



ענף הנעה
המחלקה לאווירונאוטיקה
היחידה למו"פ-היחידה לתשתיות
מנהלת פיתוח אמל"ח ותשתיות
משרד הביטחון



DEPARTMENT OF
AEROSPACE ENGINEERING

המעבדה למנועי סילון וטורבינות גז
הפקולטה להנדסת אוירונאוטיקה וחלל
הטכניון, חיפה
<http://jet-engine-lab.technion.ac.il>



ענף הנעה
מחלקת מטוסים
להק ציוד
חיל האוויר

יום העיון השישה עשר במנועי סילון וטורבינות גז

16th Israeli Symposium on Jet Engines and Gas Turbines

November 9 2017,
Department of Aerospace Engineering,
Technion, Haifa, Israel

BOOK OF ABSTRACTS

יום ה', כ' חשוון ה'תשע"ח, 9/11/2017
אודיטוריום, בניין הפקולטה להנדסת אוירונאוטיקה וחלל, טכניון,
חיפה.



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THE 16th ISRAELI SYMPOSIUM ON JET ENGINES AND GAS TURBINES

Venue: Auditorium (room 235), Faculty of Aerospace Engineering, Technion

Thursday, November 9 2017, Technion, Haifa

This year, as in the previous 15 years, we plan to hold the Israeli Symposium on Jet Engines and Gas Turbines. During the last few years there has been a steady expansion of activities in Israel in turbo jet propulsion. This is in addition to the serial production of small engines, increased electricity generation using gas turbines and combined cycles, production of various engines' spare parts and maintenance work. In Israel, many bodies are active in jet engines and gas turbine area, including: MAFAT (MoD), IAF, Israel Navy, EL-AL, IAI, Beit Shemesh Engines, RAFAEL, TAAS, ORMAT, Israel Electric Corporation, R-Jet & Becker Engineering, the Technion and more.

Improved engineering & technological innovations and new projects in Israel calls for continued professional meetings' for the exchange of information, for cross-pollination and for creating a fertile seedbed for cooperation. During the previous 15 symposia, in every one, more than hundred scientists and propulsion engineers met and presented their work from the various industries, the MoD and Academia. These symposia were a success, wetting the appetite for more such meetings.

The 16th symposium includes invited introductory lectures on selected subjects (from large engine manufacturers and Academia). In addition there are presentations that concern activities in different Israeli industrial firms, institutes and, upon request, a tour to the faculty's renovated Turbo and jet Engine laboratory. This is also a good opportunity for professional meetings, exchange of ideas and presentation of jet engine models and products from various companies.

During the symposium there will be an opportunity to discuss all topics relevant to jet engines and gas turbines, including innovative cycles, aerodynamics of turbo-machines, combustion, heat transfer, structures and dynamics, simulations, control, production processes and maintenance, combined cycles and more. Preference will be given to subjects of interest in Israel.

Typically, the first half of the symposia (till lunch time) will be held in English.

Please note that the presentation from the present 16th and the previous symposium (the 15th) symposium can be seen in the following (Technion's Jet Engine laboratory's) website:

[/https://jet-engine-lab.technion.ac.il](https://jet-engine-lab.technion.ac.il)

All presentations will be published in full, or as a "censored" version, after the conference on the Jet Engine Laboratory website (see below).

Looking forward for a fruitful and enjoyable symposium!

Professor Yeshayahou Levy
Chairman of the symposium
Technion, Faculty of Aerospace Engineering,
e-mail: levyy@technion.ac.il, <http://jet-engine-lab.technion.ac.il>



16th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES,
TECHNICAL PROGRAM



	16th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES, NOVEMBER 9 2017, Auditorium , Faculty of Aerospace Engineering (room 235)
07:45 - 09:00	(Registration) הרשמה
09:00	Opening: Professor Yeshayahou Levy, Chairman, Faculty of Aerospace Engineering, Technion.
	Professor Wayne D. Kaplan Executive Vice President for Research Technion – Israel Institute of Technology
	Professor Yaakov Cohen, Dean, Faculty of Aerospace Engineering, Technion.
	Major Yigal Ben Shabat, Head, Propulsion Systems Branch, Aeronautical Division, MOD/MFAT
	Lieutenant Colonel Avi Yosfan, Head of Engineering, Propulsion Branch, IAF
09:20 - 13:10	מושב ראשון (First Session, In English)
	RECENT ADVANCEMENTS IN ENGINE DESIGN
35 min. lectures	Session Chairman: Yeshayahou Levy, Technion
A1	"Integrated Thermal Management Systems" Glenn Crabtree Consulting Engineer, Military Systems Engineering, GE Aviation,
A2	"The Technical Evolution of Fighter Engine Propulsion in the IAF" Tom Prete Vice President, Engineering, Military Engines Pratt & Whitney
A3	" Thermal Mechanical Analysis of an Internally Cooled Stator" Bruno Aguilar Honeywell
11:05 - 11:25	(Break and refreshment) הפסקה וכיבוד קל
A4	"Effects of manufacturing variability on unsteady interaction in a transonic turbine" John Clark Principal Engineer in Turbine Engine Division, US Airforce
A5	"Integrated Approach for Direct Calculation of Off-Design Performance of Gas Turbine Engine" Abdul Nassar Managing Director, Softinway
A6	"A Radical View on the Improvement of Gas Turbine Technology and Future Direction" Changmin Son Pusan National University, S. Korea
13:10 -14:30	ארוחת צהריים וסיור במעבדה למנועי סילון (Lunch and laboratory visit)



16th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES,
Faculty of Aerospace Engineering, Technion, Haifa, Israel
November 9 201,7



TECHNICAL PROGRAM (Cont.)

Lectures in Hebrew, 20 min. lectures. 14:30 - 17:10 כל ההרצאות 20 ד' ובעברית.			
Second Session מושב שני 14:30 -15:30 room 165		Third Session מושב שלישי 14:30 -15:30 room 235	
Design & Optimization		Turbomachinery	
Session Chairman: Savely Khosid, Rafael		Session Chairman: Beni Cukurel, Technion	
B1	"Optimization in design of a miniature turbojet engine: Existing tools and potential of implementation" Savely Khosid, Ohad Miller, Manor, Rafael LTd.	C1	"Influence of Turbine Exit Flow Swirl on Exhaust Nozzle Performance" Ram Evron, Zvi Goral, BSE LTd.
B2	"Economic Dispatch and Unit Commitment of a Single Micro-Gas Turbine under CHP Operation" Dan Zelazo, Beni Cukurel Technion	C2	"Increasing Efficiency of UAV Internal Combustion Engines via Inverted Brayton Cycle" Idan, Chazan, Beni Cukurel Technion
B3	"Aero-Engine Fan Gearbox Design" Ilan Berlowitz Israel Aerospace Industries,	C3	"Mean-line optimum design of a small axial turbine with millions configurations" S.Khosid, M. Goldbaum, R. Priampolsky Manor, Rafael LTd.
15:30- 15:50 (Break and refreshment) הפסקה וכיבוד קל			
Forth Session מושב רביעי 15:50 -17:10 room 165		Fifth Session מושב חמישי 15:50 -17:10 room 235	
Fuel & Combustion		Systems & Maintenance	
D1	"On the Conversion of a Large Turbo Fan Engine's Combustor To Be Fueled By Natural Gas" Yeshayahou Levy Technion	E1	"OT or Not? Issues concerning Over-Temperature in Turbine's Blades" Capt. Nitzan David Foucks, M&P Dept., IAF
D2	"On the Development of a SMD Correlation for a Spray Exiting from a Slinger Atomizer SMD" Ariel Cohen, BSE Ltd	E2	"Monitoring Engine Gearbox as preventive maintenances" Yosi Pickel, IAF
D3	"Lean Premixed Prevaporized Combustion for Gas Turbines" Aharon David, LPP Combustion LTd.	E3	"The Danger of Water in Aircraft Fuel Systems" Orian Elmaliach and Michal Yardeni Fuel and Chemistry Department, Materials Division, IAF
D4	"Impact of fuel composition on the dynamics of lean premixed combustion" Dan Michaels, Technion	E4	

תודתנו נתונה לגופים ומוסדות אשר תמכו ביום העיון:

ACKNOWLEDGMENTS

	חיל האוויר
	מפא"ת
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	תודתנו לפרסום הכנס: לאגודה למדעי התעופה והחלל בישראל ולאגודות מהנדסים, לשכת המהנדסים והאדריכלים

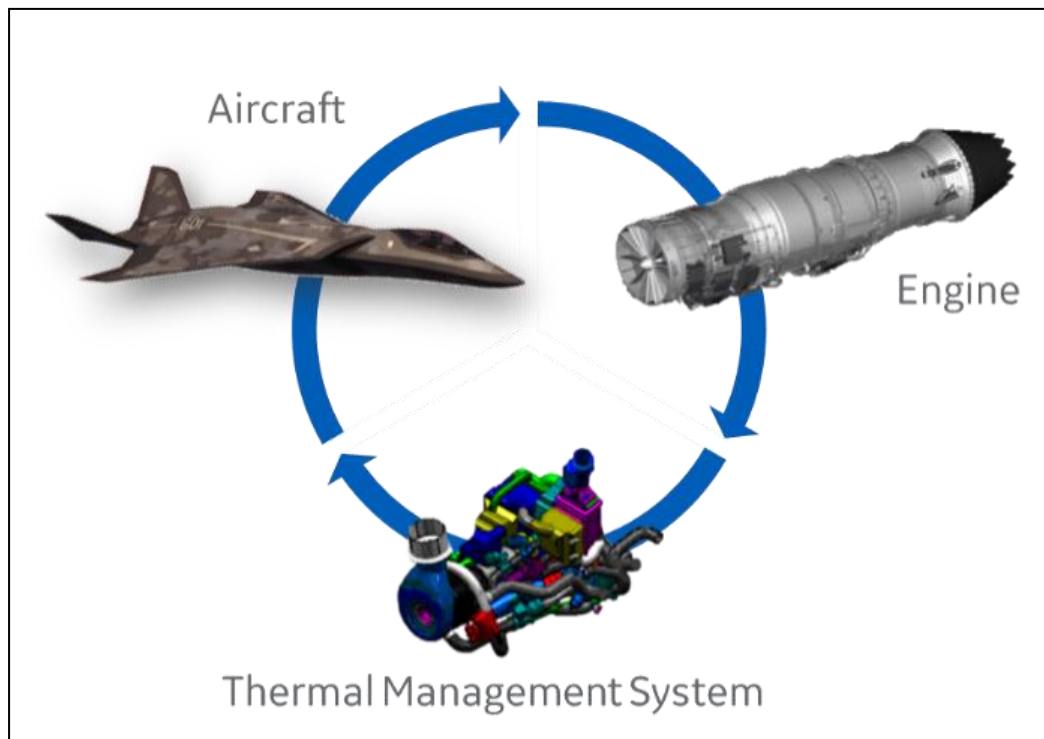
A1

Integrated Thermal Management Systems

Glenn Crabtree

Consulting Engineer, Military Systems Engineering, GE Aviation,

Current and emerging military aircraft have an exponentially increasing demand for power to operate flight systems, avionics, and weapon systems. This power demand creates significant challenges for aircraft thermal management systems to reject this heat without compromise to the aircraft, mission systems, or operational capability. Simply expanding the capability of current designs drives sub-optimal weight and volume of the power and thermal management sub-system, resulting in compromised aircraft operational capability. To develop an optimal aircraft platform, a thermal management sub-system concept must be developed in parallel with both the engine cycle and aircraft in the conceptual design phase. Consequently, system level integration becomes a more critical constraint in the early stages of the design process. This presentation seeks to discuss these challenges, and describes components, sub-system, and system level approaches to improving future aircraft capability.



A2

The Technical Evolution of Fighter Engine Propulsion in the IAF

Thomas W Prete

Vice President, Engineering, Military Engines

Pratt & Whitney

The Israel Air Force has a long, rich heritage of iconic fighter aircraft in their arsenal. Over these many years there have been many important technical advancement and innovations in the design, development and manufacturing of the propulsion systems for these aircraft that continually improve the capability of these weapon systems and define their place in aviation history.



This talk explores and examines the evolution of these technical advancements and innovations related to fighter aircraft jet engine propulsion systems over the last 40 years beginning with engines like the J52 powering the A-4 to the present F135 which powers the F-35I fighter. It presents the design considerations of these systems in the context of jet engine performance attributes such as thrust-to-weight, fuel consumption, safety & reliability, and cost of ownership. The talk then explores how product technologies and innovations, design and analytical capability, and advancements in manufacturing and manufacturing modelling have resulted in profound improvements in each propulsion system attribute. Finally, the talk ends with a discussion about the future of propulsion system capability and what innovations are being looked at to continue to improve their capability.

Thermal Mechanical Analysis of an Internally Cooled Stator

Bruno Aguilar
Honeywell

The demand for high performance and durable gas turbines continues to grow. Next generation high-efficiency turbine engines are increasing inlet temperatures to achieve higher performance that consequently affects the durability of flow path components in the hot section. For instance, the stator in Figure 1a experiences cyclical mechanical and thermal loading leading to fatigue. This phenomenon is known as Thermo-mechanical fatigue (TMF). Therefore, the prediction of accurate metal temperatures is becoming increasingly important to predict cyclic thermal stresses and component life.

In the past, the prediction of metal temperature required multiple assumptions. Industry in-house code or the correlations in open literature and textbooks are typically used to generate the internal and/or external convective boundary conditions. In many complicated cases these convective boundary conditions relied on computational fluid dynamics (CFD), especially when the full 3D CFD code matured and became a practical tool for gas turbine thermal design. However, this CFD calculation required assigning wall temperature or heat flux as the boundary condition where fidelity of the metal temperature highly depended on the accuracy of the assumptions.

In this study a conjugate heat transfer (CHT) analysis, Figure 1b, was implemented to calculate steady state metal temperatures. CHT has the ability to compute conduction of heat through solids coupled with convective heat transfer from a fluid. This new technique removes the uncertainty associated with calculating metal-fluid boundary conditions. Results from the CHT were used to obtain boundary conditions to create a conduction thermal model to obtain transient metal temperatures. An engine transient thermal survey was completed to validate the predictions from the thermal models. Finally, a 3D transient stress model was utilized to identify locations of high stress locations and identify design changes to improve part durability in the field.

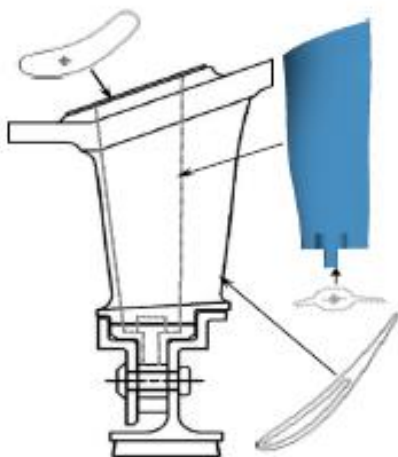


Figure 1a: Stator configuration

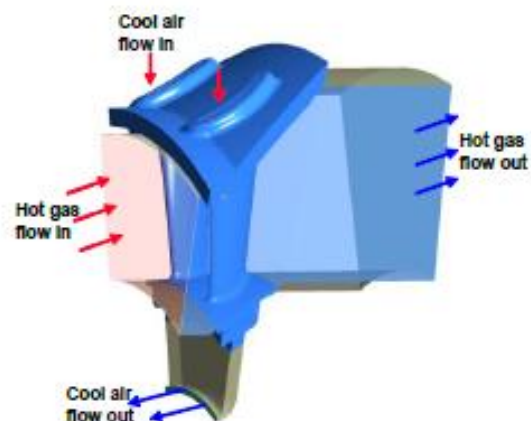


Figure 1b: Stator configuration

The Effect of Manufacturing Variations on Unsteady Interaction in a Transonic Turbine

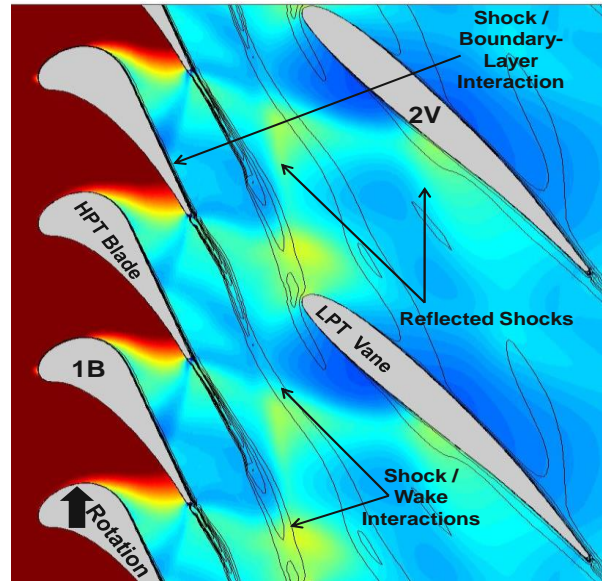
Dr. John Clark

Turbomachinery Branch, Turbine Engine Division, Aerospace Systems Directorate
Air Force Research Laboratory, WPAFB, OH
USA

The unsteady flowfield in a single-stage, high work, high pressure turbine that is paired with a contra-rotating low pressure turbine is exceptionally complex and dominated by shock interactions. Recently, a stage-and-one-half research turbine (See Fig. 1) was developed at the Air Force Research Laboratory (AFRL) in part as an effort to improve the accuracy of forced-response predictions in such a situation. Special attention was paid to the design of the blade to ensure that the stage had as high efficiency and as low trailing-edge shock strength as possible given the design point of the turbine. Initial testing with the turbine indicated that the overall physics of the shock interaction with a downstream vane was well predicted, and this gave credence to efforts to reduce the unsteadiness via 3D unsteady optimization. However, in initial experiments there were still significant discrepancies between predicted levels of unsteadiness on the blade suction side due to shock reflections from the downstream vane and those measured in experiments. Accordingly, an effort is underway to determine the source of such discrepancies and suggest improvements to the designer/analyst engaged in high-work turbine development. Specific studies are underway to improve the fidelity of grids, to include additional, perhaps relevant physics such as conjugate heat transfer and fluid-structures interaction, to utilize more rigorous cooling and viscous flow modeling, and to include as-measured geometries in the analysis.

This effort focuses on the comparison of unsteadiness due to as-measured turbine blades in the transonic turbine to that obtained with blueprint geometries via Computational Fluid Dynamics (CFD). A Reynolds-Averaged Navier-Stokes (RANS) flow solver with the two-equation Wilcox turbulence model is used as the numerical analysis tool for comparison between the blueprint geometries and as-manufactured geometries obtained from a structured light optical measurement system. The nominal turbine CFD grid data defined for analysis of the blueprint blade was geometrically modified to reflect as-manufactured turbine blades using an established mesh metamorphosis algorithm. This approach avoids the tedious manual regeneration of the CFD grid and does not rely on geometry obtained from Coordinate Measurement Machine (CMM) sections, but rather a point cloud representing the entirety of the turbine blade. Here, surface pressure traces and the discrete Fourier transforms thereof from numerical predictions of as-measured geometries are compared both to blueprint predictions and to experimental measurements. The importance of incorporating as-measured geometries in analyses to explain deviations between numerical predictions of blueprint geometries and experimental results is readily apparent. Further analysis of every casting produced in the creation of the test turbine yields variations that one can expect in both aero-performance and unsteady loading as a consequence of manufacturing tolerances. Finally, the

use of measured airfoil geometries to reduce the unsteady load on a target blade (See. Fig. 2) in



a region of interest is successfully demonstrated.

Fig. 1. Unsteady interaction between a transonic turbine blade and a downstream vane that is consistent with a counter-rotating Low Pressure Turbine.

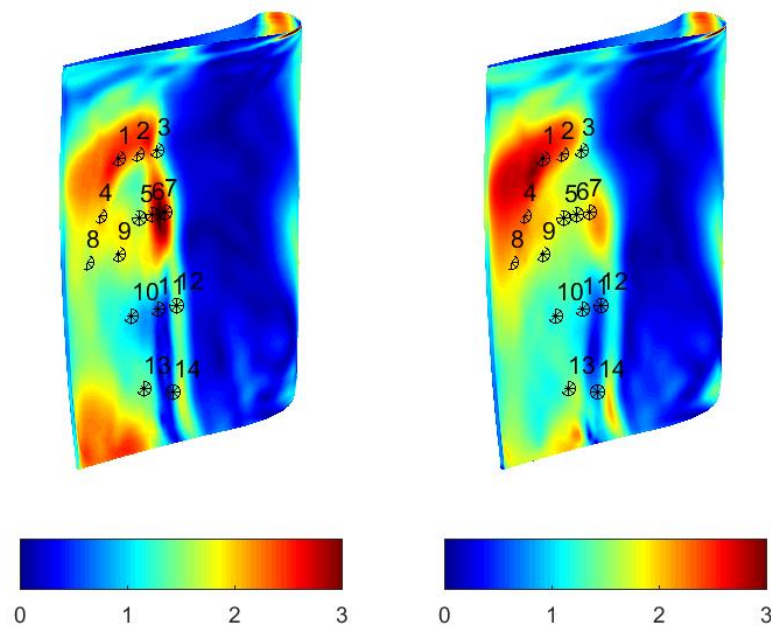


Fig. 2. Discrete Fourier Transform magnitudes (as a percentage of inlet total pressure) on the blade surface due to shock reflections from the downstream vane. On the left is the prediction on a measured blade of interest. On the right is a prediction of reduced unsteadiness at sensor 7 due to replacement of selected blades.

Integrated Approach for Direct Calculation of Off-design Performance of Gas Turbine Engine

Abdul Nassar
Managing Director, Softinway

Due to the versatility of the gas turbine to operate in both design and off-design conditions, they find their use in a number of applications as shaft power or propulsion power. Many a times, they are forced to operate at conditions away from the design point thus, making it important to understand the performance at off-design operating modes and possibility optimizing for even these modes if possible. The complexity of predicting the off-design performance increases when the gas turbine unit has cooling and secondary flows. The common approach to predict the off-design performance of the gas turbine unit is mapping the compressor and turbine separately and the consequent matching of the common operating points. However, this approach might be rather inaccurate when the cooling and secondary flows are considered. This affects not only on the efficiencies predicted but also on the operating margin and blade burnouts.

In this article, a virtual test facility for predicting the off-design performance using a direct calculation approach is presented. Here the compressor and turbine performance is calculated jointly in a single environment considering the cooling and secondary flow, which gives a more reliable prediction method for off-design operation without considering the individual performance maps. Figure 1 shows the general gas turbine layout with cooling flows extracted from different stages of the compressor and the cooling flow injected into different stages of the turbine for nozzle and blade cooling.

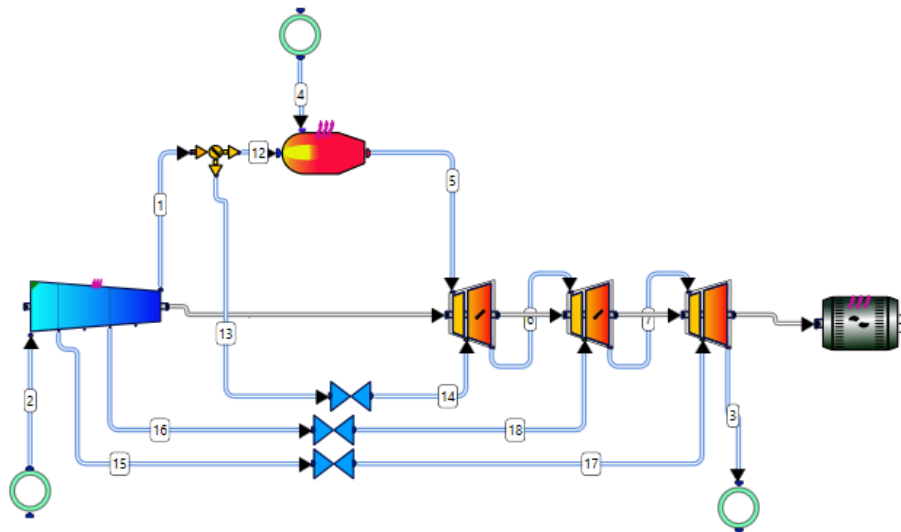


Figure 1: General gas turbine layout with cooling flows

Typically the performance is calculated using maps of the compressor and turbine. In the virtual test facility the detailed calculation of the compressor and turbine is performed on a real time basis using streamline calculation method. More sophisticated calculation can be performed by considering full 3D fluid flow analysis, but it becomes computationally

expensive. Here a simplified yet accurate method of calculation using the combination of streamline solver for the flow path calculation of compressor and turbine and one-dimensional flow and heat network for analyzing the cooling and secondary flows is used to predict the off-design performance. Figure 2 shows the virtual test facility flowchart for performing direct calculation considering the cooling and secondary flows for a gas turbine unit with power output of 166 MW. Figure 3 shows the comparison of gas turbine efficiency considering the direct calculation using virtual test facility and traditional approach using component maps.

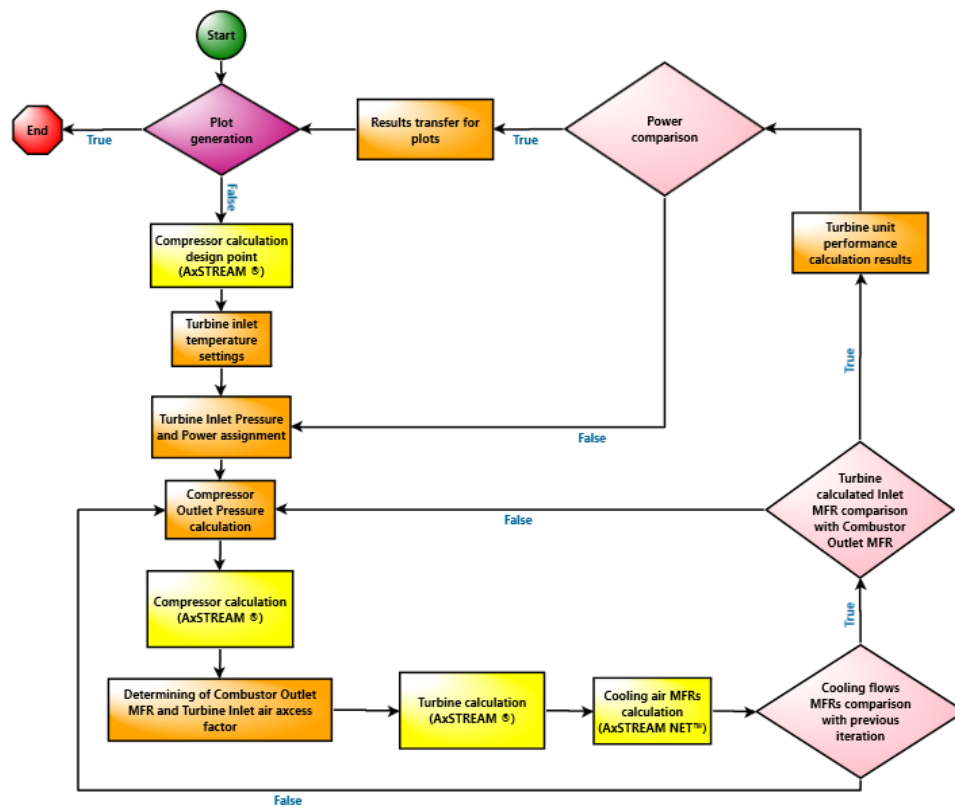


Figure 2: Virtual test facility flowchart based on AxSTREAM® platform tools powered by AxSTREAM ION™

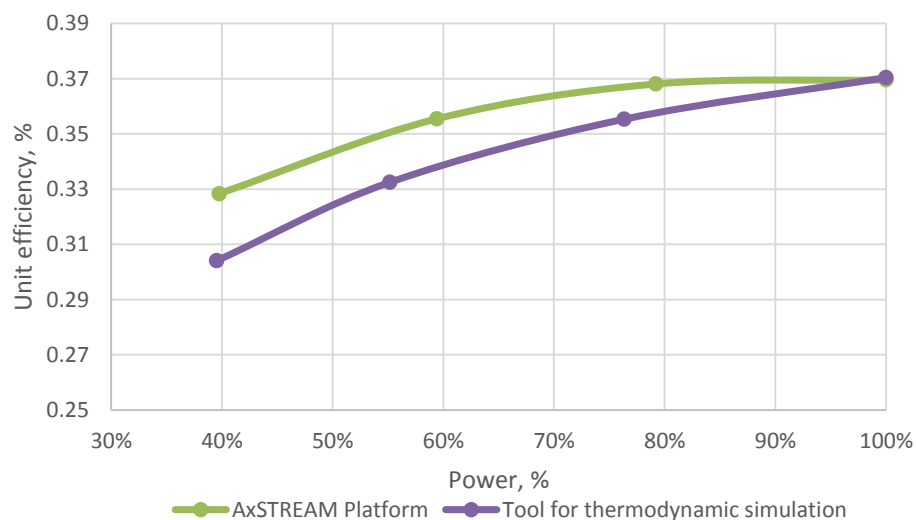


Figure 3: Gas turbine efficiency vs. its power considering virtual test facility and maps utilization approach

A Radical View on the Improvement of Gas Turbine Technology and Future Direction

Prof. Changmin Son
Pusan National University, Busan, Korea
changmin.son@pusan.ac.kr

The global trend of gas turbine development is to increase overall pressure ratio together with turbine inlet temperature. It is even more crucial to achieve small core development for next generation turbofan engine, ultrahigh bypass ratio gas turbine. Such a trend is also valid for UAV applications since smaller engine provides compact integration opportunities which can save overall size and weight hence improve reconnaissance capability. However, engine faces severe challenges to maintain its mechanical integrity at high pressure, temperature, operational speed, and etc. The associated aerodynamic losses, and heat management requirements are also increasing in principle. Therefore, a fundamental question is raised whether the trend is heading toward right direction.

In this presentation, the product thermal efficiencies will be reviewed against its theoretical limit. This observation will provide if the technologies contribute to reduce the gap between the product and theoretical efficiencies. Furthermore, loss mechanism of compressor and turbine is also reviewed, as a part of effort to understand the present challenges. New off-design profile loss models have been introduced by performing thorough investigations on compressor performance prediction. In this study, three sets of selected loss models were applied to predict axial flow compressor performance using stage-stacking approach. The results were compared with experimental data as well as CFD results. The comparison shows an interesting observation in choking region where the existing loss models cannot capture the rapid decrease in pressure and efficiency while CFD predicted the characteristics. Therefore, an improved off-design profile loss model is proposed for better compressor performance prediction in choking region. The improved model was derived from the correlation between the normalized total loss and the incidence angle. The choking incidence angle, which is a major factor in determining the off-design profile loss, was derived from correlations between the inlet Mach number, throat width-to-inlet spacing ratio, and minimum loss incidence angle.

The revised stage-stacking program employing new profile loss model together with a set of loss models was applied to predict a single and multistage compressors for comparison. The results confirmed that the new profile loss model can be widely used for predicting the performance of single and multistage compressor.

Similar approach has been implemented to improve the turbine profile loss model and the results were promising.

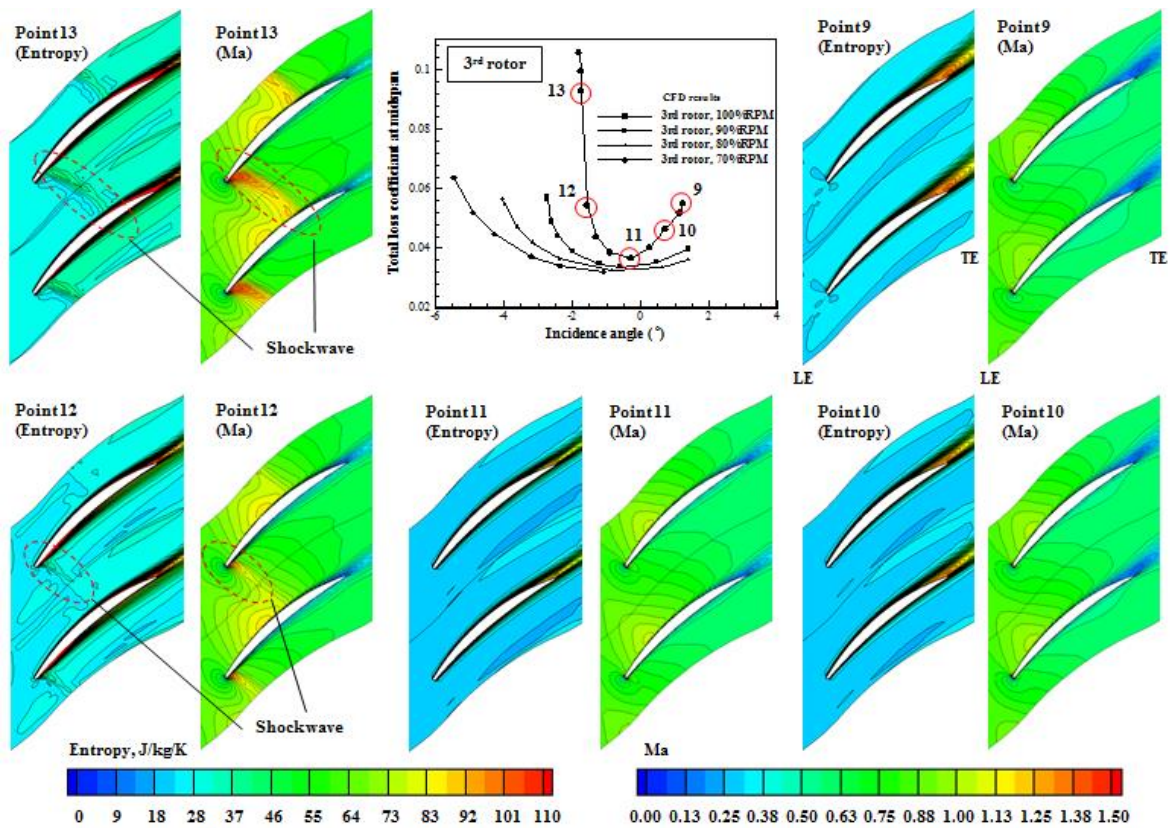


Figure 1 Improved off-design profile loss models for a compressor

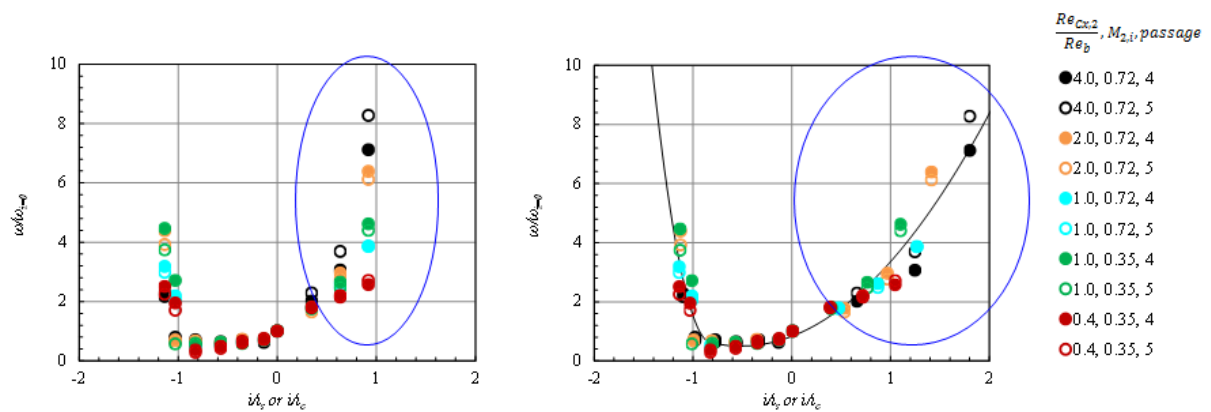


Figure 2 Improved off-design profile loss models for turbines

Optimization in design of a miniature turbojet engine: Existing tools and potential of implementation

Savely Khosid and Ohad Miller

Rafael – Advanced Defense Systems Ltd., Haifa, 3102102, Israel

Abstract

Increasing interest in expendable low-cost turbojet engines for civil and military purposes in the world leads to design and production of many miniature turbojet engines, by companies and groups of enthusiasts. These engines are usually equipped with a small low-pressure turbocharger centrifugal compressor, driven by a low-pressure ratio, one-stage axial turbine. Engine performance is also quite low, with the SFC in the range of 1.3-2.0.

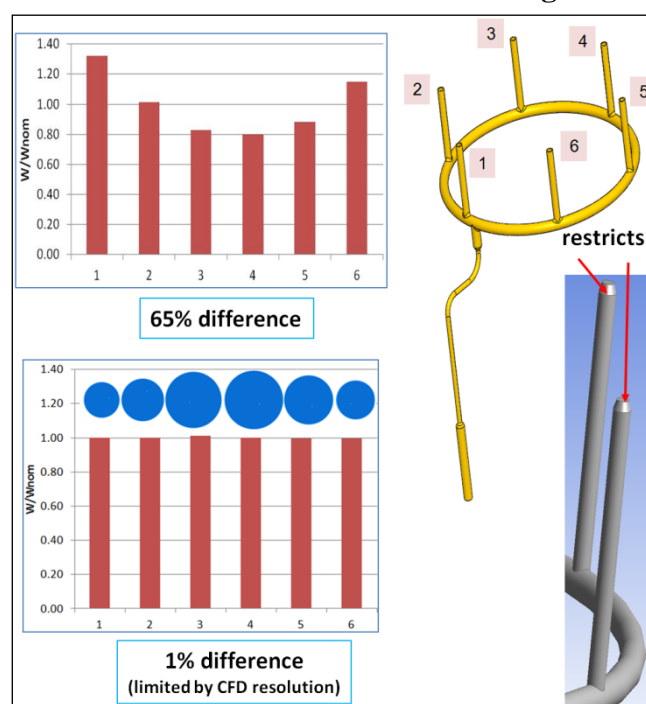
Large relative losses due to small size of the components are responsible for low performance of the miniature turbojet engines. On the other side, main components of the engines are usually not optimized, due to low cost of the engine and their design.

In this work, we describe a simple way to optimize performance of different components of a small turbojet engine, using fast state-of-the-art design software and well-established genetic algorithm tool (modeFrontier). Examples of optimization include:

- thermodynamic cycle (GasTurb);
- centrifugal compressor (BorgWarner, Concepts-NREC);
- combustion chamber (CD-Adapco India);
- fuel manifold (Rafael);
- Allison ring for rotor dynamics (Rafael);
- axial turbine performance and structure analysis (Rafael);
- exhaust propelling nozzle (Rafael).

In the present analysis we show that the engine performance can be sufficiently improved through a parametric optimization, up to 5% and even more.

Fuel manifold: flow rate leveling



Economic Dispatch and Unit Commitment of a Single Micro-Gas Turbine under CHP Operation

Daniel Zelazo[†] and Beni Cukurel^{‡*}

I. abstract

The global demand for energy supply is expected double as compared to the consumption over the last 20 years . Recent studies commissioned by the European Union, the U.S. Energy Information Administration (EIA), and the World Bank all present similar projections of electricity demand increase by roughly 100% from 2000 to 2050 . In order to satisfy this demand, the choice of fuel is among the challenges of economic policy, which is significantly dependent on national resources and long-term political interests. According to this EU energy market simulation , the future demand for power generation will be exceedingly accommodated by the renewable energy sources, as well as natural gas.

The largest increase in the use of natural gas for power generation will primarily be accommodated by the introduction of gas turbines (GT), mainly in combined cycle forms. Moreover, the trend towards deregulation of the electricity supply market vastly enhances the emerging distributed power generation for efficient delivery, as well as towards minimizing transmission and congestion losses . Furthermore, in order to cope with the intermittent availability of the renewable energy sources, it is essential to develop back-up systems . There is a particular interest in the potential of technologies such as micro gas turbines, especially in combined heat and power (CHP) applications and polygeneration systems, where the local main energy consumers become the provider for their electricity, hot water, heating and chill production . Numerous small and efficient gas turbine units can gradually be introduced in order to fulfill the new demands and to replace the larger aging power plants . Consequently, the non-centralized energy infrastructure network becomes more robust, cheaper (gains in distribution losses), safer, and also more versatile.

Micro-turbines offer additional advantages compared to other technologies for small-scale power generation such as high power-to-weight ratio, relative size (low terrain footprint), reliability (smaller number of moving parts), lower noise and vibrations, multi-fuel capability and lower greenhouse gas emissions . Furthermore, the recent developments reflect upon the potential of MGT to serve for polygeneration of energy (CCHP = electricity, heat and chill production). Such systems could theoretically achieve combined thermal efficiencies of above 85% , thus reducing running costs and CO2 emissions. Due to their relative low thermal and mechanical inertia, micro gas turbine units are agile and flexible, capable of short start-up times , along with rapid operational transitions between partial and full-load . Furthermore, micro gas turbines can be stacked up to create a bank which meets the instantaneous local power demand of their vicinity throughout

^{*}Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, Haifa, Israel. dzelazo@technion.ac.il, beni@cukurel.org, p.michael@campus.technion.ac.il

[†]The work was conducted during an internship at the Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, Haifa, Israel.

the day which is extremely relevant for “peak (power) shaving,” reducing the need for large power plants as backup during prime energy consumption intervals.

The integration of micro-gas turbines into the smart-grid as a polygeneration source can be approached as an economic dispatch (ED) and unit commitment (UC) problem. The ED and UC problems determine an optimal schedule and commitment level for each generating unit in a power system based on a set of constraints, including reserve power, operating parameters, and forecasted loads over a finite time horizon . In a smart-grid scenario where power demands can be mitigated locally, a detailed model-based optimization strategy has the potential to offer significant improvements.

While many optimization-based approaches to the operation of the smart-grid have been studied , to our knowledge, a focused effort towards optimally integrating a realistic micro-gas turbine with electricity and heat/chill production considerations, along with part load performance, has not been attempted. Furthermore, the base time step for the turbine dynamic modeling usually is in the order of minutes , while our more realistic model describes the dynamics of the turbine with a base time step on the order of seconds, allowing for a much more accurate dynamic model.

In this direction, the current work provides a complete solution for the integration of a micro-gas turbine in a smart-grid environment. The main contributions are:

- **Modeling of a Micro Gas Turbine** - A detailed thermodynamic cycle analysis is conducted on a representative MGT unit with non-constant component efficiencies and recuperator bypass. This model provides a detailed MGT performance characterization in a range of operational conditions.
- **Economic Dispatch of an MGT** - An optimization model for the operation of an MGT is provided and it includes characterization of all operating costs and constraints. This model is integrated into an economic dispatch framework by casting the optimization as a *shortest path* problem.
- **Detailed Case Studies** - To demonstrate the advantage of utilizing MGTs for CHP, a detailed simulation is conducted for a residential neighborhood. Analysis of the operational profile of the MGT and its economic benefit is presented.

In addition to an economic analysis of integrating the MGT into the grid, the case studies also revealed that the MGT operates under four distinct modes: *electricity driven*, *heat driven*, *revenue driven*, and *maintenance-cost driven*. Each mode describes the economically optimal way to operate for a given demand profile, fuel costs, and the tariffs. This leads to important insights into the economic dispatch solution and a high-level understanding of how the MGT can best be integrated into the grid.

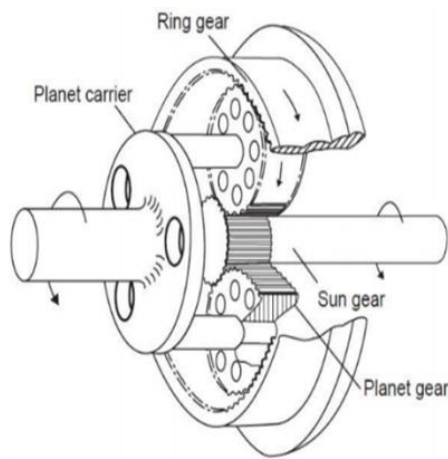
Aero-Engine Fan Gearbox Design

Ilan Berlowitz

Israel Aerospace Industries, BEDEK Aviation Group, Aircraft & Programs Division
iberlow@iai.co.il

Aero gearboxes are usually used as accessory. However in engines such as prop-fan, open-rotor and turbofan, gearboxes are in-line and differ from accessory gearboxes. These types of engines were developed in order to reduce the fuel consumption mainly in the 1980s. Pratt & Whitney (P&W) PurePower turbofan engine differs from conventional engines in that it has an in-line gearbox, similar to gearboxes found on turboprop engines which tends to be more fuel efficient than turbofans. This presentation examines the design of a gearbox for an aero-engine. After studying geared engines, the selected one was a turbofan. The comparison helps to choose design parameters, such as the type of gears, bearings and couplings.

Once the engine was selected, the design of the gears is made based on the power and speed of this engine. The design is made using the British Standard ISO 6336 [*Calculation of load capacity of spur and helical gears*] along with KISSsoft design software for mechanical engineering applications. Gear design is made in parallel to the bearing design. The bearing design is based on tribology calculations and with KISSsoft. The spline mounting system is then calculated and the shafts are designed based on fatigue calculations.



Planetary (Epicyclic) Gearbox

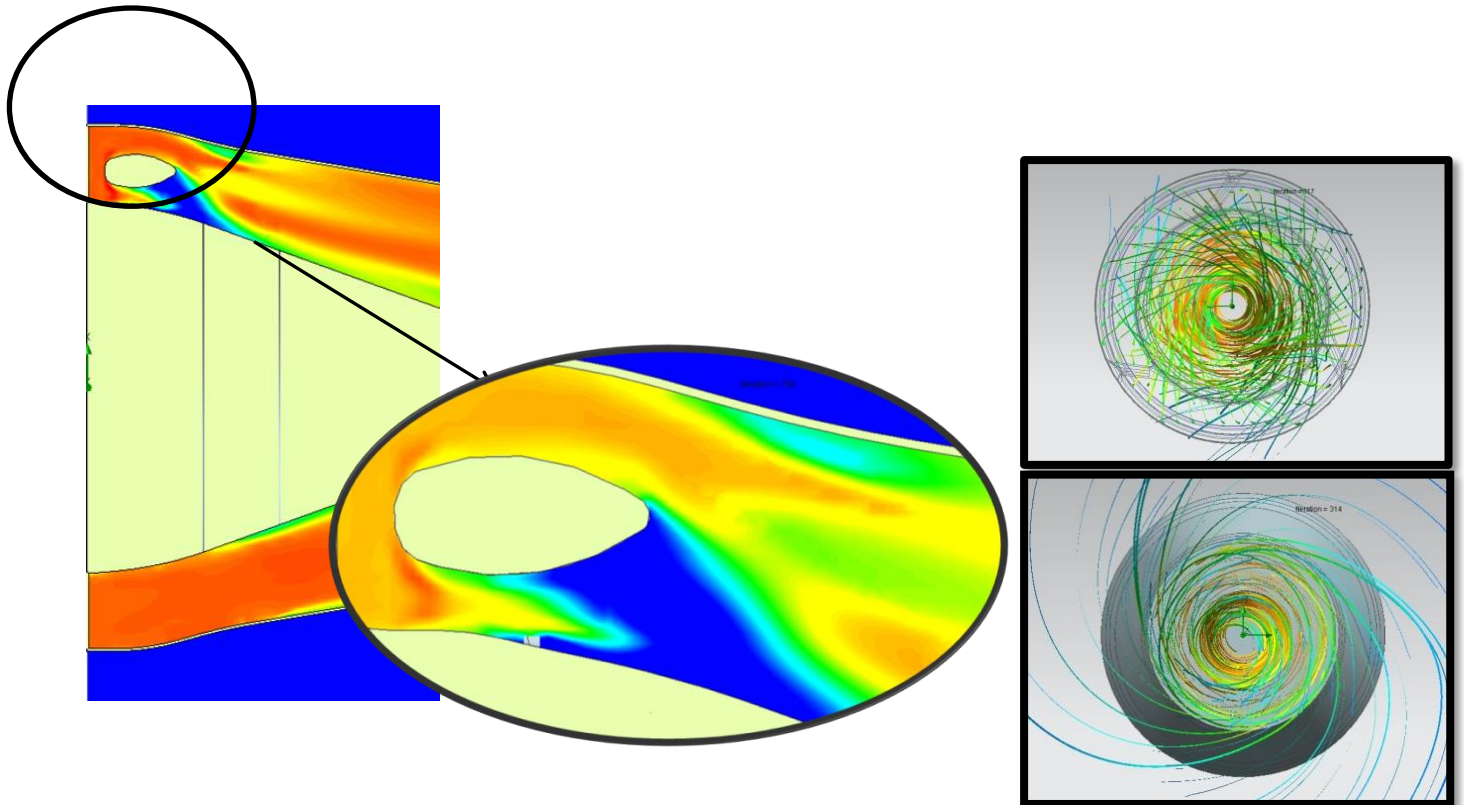
Influence of Turbine Exit Flow Swirl on Exhaust Nozzle Performance

Ram Evron, Zvi Gorelik and Ori Kam, Bet Shemesh Engines, Israel

The exhaust flow coefficient, C_D , and thrust coefficient, C_V , are used in jet engine one-dimensional cycle calculations in order to account for, amongst other phenomena, non-uniformity of the gas flow direction and velocity magnitude at the exhaust nozzle exit.

After sea level performance tests of an experimental engine showed that the C_D and C_V values – deduced from the measured engine thrust and airflow – were much lower than expected when compared to published data in the literature, CFD simulations of the turbine and exhaust nozzle flows were performed. Initial results achieved without carrying over the tangential flow components – deemed negligible during the design stage – from the turbine outlet to the nozzle inlet, did not match the experimental data.

Further simulations, in which the tangential flow *was* accounted for at the nozzle inlet, demonstrated good agreement with the experimental data, indicating that indeed the swirl angle distribution at the turbine exit is the cause of the unexpectedly low C_D and C_V values.



Research Effort

The research group is developing an experimental facility to demonstrate the potential of the IBC in providing additional shaft power through thermal energy extraction from IC waste gases. IBC enables expansion into sub-atmospheric pressures, increasing potential energy recovery from near-atmospheric exhaust gas. Furthermore, reduction to sub-atmospheric pressure alleviates the issue of backpressure load on the exhaust stroke. IBC system can be installed on existing engines with little modification, since IBC does not interfere with the primary power cycle. Figure 2 presents the experimental facility design.

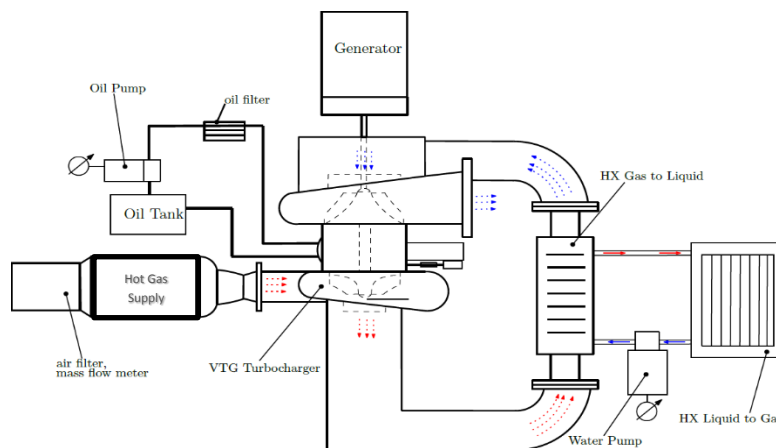


Figure 2: IBC Test Facility

Preliminary Analysis

Preliminary assessment of the potential impact of an IBC system for a typical Hermes 900 UAV mission has been conducted based on engine and mission data [2]. The data suggests that the additional power that could be produced from a turbocharged four-cylinder IC engine through IBC addition would amount to approximately 10%, which in this application would result in added 6 kW of electric power. It is estimated that the extra power benefits would allow decoupling the actuator load from the main power cycle. Overall, it would result in significant savings in fuel demand and yield a net reduction of over 30kg from the overall UAV mass that can be utilized for extension of mission duration or increased payload.

References

- [1] C.D. Copeland, Z. Chen, The Benefits of an Inverted Brayton Bottoming Cycle as an Alternative to Turbo-Compounding, in: ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, Montreal, Quebec, Canada, Monday 15 June 2015, V008T23A006.
- [2] Rotrex, Produktdatenblatt_914_115hp_rev.BRP-Rotax_20160823.

Mean-line Optimum Design of a Small Axial Turbine with Millions Configurations

Savely Khosid and Mark Goldbaum

Rafael – Advanced Defense Systems Ltd., Haifa, 3102102, Israel

Rafail Priampolsky

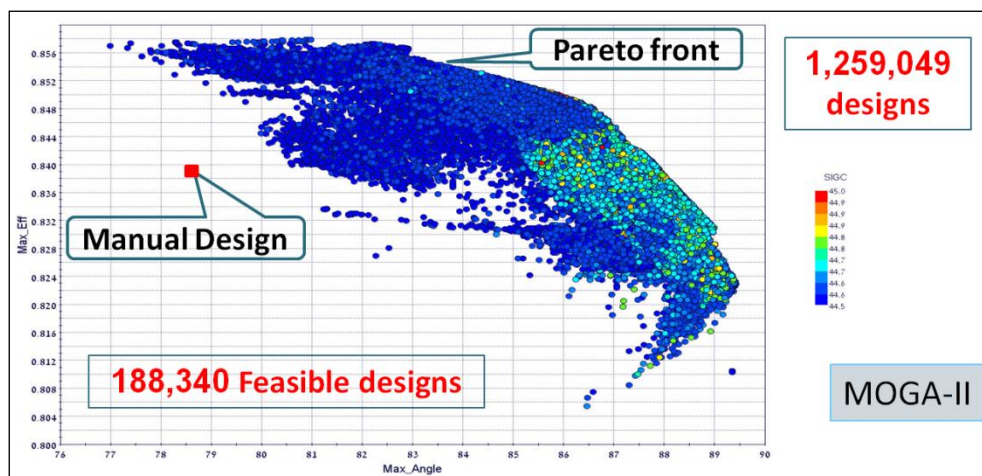
Becker Engineering Ltd., Tel-Aviv, 3102102, Israel

Increasing interest in expendable low-cost turbojet engines for civil and military purposes in the world leads to design and production of many miniature turbojet engines, by companies and groups of enthusiasts. These engines are usually equipped with a small low-pressure turbocharger centrifugal compressor, driven by a low-pressure ratio, one-stage axial turbine. Engine performance is also quite low, with the SFC in the range of 1.3-2.0.

Large relative losses due to small size of the components are responsible for low performance of the miniature turbojet engines. On the other side, main components of the engines are usually not optimized, due to low cost of the engine and their design. For example, axial turbines for these engines usually have low pressure ratio, simple design of blades and vanes, and a relatively low turbine performance.

In the work, we describe a simple way to optimize performance of a small axial turbine at the preliminary design stage, using a fast mean-line-design code and well-established genetic algorithm tool. We show that the turbine characteristics, such as efficiency and exit flow angle can be sufficiently improved through a parametric optimization. Fast code for mean-line turbine design allowed us to check more than two millions configurations, using genetic algorithm tools. Time that was spent is usually sufficient to “manually” check a few dozens of designs only. 33 parameters and 139 constrains were taken into account, together with two targets for optimization. Efficiency is improved by 1.5%, and exit angle by 2-6deg. According to Smith chart, a maximum efficiency of this axial turbine is ~4% above the value achieved manually. So, about 40% of the potential efficiency gain was closed by the optimization. Advanced blade geometries, hub and tip contouring, abradable seals, stacking and 3D blade design can close the remaining gap.

Optimization with $N > 1,000,000$ designs



On the Conversion of a Large Turbo Fan Engine's Combustor To Be Fueled By Natural Gas

Levy Yeshayahou, Sherbaum valery, Matan Zakai, Alex Roizman Vladimir Eerenburg, Technion

Ofir Harari, Israel Aircraft Industry

Aviation gas turbines have been the workhorse of the aviation industry, powering most of the commercial aviation activities in the world today. Development efforts, since the 1960's, in Heavy Duty gas turbines have led to gas turbines becoming a dominant player in the power-generation market. But there has been a steady growth in the use of aeroderivative gas turbines, which are stationary variants of aeroengines – being used by manufacturers to tap into potential areas such as mechanical drives and small-scale power generation units, in competition for their smaller weight and dimensions with diesel engines. These aeroderivative engines occupy a position between aviation gas turbines and heavy-duty gas turbines, greatly benefitting from the experience and research gained from both these industries. Development of aeroderivative gas turbines has historically been achieved by converting existing aviation jet engines to suit the needs of the customer, while working under restrictions imposed by governmental agencies for land-based power generation units. Figure 1 provides an overview of the development cycle of General Electric's aeroderivative gas turbines. With a focus on the changes to the combustor, this would involve having a gas turbine that is capable of operating on different fuels while giving maximum and stable performance for the desired operating point. This is further complicated by the need to stick to stringent pollutant emissions restrictions that are imposed on land-based gas turbine power generation units. The current work is an attempt to study the conversion an aviation jet engine to an aero-derivative gas turbine, with a focus on changing its fuel from jet fuel (kerosene) to Natural Gas (Methane) while assuring its CO and NOx emissions not to exceed its design levels and maintain stable combustion performance.

The restrictions imposed on this study:

- Dry operation, i.e. no water/steam injection
- No changes in the geometry except for the fuel nozzles
- Operation with natural gas (methane)

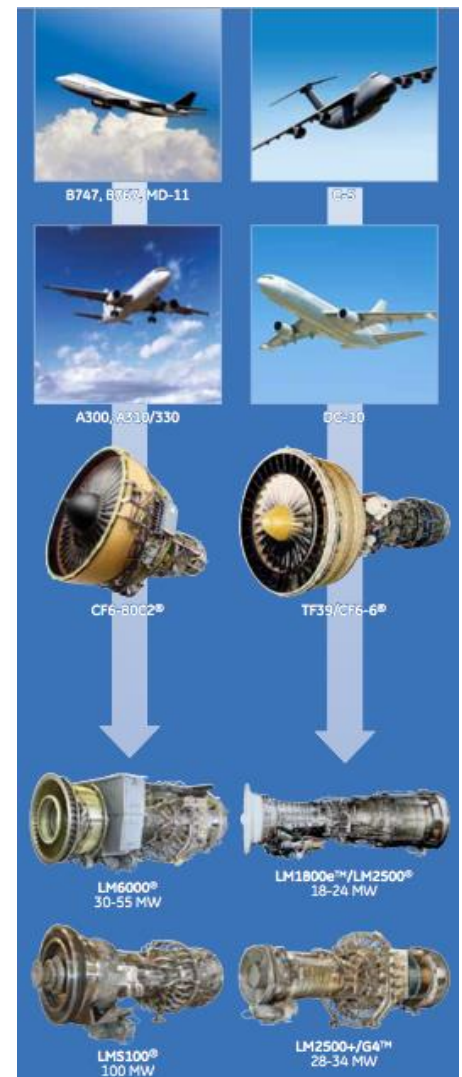


Figure 1: An example of Aeroderivative Gas Turbine Development Cycle (by General Electric)

Methodology

The work is conducted in four main stages. The first stage of the study (**Stage1**) was achieved through numerical simulation of the actual combustor, shown in Figure 2, and fueled with jet fuel. **Stage 2** of the work involves designing new fuel nozzles for injecting natural gas. This stage includes CFD calculation with the modified nozzles and the gaseous fuel and comparison of the results. The work continues to **stage 3** where an experimental campaign is performed to validate the results of the numerical simulations. Due to the limitations of the available infrastructure at the Jet Engine Laboratory at the Technion, the tests are designed to be performed at atmospheric pressure and at a 54° sector of the combustor (with 3 fuel nozzles out of 20 in the combustor) and with limited preheating upstream of the combustor. This stage includes operation using jet fuel as well as gaseous fuel. While operating at a reduced pressure, the air flowrate is reduced accordingly with an attempt to maintain similar air velocities at the entrance to the combustor. Following the reduction of the airflow rates, similarly the fuel flow rates have also to be reduced with respect to the design values, for both, liquid and gaseous fuels. **Stage 4** of the study involves numerical simulations of the combustion process at conditions similar to those at the atmospheric conditions for the comparison with the experimental results. It is reasonable to assume that certain calibration of the chemical kinetic and numerical models will be required. Finally, upon successful compatibility between the results of the numerical predictions at atmospheric pressure and the experimental results, one could consider the validity of the CFD to serve as a useful tool for evaluating the combustion performance at real operational conditions. Figure 2 show the original combustor as well as the sector of the combustor that is currently under construction. Figure 3 show a sample of the simulation results that will be described in details within the presentation.

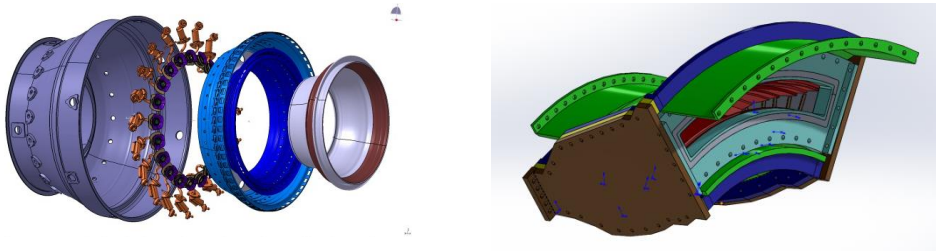


Figure 2 – Exploded view of the CAD model and the sector of the combustor

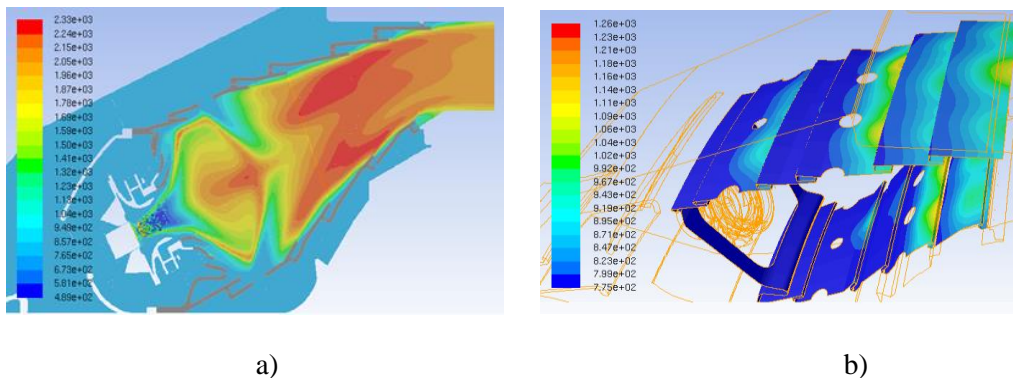


Figure 3. Temperature distribution along the combustor during operation at cruise conditions using jet fuel (kerosene), a) (cross-section at center of the sector); liner temperature distribution, b).

Correlation for the Estimation of Rotating Fuel Injector (Slinger) Droplet Size

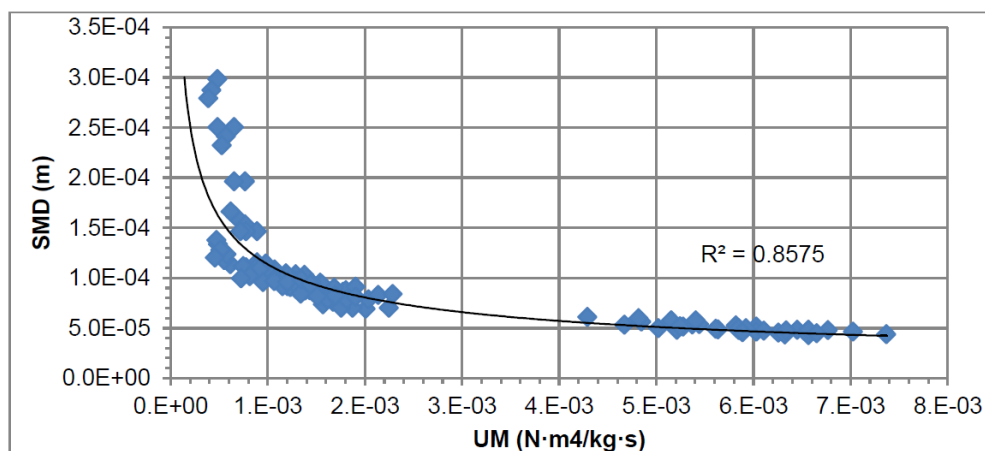
Ariel Cohen, Bet Shemesh Engines, Israel

Rotating fuel injectors deliver a finely atomised spray which enables combustion efficiencies above 99% throughout the engine operating range – including at low RPM values – without the requirement for high pressure fuel supply. To facilitate the simulation and design of turbo-machinery combustors based on rotating fuel injectors, an estimation of the mean droplet size (*SMD*) as a function of the injector operating conditions is required.

Based on a number of published sets of experimental data, a method is proposed by which the various data-sets may be correlated and calibrated according to the required geometrical and operating parameters.

In a pioneering paper (1981), Morishita concluded that the droplet size is primarily dependent on the linear velocity at the injection location. He further defined a parameter (*M*) as a correction to his correlation for liquids other than water (the majority of experimental data is for water). The parameter *M* is a function of the density, viscosity and surface tension of the fluid. Beginning in 2008, a number of publications, using more advanced experimental apparatus, suggested alternative correlations for Slinger droplet sizes; however each researcher focused on different operating conditions.

In the final analysis, it is possible to represent all of the published data (besides the historical data of Morishita) using a single correlation similar to that suggested by Morishita – $SMD = f(UM)$.



Lean, Premixed, Prevaporized (LPP) Combustion for Gas Turbines

Richard J. Roby, P.E., Ph. D.; Leo D. Eskin, Ph.D.;

Michael S. Klassen, P.E.; Ph. D., Aharon David, B.Sc. MBA

LPP Combustions LLC

The development of Dry, Low Emissions (DLE) combustion systems for use with natural gas-fired gas turbines brought a revolution to electric power production, providing an order of magnitude reduction in pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), unburned hydrocarbons (UHCs), and combustion-generated particulates, without the need for the substantial water addition. Unfortunately, DLE has been limited to natural gas with tight fuel composition specifications and has not been achievable with liquid fuels, requiring power producers with a need to run on both natural gas and liquid fuels to have a dual-fuel gas turbine with two entirely different fuel delivery and combustion systems depending on whether the gas turbine is operating on natural gas or on fuel oil. Moreover, even small amounts of natural gas liquids or higher hydrocarbons in the natural gas would cause autoignition and flashback that could rapidly destroy gas turbines, until now.

The recent development of a real-time liquid fuel processing system, converting a range of liquid fuels into a substitute for natural gas – LPP Gas[™], now allows Lean, Premixed, Prevaporized (LPP) combustion of liquids fuels. This fuel processing system allows LPP combustion of a wide range of liquid and/or gaseous fuels in DLE natural gas combustion systems while providing nearly "Natural-Gas-level" performance, emissions, and maintenance of the gas turbine.

The LPP technology is able to process a wide range of hydrocarbon liquid and/or gaseous compositions up to No. 2 fuel oil and biodiesel, and even varying liquid/gaseous fuels stream compositions – by continually adjusting the amount of dilution to maintain a heating value consistent with natural gas.

The LPP technology has been successfully demonstrated in commercial gas turbine DLE combustion systems and has achieved over 2,000 hours of clean power generation on a 30 kW Capstone C30 microturbine, testing for 15 different types of liquid fuels, including liquid propane, pentane, naphtha, and other liquids, blended with methane to simulate the vaporization of NGLs. Emissions for all cases have been comparable to ordinary natural gas

emissions, of 3 ppm NO_x and 30 ppm CO. Autoignition of the vaporized liquid fuels in the gas turbine is controlled by the fraction of inert diluent added in the vaporization process.

Results of actual gas turbine testing in a Solar Turbine Taurus 60 combustor and Capstone C-30 gas turbine will be presented, as well as detailed thermodynamic modeling of several different commercial gas turbines, to demonstrate the efficiency benefits of LPP Combustion compared to conventional gas turbine spray combustion of liquid fuels.

Recently, a 65 kW Capstone C65 microturbine commercial installation has taken place at EnviroSystems Canada/Atlantic Industrial Services, a hydrocarbon reclamation and disposal facility in Debert, Nova Scotia, Canada – initial feedback and insights will be discussed.

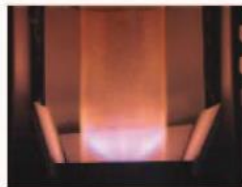
Finally, the broad spectrum of potential applications for the LPP technology will be discussed, with emphasis on applications that have already been tested, demonstrated and/or currently actively pursued: Oil & Gas power supply, organic/liquid Waste-to-Power, off- and on- Grid utility-level power.

Conventional Liquid
Fuel Flame



The Problem

Natural Gas
Flame



The Goal

Liquid Fuel (Biodiesel)
Using the LPP System



The Solution

Scaling of the flame-flow interaction in premixed flames

Dan Michaels

Lecture, Department of Aerospace Engineering, Technion.

The impact of the fuel composition on flame stabilization of premixed flames in gas turbine combustors has drawn significant interest, driven by the variability in natural gas supply and in the composition of syngas as derived from coal or biomass. It is desirable to have stable combustor operation with the widest possible variation in the fraction of CH_4 , CO and H_2 in the fuel. The influence of fuel variability on flashback, blowoff and dynamic combustion instabilities has been reviewed in. One of the outstanding issues is the influence of fuel composition on combustion instabilities, for which the most prominent mechanisms in lean premixed flames are flame-vortex interaction and fuel-to-air ratio oscillations.

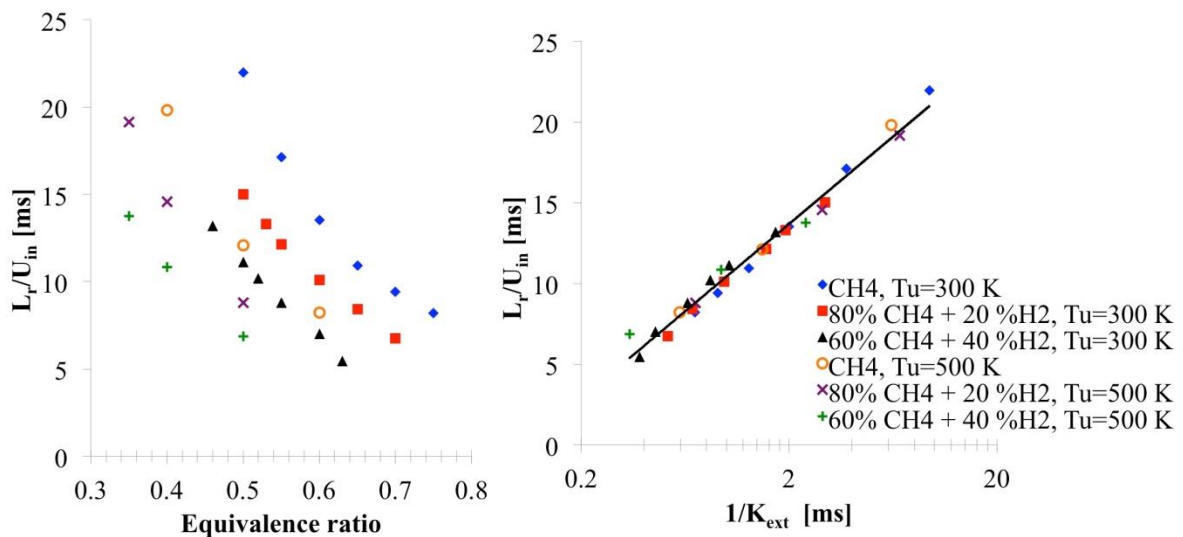


Figure 2: Relation between the recirculation zone length (L_r) and the equivalence ratio or a chemical time scale defined by $1/K_{ext}$ (From Michaels, Shanbhogue and Ghoniem, Combustion and Flame 2017).

Simulation of recirculation-zone stabilized flames with detailed chemistry and diffusion models provide a framework to identify the characteristic chemical time scales that governs flame-flow interaction. Recent direct numerical simulations of a laminar bluff body stabilized flame reveals similar scaling of the flow structure as function of the composition extinction strain rate (see Fig. 1), as in recent experiments of turbulent flames in a backward facing step combustor or a swirl stabilized combustor. Simulations were conducted for a wide range of conditions: fuel compositions ranging from 100% CH_4 to a 60:40 mix of CH_4/H_2 , inlet

temperatures ranging 300–500 K, and equivalence ratios ranging 0.35–0.75. The numerical investigation reveals that not only does the flame adjust to the flow field passively, but the flow is impacted significantly by change in the reactants' composition and temperature. The change in the flame location is predominantly due to its ability to withstand the flow strain, and the change in the flow field is mainly due to the gas expansion across the flame.

In the presentation I will survey evidence from different premixed combustors, flow regimes (laminar/turbulent) and fuel compositions that indicated that the flow field, flame structure and combustion instabilities can be scaled according to the reactants extinction strain rate. I will show comparison of the Damköhler numbers based on the recirculation zone length and the extinction strain rate from the different experimental and numerical data. Capturing similar behavior and scaling in laminar and turbulent flames indicates that this scaling has a fundamental origin and can be useful for other combustors in which the combustion instabilities originate from the flame-vortex interaction and operation with different fuels and inlet conditions is desired.

E1

OT or Not? Issues concerning Over-Temperature in Turbine's Blades

Capt. Nitzan David Foucks, M&P Dept., IAF

Over-Temperature ("Over-Temp" or "OT") is one of the main issues facing a metallurgist in determining if a turbine's blades are intact. OT is a condition where the blades are exposed to temperatures near or above the solution temperature of the blade's material. At that temperature area, the γ precipitants lose their cubic shape and start to dissolve into the γ matrix. Since these precipitants are the main strengthening mechanism of most Nickel-based super alloys, their dissolving causes a mechanical degradation of the blades' properties. Under the right conditions, this can lead to failure of the blades.

It is therefore important to determine if the blades underwent OT, in both regular inspections and failure analysis. In regular inspections, such as during depot-level maintenance, OT blades are rejected and must be replaced, causing an increase of both the time and the cost of the engine's repair process. In failure analysis, determining that there was an OT will cause the investigation to change direction, searching for reasons why the engine's working temperature went above normal levels. If there are no evidences for abnormal engine temperature, an OT might indicate that there was a failure in the manufacturing process.

Yet although OT is so highly important for both inspection and investigation, it is mostly based on a comparative visual inspection. One needs to both find an intact microstructure and compare it to the one suspected of undergoing OT. But since Jet turbine blades are manufactured by casting, no two areas – even in the same blade – are exactly alike. The OT inspection must therefore distinguish between changes in the microstructure that are caused by the manufacturing process, and are normal, and changes caused by OT. Furthermore, during the blade's life time the microstructure will degrade, but will still be acceptable in accordance with the manufacture's criteria.

The present lecture will seek to highlight these dilemmas and more, sharing the IAF's M&P dept. experience with examining and determining OT.



E2

“Monitoring Engine Gearbox as preventive maintenances”

Maj. Yossi Pikel Fighter Group A Propulsion Branch

IAF

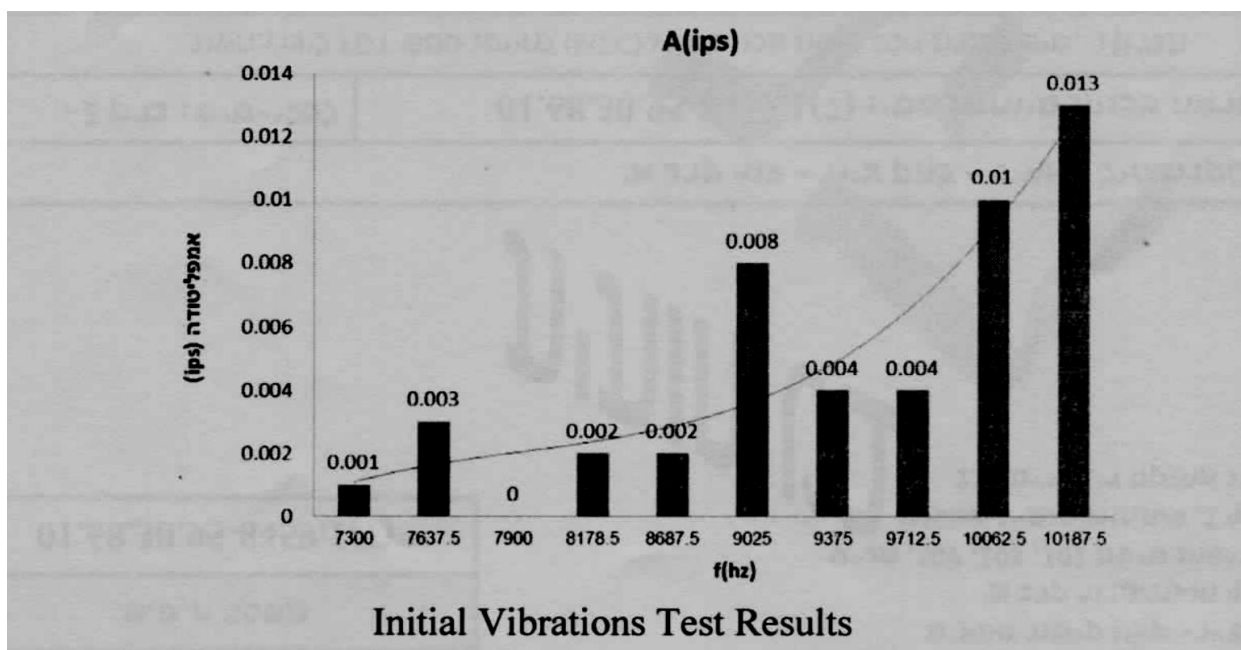
The IAF experienced Depot findings of excessive wear at the gearbox bevel gear groove. The groove is the geometrical location of two damping rings. The rings design damps the bevel gear vibrations (3rd mode). The gearbox is installed on a single engine major fighter aircraft.

A collaborative investigation with USAF and the Engine manufacturer was performed, in order to determine lifetime for the gears (Preventive Maintenance). Since the IAF found it has a unique Fleet status and severe wear findings, a project targeting condition based maintenance was initiated.

Analysis of the frequencies of interest determined that, in case of excessive wear in the bevel gear damper groove, higher vibrations would be indicated at high engine RPM. Analysis of the damping force produced a further focus of the vibrations spectrum.

The IAF has installed vibration sensors on engines in the engines test stand, and performed test on several engines, indicating that the frequencies of interest are directly correlated to the engine RPM. This phenomenon is expected and strengthens the possibility for determining maintenance policy that is based on test-stand vibration measurements.

Currently, the IAF is in the Final stages of determining a predicting maintenance policy for the engine gearboxes.



E3

The Danger of Water in Aircraft Fuel Systems

Orian Elmaliach and Michal Yardeni

Fuel and Chemistry Department, Materials Division, Depot 22, IAF

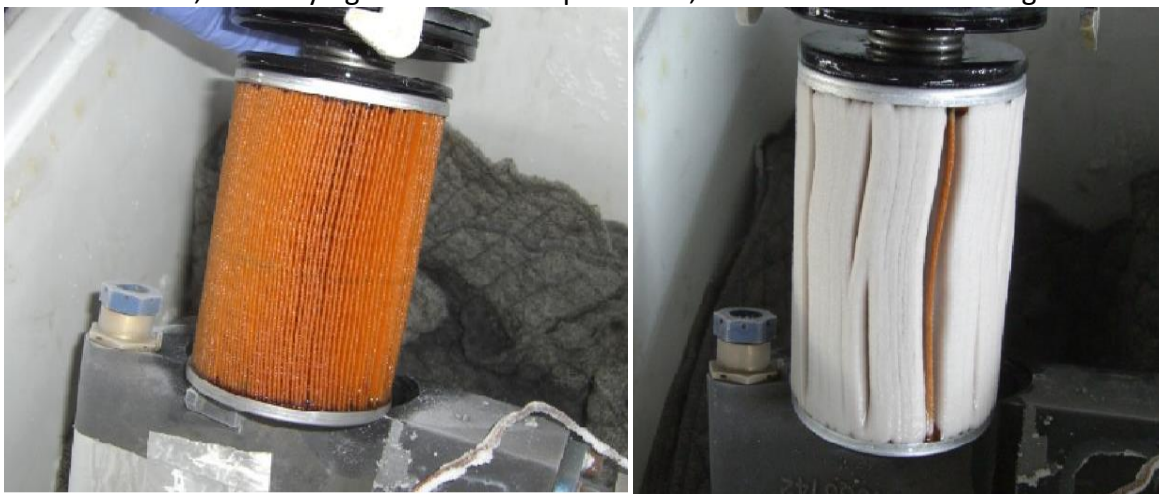
Water is a ubiquitous part of our environment and therefore, water unavoidably infiltrates fuel systems. The effects of water on fuel systems can be extremely destructive. Once water has entered the fuel, corrective maintenance must be performed to remove the water else it damage the fuel system. Worldwide standard procedures are used to recognize the presence of water to ensure the safety of the aircraft.

The presence of water in aircraft fuel systems can be devastating. Leaving water unchecked in fuel can lead to severe consequences:

1. Water promotes microbiological growth as water provides an optimal living environment while jet fuel acts as their carbon source (food). Therefore, the microbiological growth takes place in the interface between the fuel and the water. These fungi and bacteria can form biomasses or biofilms that clog filters. They can also cause corrosion and changes in the fuel chemistry. Microbiological contamination can also give false readings in fuel gauges.



2. Water has a freezing point of 0°C while jet fuel has a maximum freezing point of -47°C . Therefore, when flying at subzero temperatures, water will freeze and clog filters.

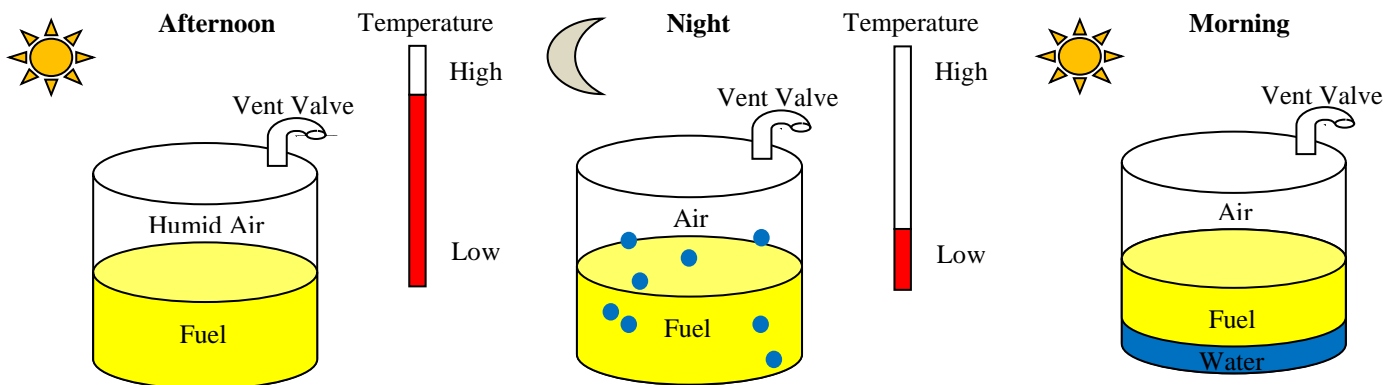


3. Even if the water does not freeze (certain additives in the fuel can lower the freezing point of water), filters that are overexposed to water may have a lessened ability to separate water from fuel and as a result can no longer protect the engine from water.

The water interferes with the efficient burning of the fuel creating carbon deposits (soot) that increase the wear of the engine.

There are many ways in which water can get into a fuel tank. Some examples are rain, incorrect maintenance of the fuel before aircraft fueling, or, most commonly, condensation from the air.

Water is perpetually present in air. During the night, when the air cools its water saturation point is lessened and so water precipitates out. Thus, anywhere that has air, including fuel tanks, is in danger of a build up of water.



Since water can easily find its way into the fuel, high awareness and daily maintenance is crucial. Water in fuel systems is unavoidable but manageable.

The two main methods of corrective and preventative maintenance of water in fuel are the following:

1. Draining of the water. Water is denser than fuel and so when left to settle, water collects at the bottom of fuel tanks forming a layer that can be drained out. Consistent water drainage is necessary in all types of fuel tanks (those in aircrafts and those on the ground) according to standard operating procedures.
2. Proper selection of the location of drain valves. Location is crucial for the effective removal of water. Therefore, during the design of fuel tanks, low points and other vulnerable areas must have drain valves.

In order to properly drain water, the water must be detected. Two standard methods are used for this:

1. Visual Test – If both fuel and water is drained an interface will be present between the two. In addition water may present itself as drops or cloudiness in the fuel.
2. Water Indicator Test – Using a color changing water indicator (such as the Merck Millipore brand paste that turns from green to purple in the presence of water), presence of water can be identified.

In conclusion, water, though dangerous, is a manageable problem through daily maintenance and good housekeeping.

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