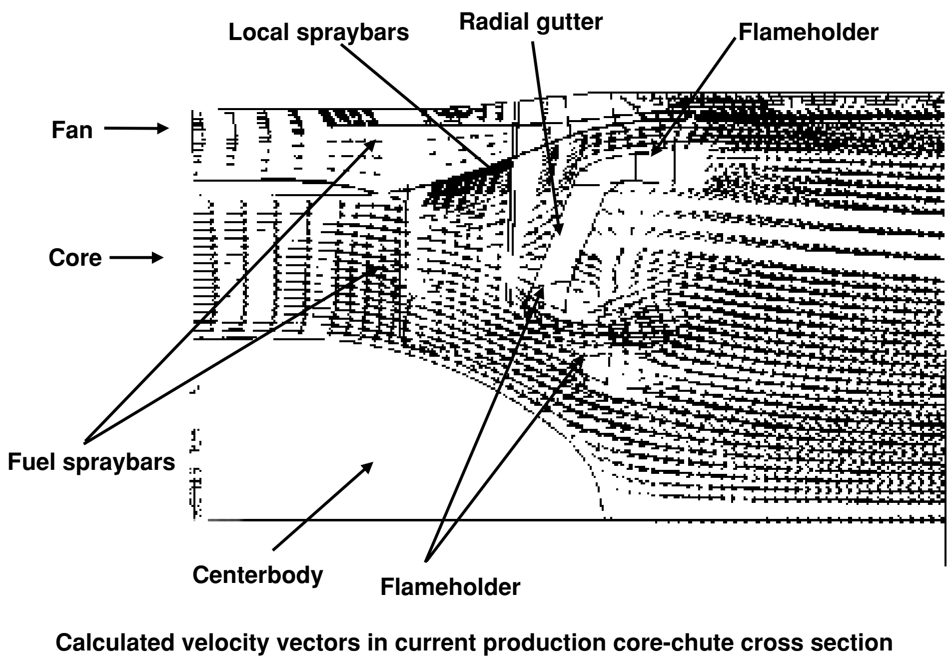

Figure 13: Calculated velocity vectors for the current production F110-GE-129 augmentor

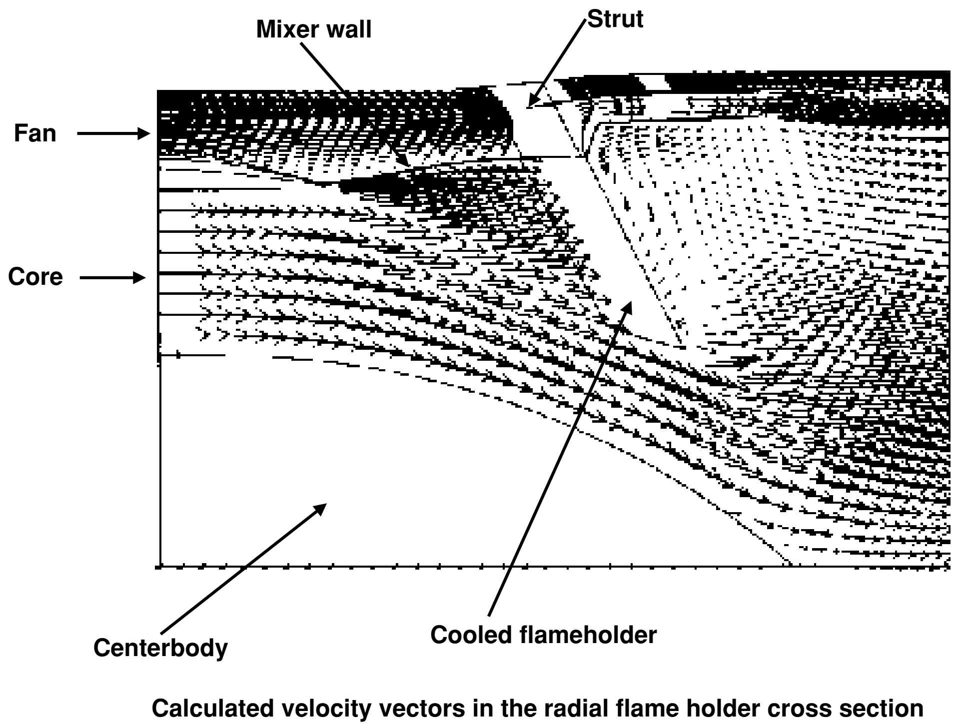

Figure 14: Calculated velocity vectors for the F110-GE-129 EFE radial augmentor

computer code. The radial augmentor design was analyzed using the calibrated 3D analyses. The analytical results were used to improve the radial augmentor design. The analyses provided a significant reduction in the time spent on developing the augmentor on the engine. Figures 13 and 14 show a typical example of the large body of data generated by the 3D analyses. Shown here are the velocity vectors in a cross section of the current production (IPE) and the EFE radial augmentors, respectively. The large flow re-circulation (vortex) downstream of the flameholder, shown in Figure 14, provides more useful mixing in the case of the radial augmentor. The temperature contours for the EFE radial augmentor calculated by the complex 3D analyses at a prescribed after burner flight condition is shown in Figure 15.

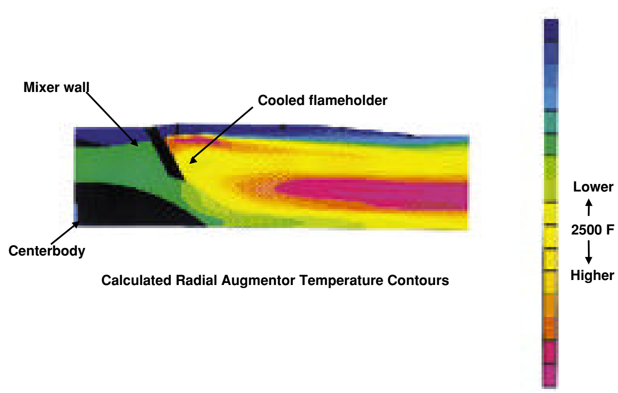

Figure 15: Calculated temperature contours for the F110-GE-129 EFE radial augmentor at a prescribed flight condition.

The radial augmentor, developed using the 3D CFD analyses, demonstrated good efficiency and light-off characteristics (quick and stable lights) in 450 hours of total test time on the engine. The augmentor accumulated 99 hours of testing at sea level and 351 hours at altitude conditions. 85 test hours were spent in combination of maximum A/B and part power A/B operation which is significantly more than required for 2000 EOH life. The radial augmentor components demonstrated excellent reliability in rigorous testing across the entire flight envelope. The radial augmentor permitted operations at higher cycle temperatures without flameholder burning and demonstrated low screech.

F110-GE-129 EFE EXHAUST NOZZLE OPTIONS

The current production F110-GE-129 IPE exhaust nozzle assembly provides high reliability and smooth thrust modulation throughout the flight envelope. The F110-GE-129 EFE nozzle design is nearly identical to the proven F110-GE-129 IPE engine with years of successful service, but with significant life and maintainability benefits.

The F110 exhaust nozzle, shown in Figure 16 utilizes a converging-diverging exhaust nozzle design having variable throat area and variable exhaust expansion ratio. This concept provides high cruise performance and low drag, and aids in smooth thrust modulation. The full authority digital electronic control continually schedules the exhaust nozzle throat area to maximize engine thrust while maintaining sufficient fan stall margin for excellent engine operability throughout the flight envelope.

The exhaust duct liner directs film cooling air back to the nozzle flaps and seals, and also provides effective augmentor screech suppression. The nozzle convergent section is comprised

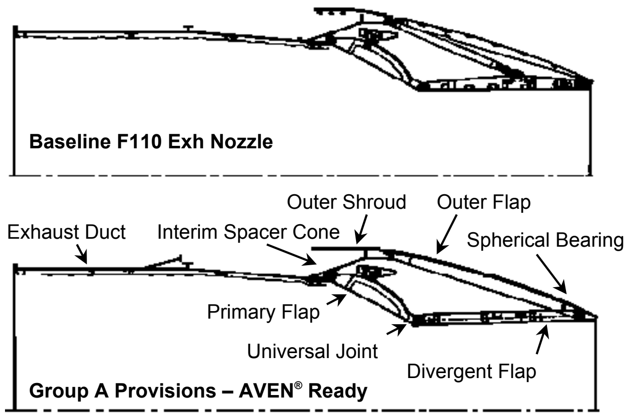

Figure 16: Comparison of the F110-GE-129 Baseline Exhaust Nozzle features with the AVEN Ready Exhaust Nozzle features

of primary flaps and seals while the divergent nozzle section is comprised of divergent flaps and seals. Thermal barrier coatings have been introduced on the divergent flaps and seals to reduce thermal fatigue, extend nozzle life and reduce maintenance.

The F110-GE-129 EFE, like it's IPE predecessor, is structurally capable of accepting the Multi Axis Thrust Vectoring (MATV) with the modifications to the exhaust nozzle as shown in Figure 16.

The ejector nozzle, shown in Figure 17, is another potential option available on F110-GE-129 EFE. The fundamental idea behind this concept is to use air from the engine bay to cool the nozzle parts. This results in a significant improvement in exhaust nozzle parts life (4X) and a large (50% to 90%) reduction in LRU replacement times. Other benefits of the ejector nozzle are a reduction in parts count, reduced spare parts cost, reduced inspection time and lower exhaust system weight.

SUMMARY

The F110-GE-129 EFE, developed using General Electric's low risk derivative engine technology, is being offered at two different thrust/inspection levels. The engine can be operated by the customer at either of the two thrust / life ratings. In engine tests the EFE has demonstrated over 34,000 pounds of maximum augmented thrust, and will be qualified at 34,000 pounds thrust rating. Two key new features on the engine include an increased airflow, high efficiency, three-stage long chord blisk fan and an advanced radial augmentor that reduces complexity, improves maintainability and provides increased parts life. A detailed description of the new features of the F110-GE-129 EFE have been presented. The engine has completed final component validation and is being prepared for qualification testing.

The engine utilizes leading edge technology with new features that provide excellent reliability for new and derivative F-15, F-16 and F-2 aircraft. Building on the success of the F110-GE-100 program and leveraging low risk derivative engine technology has produced a very high efficiency robust blisk fan for the F110-GE-129 EFE. This fan is capable of providing increased thrust or improved engine life to new aircraft and is also available as a retrofit kit for the current United States Air Force and foreign military customer fleets without any airframe mount location modifications. Similarly, the radial augmentor provides significant durability improvements and can be retrofitted to existing engines as well. The improved durability and maintainability features of the F110-GE-129 EFE result in reduced operational cost, with production availability in 2002.

In October 1999, the United States Air Force officially informed GE Aircraft Engines that it had designated the F110-GE-129 EFE 32,000 pound (minimum) thrust / 4,300 TAC inspection interval engine option as the F110-GE-132. The F110-GE-129 EFE's 29,000 pound (minimum) thrust / 6000 TAC inspection interval option has been designated as the F110-GE-132A and the 34,000 pound thrust version of the EFE has been entitled as the F110-GE-134.

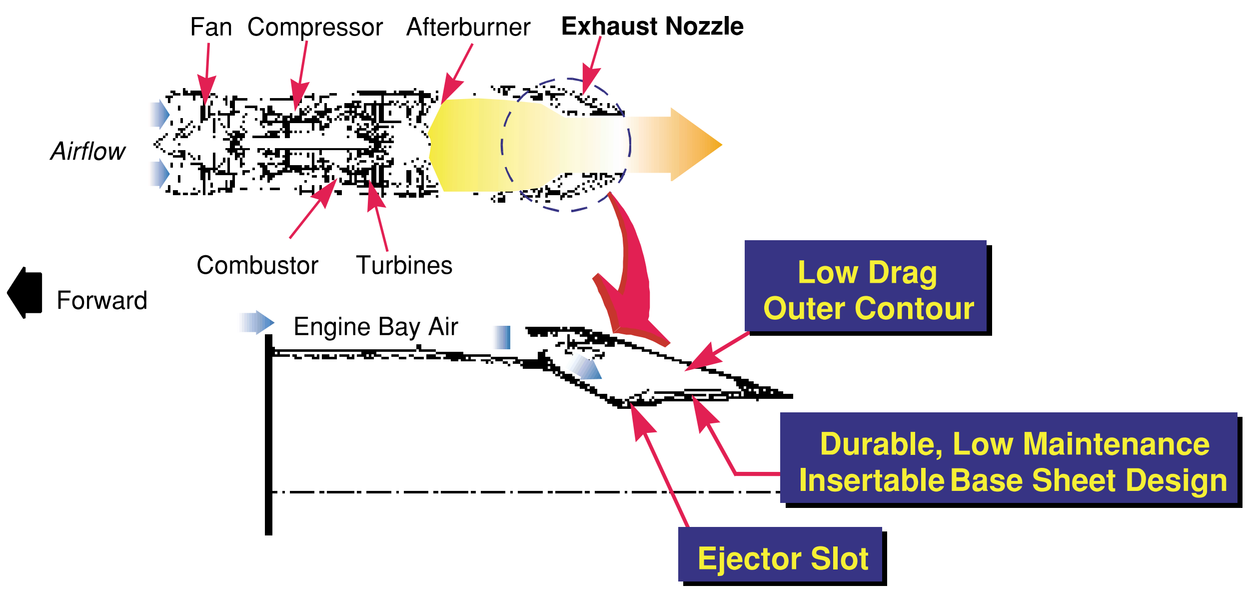

Figure 17: F110-GE-129 EFE Optional Ejector Nozzle Features

ACKNOWLEDGEMENTS

The authors would like to acknowledge Robert Griswold, General Manager, Large Military Engine Programs, Thomas Maxwell, F110 Program Manager, Ron Hutter, Military Marketing and Sales Manager and Alan Ewing, Jeffery Reno and Bjorn Gidner, F110 Marketing and Sales for their support of the EFE development and qualification program. The authors would also like to acknowledge the support provided by several branches of the United States Air Force (AFRL, ATTD, JTDE, CIP and ASC/LPP) to develop the long chord blisk fan and other key components for the F110-GE-129 EFE. The authors are grateful to GE Aircraft Engines for permission to publish this paper.

REFERENCES

Andersen, R.H., 1990, "F110: Power for the 90's and Beyond," presented at the 37TH ASME Turbo Expo, Cologne, Germany, June 1–4, 1990.

Hemsworth, M.C., 1969, "Development and Experiences of the First High-Bypass Ratio Engine, TF-39," Paper No. 21 presented at the 11th Anglo-American Aeronautical Conference, London.

Kandebo, S.W., 1996, "GE Developing Longer-Life F110," *Aviation Week and Space Technology*, February, 1996, pp. 42–43.

Rubbert, P.E., Boctor, M.L., Cowan, S.J,. and Laprete, R.D., 1972, "Concept and Design of Stators Tailored to Shield a Fan from Pressure Disturbances Arising in the Downstream Fan Ducts," AIAA Paper No. 72-84.

Velocci, A.L., 1998, "Pursuit of Six Sigma Emerges as Industry Trend," *Aviation Week and Space Technology*, Nov. 16, 1998, pp. 57.

Wadia, A.R., and Law, C.H., 1993, "Low Aspect Ratio Transonic Rotors, Part 2 – Influence of Location of Maximum Thickness on Transonic Compressor Performance," *ASME Journal of Turbomachinery,* Vol. 115, pp. 226–239.

Wadia, A.R., Szucs, P.N., and Gundy-Burlet, K.L., 1999, "Design and Testing of Swept and Leaned Outlet Guide Vanes to Reduce Stator-Strut-Splitter Aerodynamic Flow Interactions," *ASME Journal of Turbomachinery*, Vol. 121, pp. 416–427.