AIJES 2022

AIJES 2022

19th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES

November 17th, 2022
Faculty of Aerospace Engineering,
Technion-IIT, Haifa, Israel

BOOK OF ABSTRACTS

מפא"ת

RAFAEL
SMART AND TO THE POINT

BET SHEMESH ENGINES

AIJES 2022

19th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES

TECHNICAL PROGRAM

November 17th, 2022 | Department of Aerospace Engineering, Technion - IIT | 08:00 - 17:00
Open for students, industry and academic staff | Free with mandatory registration until 27/10/2022
REGISTER HERE: https://aijes.net.technion.ac.il/aijes-conference-registration

08:00 REGISTRATION

08:30 OPENING SESSION - Auditorium 235

Assoc. Prof. Beni Cukurel, Chairman of the Symposium, Department of Aerospace Engineering, Technion

Lieut. Col. Yigal Ben-Shabat Head, Propulsion Systems Branch, Aeronautical Division, IMOD

Award Ceremony

09:00 KEYNOTE SESSION - Auditorium 235

Chair *Lieut. Col. Yigal Ben-Shabat Head, Propulsion Systems Branch, Aeronautical Division, IMOD*

A1 Aircraft Engine Technology Award Lecture

A2 Dedicated Service Award Lecture

A3 Gas Turbines Performance and Operation Flexibility Enhancement Enabled by Additive Manufacturing
Dr. Vladimir Navrotsky, Siemens Energy

10:25

10:40	SESSION 2B - Auditorium 235		SESSION 2C - Library 165		SESSION 2D - Classroom 240
	CYCLES		ADDITIVE MANUFACTURING TECHNOLOGIES		MAINTENANCE, REPAIR AND OPERATIONS
Chair	*Dr. Amiram Leitner, Rafael*		*Dr. Moshe Shapira, Bet Shemesh Engines*		*Maj. Shani Eitan,* Israeli Air Force
B1	Memorial Lecture in Honor of Prof. David Lior *Ori Beck, Turbogen*	C1	Standardization and Qualification for Metal Alloys in Additive Manufacturing *Dr. Gregory Brown, Velo3D*	D1	Achieving Sustainable Aviation *Dr. Michael Winter, Pratt & Whitney*
B2	Performance Evaluation of Hydrogen Oxyfuel Steam Cycles *David Bocandé, Helmut-Schmidt-University*	C2	Additive Manufacturing in Gas Turbines *Jens Karnapp, EOS GmbH*	D2	Failure Investigation of Compressor Rotor Blade *Yochanan Nahmana, Bet Shemesh Engines*
B3	Overcoming Thermodynamic Efficiency Limit on Heat Turbines *Prof. Carmel Rotschild, Technion*	C3	High Power Dynamic Beam Shaping Laser Processing *Dr. Aleksey Kovalevsky, Israeli Metal Institute*	D3	Numerical Investigation of Flow Distortion in Jet Engine Test Cell *Daniel Isakov, Israeli Air Force*
B4	Full Engine Simulation of Small Turbojets	C4	Heat Treatment Effects for 3D AM Printed 939 Nickel Alloy *Daniel Moreno, Bet Shemesh Engines*	D4	Spinning Digital Threads in Aerospace *Dr. Anil K. Tolpadi, General Electric Aviation*
B5	Starting and Windmilling Simulations Using Thermodynamic Cycle Program *Dr. Joachim Kurzke, Gas Turbine Performance Consulting*	C5	Anisotropic Properties of 3D AM Printed 316L Metal *Daniel Moreno, Bet Shemesh Engines*	D5	The Curios Incident of Blade in High Pressure Turbine *Inna Kaparovsky, Israeli Air Force*

12:20

13:10 LABORATORY VISIT

14:00 — SESSION 3E - Auditorium 235

TURBINE AERODYNAMICS AND HEAT TRANSFER

Chair: *Ariel Cohen, Bet Shemesh Engines*

E1 Aerodynamic Testing of High-Speed Low-Pressure Turbines: Challenges, Solutions, and Mistakes
Assoc. Prof. Sergio Lavagnoli, von Karman Institute

E2 Preliminary Design Studies for Turbine Suitable to Operate with Pressure Gain Combustors
Dr. Bayindir H. Saracoglu, von Karman Institute

E3 Skin Cooling of Turbine Airfoils by Single Wall Effusion
Yair Lange, Technion

E4 Acoustic Flow Control Methodology in High Lift Airfoils
Acar Celik, Technion

SESSION 3F - Library 165

REACTING FLOWS AND THERMAL MANAGEMENT

Chair: *Yochanan Nachmana, Bet Shemesh Engines*

F1 Experimental and Numerical Study of Liner Film Cooling and Combustor Swirl Flow Interaction
Dr. Anil K. Tolpadi, General Electric Aviation

F2 Schlieren Visualization of Detonating Combustion
Dr. Ionut Porumbel, INCDT COMOTI

F3 On Nanosecond-Pulsed High-Frequency Plasma Ignition Regimes in Flowing Reactive Mixtures
Dr. Si Shen, Technion

F4 Well-stirred Reactor with Homogeneous Plasma for Development of Chemical Kinetic Model of Plasma, Ammonia and Air
Galia Faingold, Technion

14:00 — SESSION 3G - Classroom 240

DIAGNOSTICS

Chair: *Ella Berlowitz Paska, Rafael*

G1 An Experimental System for Blade Tip Timing Measurements
Shachar Tresser, Rafael

G2 Acoustic Analysis of Engine Operation and Events
Yohanan Nahmana, Bet Shemesh Engines

G3 Coating Thermal Properties Measurement via Induction Phase Radiometry
Shani Eitan, Israeli Air Force

G4 Radiometric Measurements of Small Jet Engine and its Plume
Ohad Ophir, IARD Sensing Solutions

SESSION 3H - Classroom 241

SYSTEM LEVEL DESIGN

Chair: *Itche Hochmann, Edmatech*

H1 Development of 45 kW Recuperated Turboshaft Gas Turbine
Fred Frigerio, UAV Turbines

H2 Additively Manufactured Pre-Assembled Turbojet Engine (APE) for Unmanned Aerial Vehicles
Michael Palman, Technion

H3 Development of Additively Manufactured Ultra Micro Gas Turbine Generator
Lukas Badum, Technion

H4 Thrust Vectoring and After Burner System for Increasing Survivability of Micro-Jet UAVs
Dor Shitrit, Technion

15:20

15:40 — SESSION 4I - Auditorium 235

COMPRESSOR/FAN AERODYNAMICS

Chair: *Yonatan Lobovikov, Rafael*

I1 Design of a Radial Compressor for Additive Manufacturing
Prof. Tom Vestreate, von Karman Institute

I2 Investigation of Splittered Tandem Stators for Highly-Loaded Low-Aspect-Ratio Transonic Fan Stage for a Small-Scale Turbofan

I3 Comparison Between Different CFD Methods Simulating Stator Rows with Non-Equal Number of Vanes
Tom Regev, Bet Shemesh Engines

I4 Efficient High-Speed Compressors in Aircraft Engines
Dr. Hong Yu, Pratt & Whitney

SESSION 4J - Library 165

COMBUSTORS

Chair: *Assoc. Prof. Joe Lefkowitz*

J1 Analytical Investigation of a Slinger Injector
Albert Levy, Bet Shemesh Engines (retired)

J2 Multipurpose Combustion Chamber for Testing Facilities of Airbreathing Engines
Yuri Perelstein, Rafael

J3 Effect of N_2 Dilution on H_2 and H_2 enriched CH_4 Flame in Swirl Stabilized Premixed Combustor
Dr. Pawan Kumar Ojha, Technion

J4 Assessment of Methanol as an Alternative Fuel for Micro Gas Turbine
Ariel Sharon, Technion

15:40 — SESSION 4K - Classroom 240

ROTORDYNAMICS AND VIBRATIONS

Chair: *Ron Miezner, Technion*

K1 Configuration Adaptation of 3D AM Bearing Housing
Matan Zakai, Bet Shemesh Engines

K2 Ansys Turbomachinery Modelling with Aeromechanics Focus
Dvir Mendler, Ansys

K3 Effect of Dynamic Stiffness on Small Engine Rotordynamics
Ori Kam, Bet Shemesh Engines

K4 High Fidelity CFD Simulations of Hydrostatic Bearings

SESSION 4L - Classroom 241

CONTROLS

Chair: *Alex Kleiman, Technion*

L1 Development of a Modular Plant Model for Real Time Testing of a Recuperated Engine FADEC
Diego Rocha, UAV Turbines

L2 Control of Micro Gas Turbine via Dspace
Dr. Arkady Lichtsinder, Rafael / Technion

L3 Minimum Measured Parameters Required to Develop a Jet Engine Dynamic Model
Dr. Michael Lichtsinder, Bet Shemesh Engines (retired)

Gas Turbines Performance and Operation Flexibility Enhancement Enabled by Additive Manufacturing

Dr. Vladimir Navrotsky

Siemens Energy, Germany

Additive Manufacturing is a disruptive technology enabling significant enhancement of the rotating equipment competitive position. Enabled by AM Gas Turbine (GT) performance enhancement, emissions reduction, lifetime and operation flexibility extension consequently results on GT lifecycle cost reduction and powerplant profitability improvement. The current status and achieved results at Siemens Energy in the area of AM technologies: AM workshops setup, design and AM components validation and implementation, accumulated field experience will be presented and discussed in this presentation.

AM technology as the integration of Design and Manufacturing provides additional opportunities in speeding up the time to market for new products and quick upgrades of the currently installed GT fleets. Examples of this acceleration will be presented and discussed in this presentation. To support and enable decarbonization of the gas turbines Siemens Energy is working with development of high efficiency gas turbines components and has developed hydrogen capable burners. It was the AM technology that enabled these burners design. As a result, the SGT-600, -700 and -800 can today be offered to run on up to 75 vol-% H2 in the fuel. Two SGT-600 has been sold to petrochemical industry to run on process gas with up to 60 vol-% H2 with NOx emission guarantee of 25 ppm.

Utilization of AM technology for design and manufacturing of new advanced cooling system of the GT's hot gas path components enabled significant savings of the cooling airs and, as a results, substantial engine efficiency improvements. Additional engine efficiency enhancement is achieved by the vane's aerodynamic improvement due to practically unlimited capability of AM for design and manufacturing. Successful design, manufacturing, performance, and operation of SGT-700 turbine AM vanes will be discussed in this presentation as well.

Reliable operation of GT's AM components at real field operation conditions is demonstrated and will be discussed too. At Siemens Energy the total accumulated field experience of GT AM components exceeded 1 500 000 operating hours.

Memorial Lecture in Honor of Prof. David Lior

Ori Beck

TurboGen, Israel

A review of the life and work of a Professor David Lior

Professor David Lior's long life was full of tireless work in the military, industry, and academic field of Turbomachinery.

From the beginning of his journey in the Israeli air force through his work in BSE, Ashot, Carmo, his work as associate Professor in the Faculty of Aerospace Engineering, Technion, and the work he did with Rafael as the founder and president of TMC, and finally the establishment of the Turbogen.

This lecture will review David's main work to honor the life of an inventor, a true dreamer.

Performance Evaluation of Hydrogen Oxyfuel Steam Cycles for Power Generation Considering Current Technological Limitations

David Bocandé, Univ.-Prof. Dr.-Ing. Markus Schatz

Fluid Machinery for Energy Technology, Helmut-Schmidt-University, Germany

Hydrogen is considered a pivotal element in the forthcoming transition towards fossil-free electric power supply. Besides emission-free production and storage its reconversion to electricity at a large scale is of fundamental importance. Among the technologies currently under consideration, zero emission oxyfuel hydrogen cycles with steam as a working fluid are very promising. Results of previous studies in the literature suggest that, with today's technology, thermal efficiencies in excess of 70% based on Lower Heating Value (LHV) can be reached with turbine inlet temperatures (TIT) of 1700 °C.

First, this work presents a review of the proposed oxyfuel cycles with hydrogen combustion in steam from the 1970s until today. An analysis based on technically feasible process parameters allow to identify the three most relevant cycles, that are believed to be realizable in the near future and that have the highest thermal efficiencies. They can be categorized in fully condensing cycles, represented by the Toshiba-cycle and the partly condensing cycles which are the Graz-cycle as well as the one proposed by Mitsubishi Heavy Industries.

Next, since the calculations from the literature are based on different assumptions with regard to cycle parameters, component efficiencies and material limitations, uniform and state-of-the-art process and component parameters currently achievable in the turbomachinery and power plant industry are selected and used in a comparative calculation using the ASPEN solver Hysys. This includes the implementation of feed water preheating for all processes and an identical cooling model for all processes under investigation. The cooling technology used is a combination of recovery and partial film cooling called hybrid cooling that is modelled using a stage-by-stage concept in which the turbine is represented by four equally expanding stages (stator + rotor). It also calculates the cooling mass flow ratio while considering mixing losses by means of a reduced isentropic efficiency in each cooled blade row.

The calculations based on equal parameters show that the Toshiba cycle reaches an efficiency of 70 %, based on LHV (60% based on HHV). The Graz and the Mitsubishi cycles reach 73% and 75 %, respectively. The advantage of the latter cycle lies in the water injection between the compressor stages as well as the preheating of the steam entering the combustion chamber. Modelling the Graz cycle for a TIT of 1700°C implies some modification regarding the ratio of mass flow split between topping (Brayton-) and bottoming (Rankine-) cycle with compared to the process originally proposed. Moreover, a higher TIT goes together with increased cooling demand and thus higher mixing losses, counteracting the efficiency increase due to the elevated temperature. Thus, an ideal TIT for all of these cycles can be found, depending on the cooling efficiency.

Overcoming the Thermodynamic Efficiency Limit on Small External-Heat Turbines for 24/7/365 Solar Electricity, Waste Heat, and Green Hydrogen

Prof. Carmel Rotschild

Technion - Israel Institute of Technology, Israel

A high portion of reliable renewable energy in the electric grid is a prerequisite to achieving carbon neutrality. Solar power holds the key to achieving Net Zero decarbonized energy systems. However, what to do when the sun is not shining. Photovoltaics (PVs) plus batteries plus grid (Gas and coal turbines) backup are expensive. On the other hand, concentrated solar power (CSP) is considered a “nearly obsolete” technology due to its costs, yet it is the only technology that is based on a heat engine, that can replace fossil fuel heat engines. In a few consecutive days with poor solar radiation, the heat engine can be driven by green hydrogen or gas for 24/7/365 full dispatchable and reliable electricity. External-heat engines such as steam turbines are efficient (>40%) only at capacity above 25MW and economically justified only above 100MW capacity, which makes CSP a utility-scale with reliability and financing challenges. A modular-CSP (MCSP) is made of an array of small receivers where the heliostats shift from one receiver to the other along the day targeting the receiver next to the sun. This way the field efficiency is doubled with half the cost of a central CSP. The modularity, also supports an exponentially growing market, as in PVs, with a potential for a global impact in a few decades. However, such a disruptive technology requires a small (<1MW) and efficient (>40%) external-heat engine, not existing today due to thermodynamic considerations. Such an engine will also harvest waste heat and will increase the green hydrogen production capacity factor, which will reduce its cost to the level of grey Hydrogen. In all heat engines that we know, only gases are used, and for two roles; i.) Perform the thermodynamic work, which is challenging because gases tend to expand adiabatically, resulting in poor efficiency. ii.) Transfer the energy into the engine. This 2nd role is challenging because gases carry negligible thermal energy per volume (volumetric heat capacity), resulting in large size and high costs. Increasing energy density by three orders of magnitude and inducing isothermal gas expansion is what we solve by demonstrating the first turbine based on a mix of heat-transfer-liquid (HTL) and gas bubbles, where the HTL supplies the heat along with the gas expansion. In our turbine, HTL such as molten salt flows in a nozzle with a thermal energy density that is orders of magnitude higher than gasses (per volume). Pressurized bubbles of air are injected into the nozzle and expand isothermally due to the negligible heat capacity of each bubble compared to its large surface area. The bubble's expansion accelerates the HTL in the nozzle converting the heat and pressure into kinetic energy of the HTL. Converting the kinetic energy of fluids into electricity is extremely simple and achieved by a hydroelectric-like turbine, which has a tag price that is a fraction of the cost of steam turbines. We experimentally demonstrate >90% of isothermal expansion and efficient conversion to electricity. Our results may support the first true realization of an external heat engine with expected total conversion efficiency > 75% of Carnot efficiency, which is far beyond the equivalent state of the art. This will open the way for MCSP to support 24/7/365 full dispatchable electricity, waste heat recovery, and low-cost green hydrogen.

Full Engine Simulation of Small Turbojets

The development of gas turbine engines requires accurate numerical analysis of main engine components (compressor, combustion chamber and turbine) and their interactions. Therefore Computational Fluid Dynamics (CFD) simulations have become an important instrument in the design and optimization stages of gas turbine engines. In the past, the use of CFD analysis in the design of gas turbines was limited to the component level (component-by-component) due to the relatively lower computational power of computers compared to today. In component level analysis, the compressor, combustion chamber and turbine are isolated from each other and simulations are carried out separately. For this reason, separate assumptions must be made for either of the components' inlet or outlet pressure and temperature boundary conditions. However, these assumptions may not represent the actual boundary conditions of a operating engine and interactions between components may be overlooked. These interactions need to be considered during the engine design process.

Today, it has become possible to use advanced methods for reliable solutions for large and complex systems, depending on the increase in computational power. Full engine simulation methodolgy is one of the advanced methods mentioned above and is the subject of this study. Unlike component level simulation, full engine approach requires only the compressor inlet and turbine oulet boundary conditions. Since there is no need for any boundary condition assumptions for the interfaces, the uncertainties on these boundary conditions are removed therefore the interactions between the components are resolved. Beside of that, the rotational speed of the engine can be changed on the simulation to achieve the proper torque balance between the compressor and the turbine. Thus, with a single analysis, detailed information about the flow field in the engine can be obtained at desired operating condition.

This study will present full-engine CFD simulations of a micro scaled gas turbine engine which was designed for NATO SPS G5939 project at several different operating conditions. In those Reynolds-averaged Navier-Stokes (RANS) 3D CFD simulations, a single mesh will be used for the entire flow domain, from intake to exhaust, of the gas turbine. The only inputs required for the CFD simulations are the freestream conditions at cruising altitude and rotational speed of the engine. The main purposes of this study simplify the simulation workflow compared to component level simulations and converge a proper torque and power balance between compressor and turbine.

Starting and Windmilling Simulations Using a Thermodynamic Cycle Program

Dr. Joachim Kurzke

Gas Turbine Performance Consulting, Germany

Physically sound compressor and turbine maps are the key to accurate aircraft engine performance simulations. Simulation of starting, windmilling and re-light requires maps which include sub-idle speed values as well as the map region in which the pressure ratio is less than unity. How to extend the maps from the normal operating range downwards to include the region where engine starting and windmilling happens is described first.

Extension of Compressor Maps

Extending a map by extrapolation using the correlation between work coefficient and flow coefficient is based on at least two speed lines. The original data for these speed lines descend from measurements respectively calculations. The verified part of the correlation is relatively small and restricted to the map region with pressure ratios above 1.

Interpolation is inevitably more reliable than extrapolation. Using the speed line zero converts the extrapolation task to an interpolation task. The speed line zero cannot be described with a work - flow coefficient correlation, however, this operating condition (blowing through a compressor with locked rotor) can be characterized by torque and total pressure loss relationships with mass flow.

For speeds above zero is the low mass flow part of the torque/flow=f(flow) correlation linear. The relative length of this linear part increases with decreasing speed. The slope of the straight part of the lines torque/flow=f(flow) is independent from speed. With other words, all these line parts are parallel, also the line for zero speed.

Extension of Turbine Maps

For turbines exists in the incompressible flow region also a linear relationship between torque/flow and flow. The slope is independent of speed and can be found from the speed lines for which data are available. This knowledge helps in extending turbine maps into the regions where pressure ratio is less than unity.

Incompressible theory helps also with the extrapolation of maps down to zero flow. The zero-mass flow limit plays a special role in turbine maps; its shape follows from velocity triangle analysis. Another helpful correlation is how mass flow at pressure ratio of unity changes with speed. The consideration of velocity triangles leads to the conclusion that in these circumstances flow increases linearly with speed.

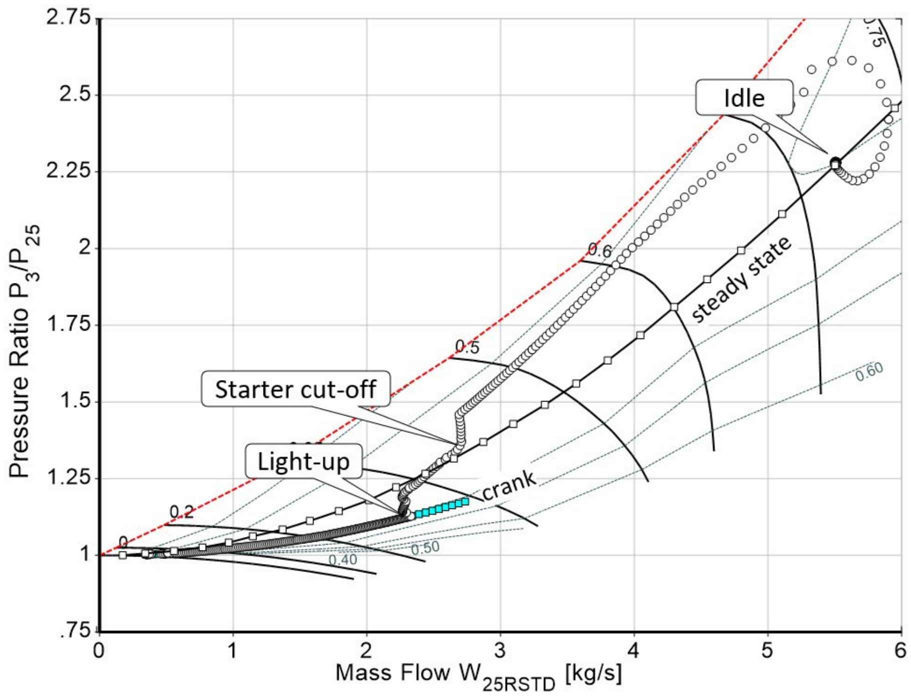
Starting and Windmilling

This section illustrates a general understanding of what happens from when the starter is activated to when stabilized idle operation is reached. Operating lines in the compressor and turbine maps are predicted depending on starter torque, starter power, burner light-up and starter cutoff speed. It is explained why knowing combustor efficiency precisely is not required for that.

An engine start begins with zero spool speed, there is no mass flow, and all temperature and pressure ratios are unity - that's trivial. The first point for which a thermodynamic cycle calculation is feasible must have positive mass flow and pressure ratios deviating from unity. Therefore, the starting simulation begins with an operating point at very low spool speed. The quality of the compressor and turbine maps determines the lowest spool speed with which the engine start simulation can commence. With a high-quality performance model, the begin of the simulation is feasible with gas generator spool speeds as low as 2% and fan speeds lower than 1%.

Some results from turbojet and low bypass ratio turbofan starting simulations are presented. A windmilling example for a high bypass ratio turbofan concludes the presentation.

Simulating engine starting and windmilling is not a magical art. The laws of physics still apply at these somewhat exotic operating conditions.



Standardization and Qualification for Metal Alloys in Additive Manufacturing

Dr. Gregory Brown

Velo3D, USA

Additive manufacturing is driving massive innovation and improving supply chains in various industries around the world. Early adopters of the technology are passionate about additive manufacturing due to its ability to transform their mission-critical parts through part consolidation, distributed manufacturing, weight reduction, and performance improvement. However, for it to see broad adoption and penetrate new industries, additive manufacturing needs standards and qualification parameters to ensure parts meet the quality expectations of engineers.

New standards are beginning to emerge to inform engineers on how to qualify various metal alloys for use in additive manufacturing. This gives engineers the confidence that their parts will perform as expected. This session will look at some of the first standards that are emerging, how they are made, and how they can give engineers the confidence they need to use metal additive manufacturing in production.

Additive Manufacturing in Gas Turbines

Jens Karnapp

EOS GmbH, Germany

Additive Manufacturing (AM) of gas turbine parts is a hot topic ever since the first metal parts were built some 20 years ago. Hardly anywhere else a small improvement in part design can have such a big lever on overall system performance. Since the first parts until today the technology has matured dramatically and additive parts can be found in the engines of most OEMs today. The presentation will give an introduction to Metal LPBF AM technology, advantages and challenges in the context of production of gas turbine parts, considerations on productivity, and production scaling. Examples of gas turbine parts in additive production will be given and a peek into the lab will illustrate materials and processes in development for future manufacture of high-performance turbine parts.

High Power Dynamic Beam Shaping Laser Processing: Initial Results and Prospects for High Temperature Applications

Dr. Aleksey Kovalevsky

Israel Institute of Metals, Technion Research and Development Foundation, Israel

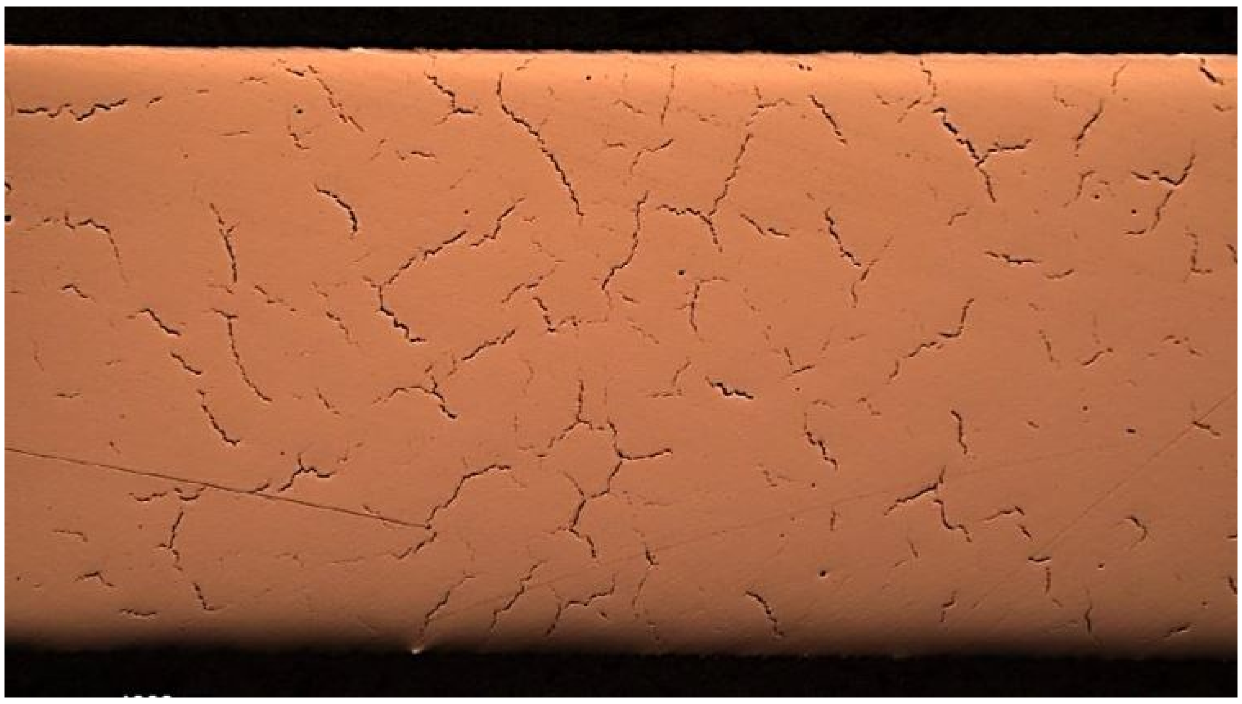
Will be submitted later

Heat Treated Effects for 3D AM Printed 939 Nickel Alloy

Daniel Moreno, Yohanan Nahmana, Matan Zakai

Bet Shemesh Engines, Israel

Nickel alloy designated 939 may be a potential candidate for use in the engine hot-section. This presentation will introduce this alloy and will show effects of the process on the quality and properties of the resulting parts. (Presented in IMEC2021)

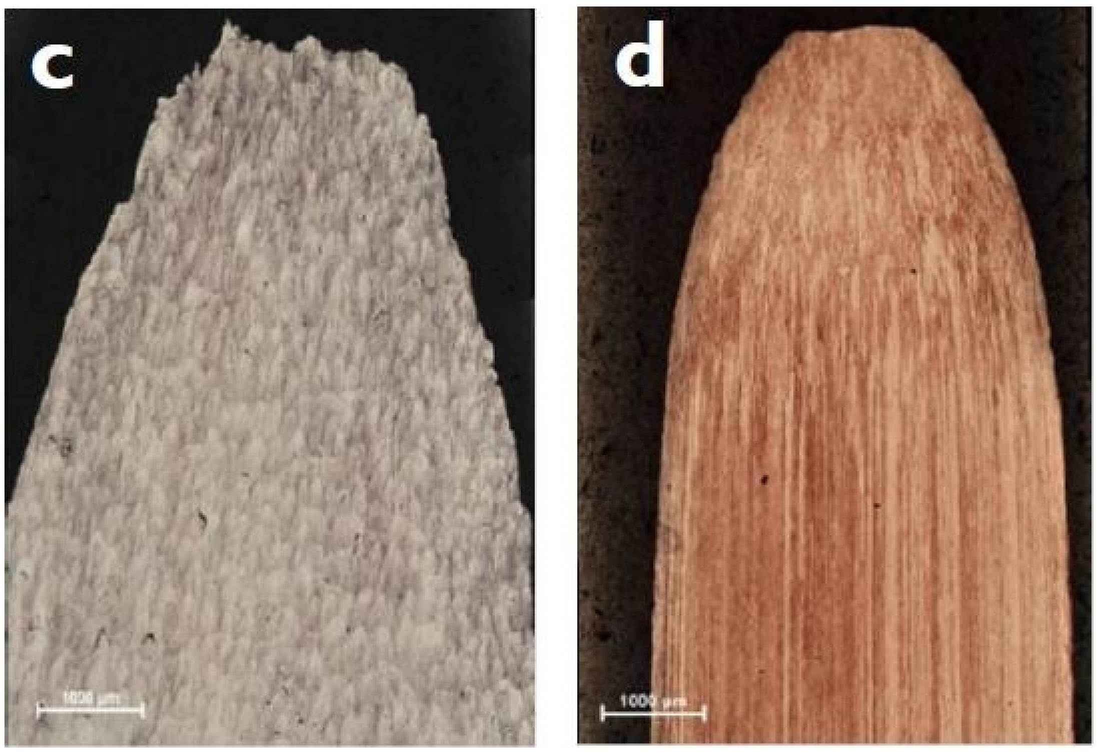


Anisotropic Properties of 3D AM Printed 316L Metal

Daniel Moreno, Yohanan Nahmana, Matan Zakai

Bet Shemesh Engines, Israel

It is common knowledge that 3D AM properties may vary in various directions relative to the print direction. Usually, the strengths (tensile and yield) are considered. This work will show that effects on the modulus of elasticity my be apparent and indications in the microstructure might be detectable by SEM inspection. (Presented in IMEC2021)

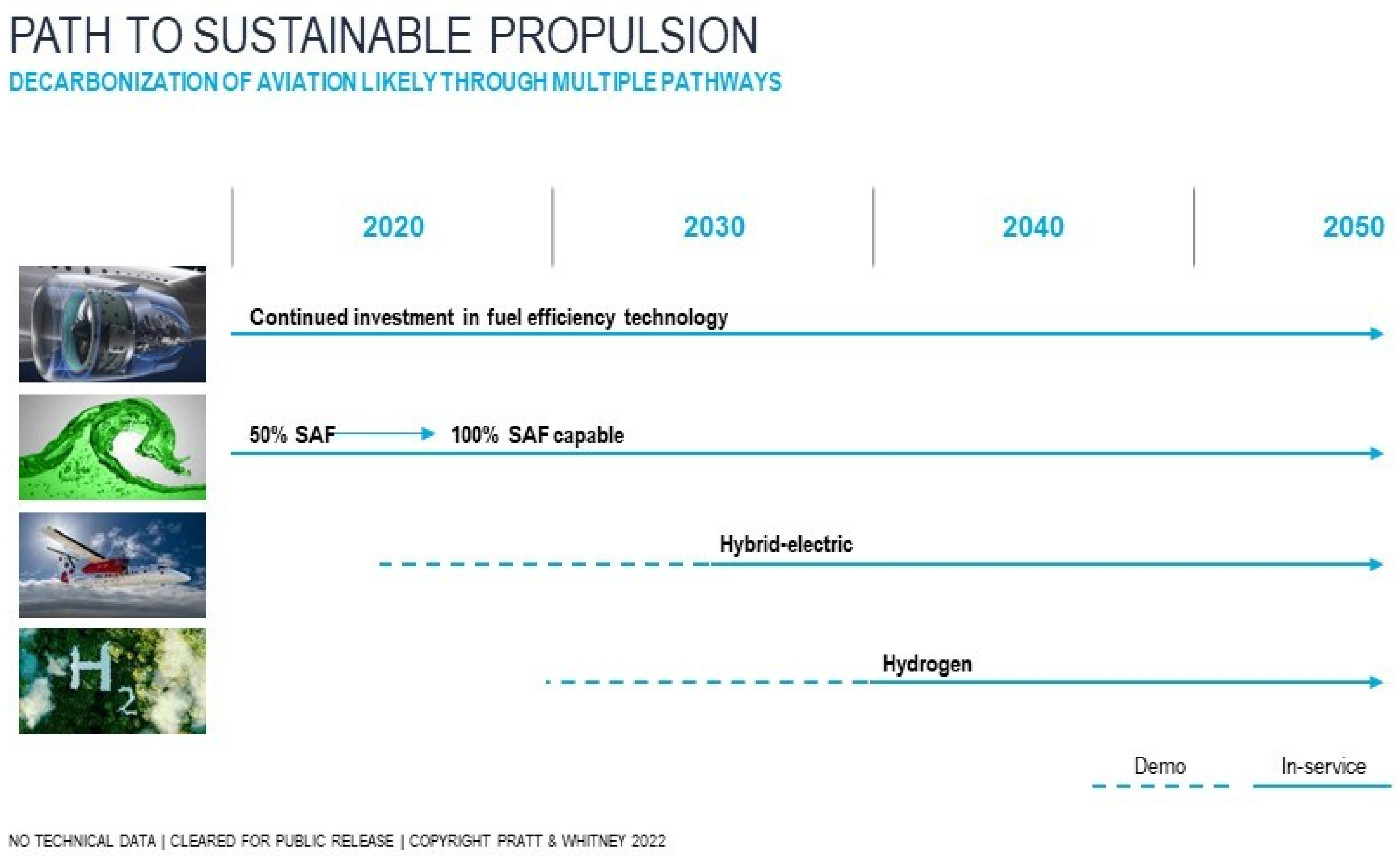


Achieving Sustainable Aviation

Dr. Michael Winter

Pratt & Whitney, USA

Emissions of CO2 from aircraft and engines occur predominately during their use; the release of carbon dioxide (CO2) from cradle-to-gate only comprises approximately 2% of emissions, with the remaining 98% being produced during operation. Additionally, over the last 80 years, continuing technology advancements have enabled engines to improve efficiency by 1-1.5% per year. Pratt & Whitney (P&W) took the first step towards meeting the International Civil Aviation Organization (ICAO) goals of carbon neutral growth beyond 2020, and 50% of 2005 levels of CO2 by 2050 by developing and fielding the Geared Turbofan (GTF) engine for single-aisle aircraft. The GTF engine's advanced technology reduced fuel consumption by approximately 16%; oxides of nitrogen by 50% relative to the prior state-of-the-art engine, and P&W expects the benefit to impact all future large commercial aircraft. Over 80% of aircraft CO2 emissions > 1,500km, which will continue to rely upon gas turbine power. The next generation of gas turbine engines for commercial aviation will require a broad range of technologies and design methods to achieve the projected fuel burn including improvements in propulsive and thermal efficiency. Other disruptive concepts will be discussed including hybrid electric propulsion, sustainable aviation fuels and combustion of hydrogen.

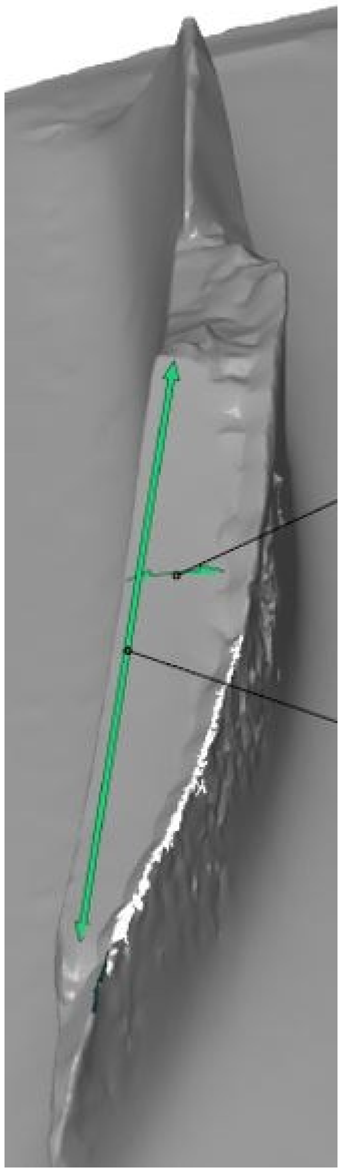


Failure Investigation of Compressor Rotor Blade

Yohanan Nahmana, Ori Kam, Tom Regev

Bet Shemesh Engines, Israel

Following a number of compressor failure events, a multidisciplinary investigation was conducted to determine the root cause of the failures, including CFD, FE, materials analysis, SEM, etc. Finally, recommendations were made to prevent similar event occurring in the future.

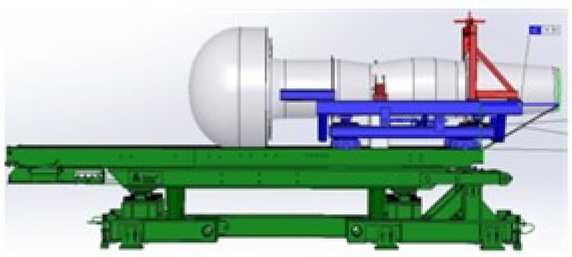


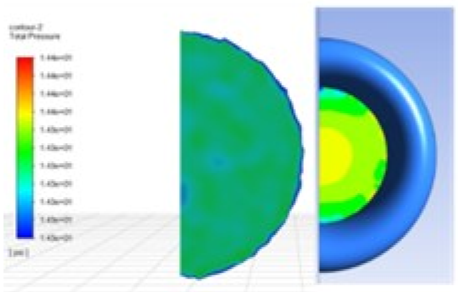
Numerical Investigation of Flow Distortion in Jet Engine Test Cell

Cpt. Daniel Isakov

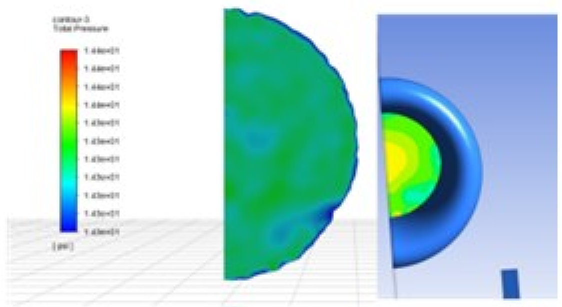
Israeli Air Force, Israel

During correlation processes of a test cell, large variations in engine performances, due to large bellmouth inlet pressure variations, were indicated, at max power points. Detailed investigation of the root cause of these large total pressure variations has led to the conclusion that the test cells unique configuration affected the flow regime, distorted it, and created thrust measurement repeatability issue. In the scope of this work, we performed an inlet flow simulation to study the origins of the pressure variations and to find possible solutions while keeping the unique versatile configuration of the cell and allowing minimization of these variations. The CFD analysis was done with ANSYS FLUENT software initially in 2D, understating the physical behavior and effects of adding a beam to a standard inlet/diffuser flow. Then in 3D, a CFD analysis was conducted to demonstrate the actual behavior of the airflow in the test cell and analyzing the influence of different beam configurations representing possible solutions such as beam cut, elliptic beam, and aerodynamic profile beam. Finally, the results showed that the large variations in engine performances were most probably resulted from vortices generation around the beam. Moreover, a possible solution of adding an aerodynamic structure which covers the beam, thus delaying the flow vortices was proved to minimize distortion. The simulation results showed a good match to the test cell measurements data. The next steps for the research plan include generating geometry and mesh improvements, while adding additional engine performance points. This work allowed design solution for the performance repeatability of engine runs, enhancing availability of a significant fleet.

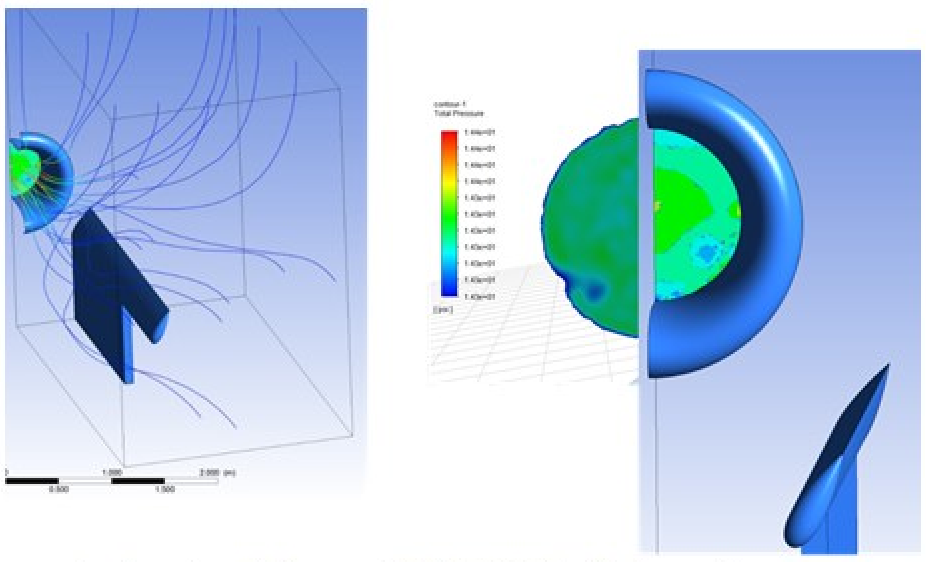




Without a beam



With a beam



Aerodynamic profile beam cut (NACA0030, 30° inclination angle)

Spinning Digital Threads in Aerospace

Dr. Anil K. Tolpadi

General Electric Aviation, USA

In the past five years, the intersection of high-speed microprocessors, inexpensive data storage, and wireless communication technology has led to a paradigm shift in how physical assets are operated and monitored. While the use of Prognostic Health Monitoring has been commonplace in military aircraft products over the past two decades or more, this paradigm shift has now bridged and expanded into the commercial aviation marketspace. Leveraging GE's deep domain knowledge with data streams from engine assets is at the heart of the Digital Industrial revolution.

Digital Industrial is more than just data. It's maximizing value for customer fleets in several ways, including: Asset Monitoring, to help reduce unplanned maintenance and inspection burden; Fleet Optimization, to ensure flight paths and fuel burn are as efficient as possible; and Improved Reliability, to understand changes in operation severity that may adversely affect the performance of the product.

Advanced manufacturing, including the advent of large-scale 3D printing, encompasses the intersection of digital and manufacturing technologies. The initial performance and geometry of aircraft engine components is the beginning of the Digital Twin life of every asset deployed in the field. Digital Twin asset models thereby demand integration of sensor and inspection technology on the manufacturing shop floor, at levels never before demanded of supply chain.

This presentation will illustrate the framework that makes the Digital Industrial possible in the aircraft engine industry, connecting the dots between sensors, digital twin models, and analytics to provide additional value to the customer. Examples will be provided to illustrate how analytics are used to help the customer and product. The presentation will also discuss some of the challenges facing industry today, providing context for future research directions.

The Curios Incident of Blade in High Pressure Turbine

Inna Kaparovsky

FAI, Israeli Air Force, Israel

Very few jet engines can operate without a blade, but even fewer, are the aircrafts which can fly without noticing a missing one.

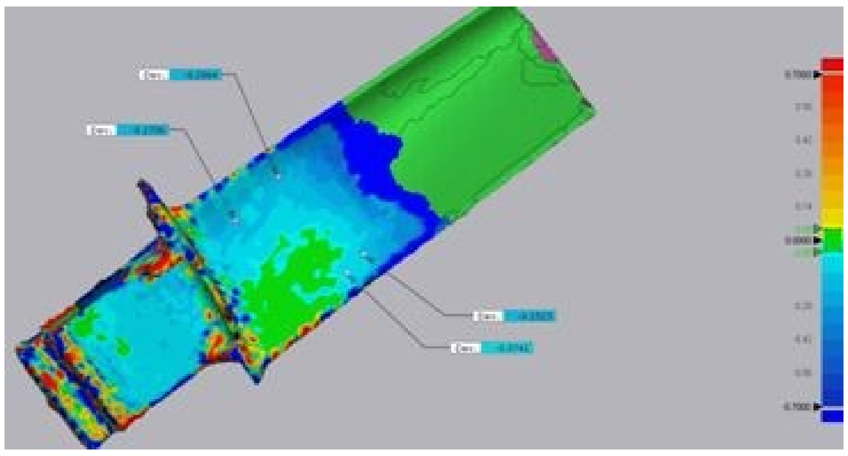
During January 2021, due to recurring leaks from the rear bearing, a jet engine was sent to a depot inspection, during which a half of the single HPT 2nd stage blade was found missing. The failure of a single 2nd HPT at mid span presents was puzzling.

Since no damage was found upstream of the separation, the focus fell on the failed blade itself, and its analysis revealed the solution.

What was so unique with the location of the failure? Which failure mechanism left behind an uncommon microscopic morphology? Why didn't the 1st stage blades indicate any problem?

The investigation began with the characterization of the 2nd blade separation event, continuing to challenging fractography analysis of two main areas; SEM (Scanning Electron Microscope), examination revealed an oxidized fracture surface with almost no familiar morphology. The area near the leading and the trailing edge was found to be consistent an overload failure mechanism. The finding was verified through comparison with an overload experiment performed on the same blade alloy. The failure mechanism of the mid area was identified through metallography as creep mechanism. As we know, creep requires three factors: overstress or high temperature and time. The HPT exhibited no indication of overheating and the blades served average number of cycles, therefore the possibility of undercooling was examined. X-ray microfocus revealed a partial blockage in the failed blade and several others.

Characterization of the blockage material aided the manufacturer to trace its source. This led to the uncovering of a potential fleet wide issue.



Aerodynamic Testing of High-Speed Low-Pressure Turbines: Challenges, Solutions, and Mistakes

Assoc. Prof. Sergio Lavagnoli

von Karman Institute for Fluid Dynamics, Belgium

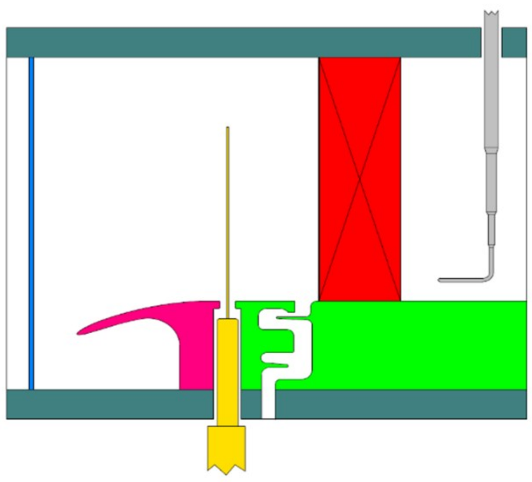
One of the key technologies to enable efficient Ultra-High By-Pass ratio geared turbofans is the low-pressure turbine (LPT). While the geared engine architecture allows a large reduction in LPT stage count and weight, the LPT operates at transonic exit Mach numbers and low-Reynolds numbers. Within this range of operating conditions, there is a critical shortage of aerodynamic and performance measurements. A lack of relevant experimental data in these engine-like conditions also concerns the interaction of the secondary-air and leakage flows with the mainstream.

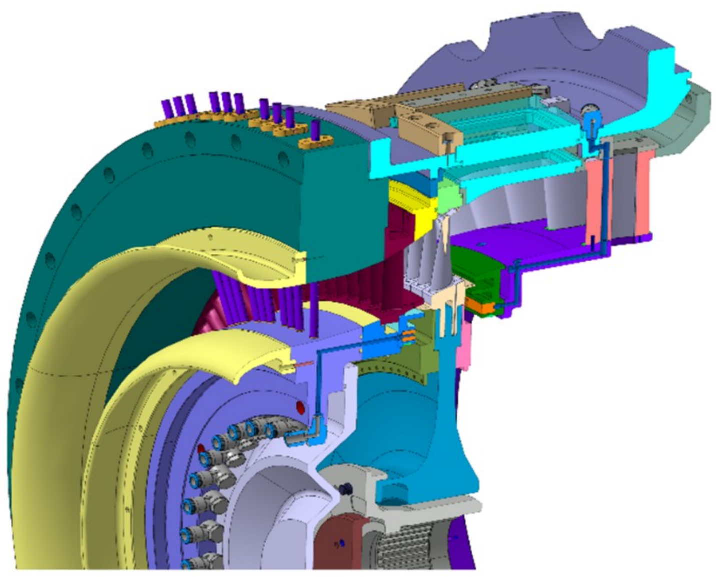
The EU-funded project SPLEEN, a collaboration between the von Karman Institute and Safran Aircraft Engines within the Horizon 2020 Clean Sky 2 program, aims at filling up this gap with an extensive experimental undertaking that investigates the aerodynamics of high-speed LP turbines of geared-fan propulsion systems.

The project focuses on the interaction of cavity purge and leakage flows with the mainstream and its impact on the turbine performance. SPLEEN addresses this challenge with detailed flow measurements in two world-class turbine rigs: a large scale, transonic, low-Reynolds number linear cascade including periodic incoming wakes, and a high-speed stage turbine rig. The project first investigates the effect of cavity geometries and purge flow rates on the local flow features and turbine performance in the VKI transonic linear cascade S-1/C. In the second part of the project, a LP turbine stage is tested at full-scale in the rotating turbine rig of the von Karman Institute. The flow structures, turbine global performance and the unsteady leakage/purge flow interactions are measured at representative engine conditions.

In this technical presentation we discuss the objectives of the project SPLEEN, and the design process to adapt and upgrade the turbine facilities, their test sections and instrumentation to test engine-scaled hardware at engine-scaled flow conditions. The complexity and effectiveness of design decisions are demonstrated not only through achievements, but also by analysis of bad design choices and their solutions.

The talk introduces the challenges and solutions to adapt a transonic linear cascade to measure endwall and purge flows in a predominantly 2-D environment. We present the integration of a flexible cavity purge and suction system with a redesigned high-speed wake generator suitable for 3D flow investigations, the blade scaling strategy, the implementation of a traversable instrumented airfoil, approaches to tackle flow periodicity limitations, and to manage unavoidable intrusiveness effects of probes in compressible flows. In the second part of the talk, we illustrate the design of experiments for a new research turbine stage for tests in a short-duration blow-down wind tunnel. We discuss the trade-offs for the test article design in terms of engine-to-rig aerodynamic scaling, instrumentation integration, facility flow range limitations, and manufacturing costs.





Preliminary Design Studies for Turbine Suitable to Operate with Pressure Gain Combustors

Dr. Bayindir H. Saracoglu

von Karman Institute for Fluid Dynamics, Belgium

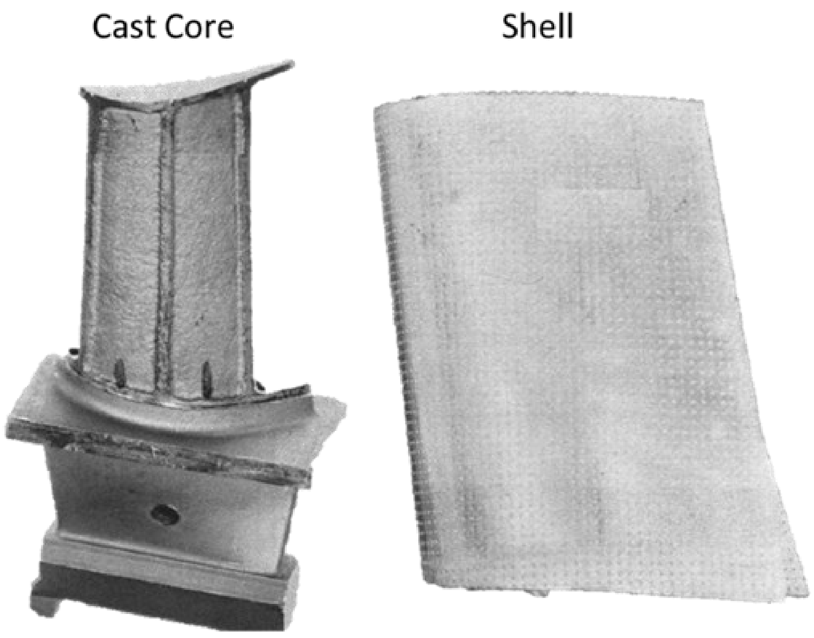
Pressure gain combustion technology promises a high theoretical thermal efficiency fairly superior than the currently used Joule-Bryton cycles. Nonetheless the application of the technology for practical use is not trivial.

Skin Cooling of Turbine Airfoils by Single Wall Effusion

Yair Lange

Technion - Israel Institute of Technology, Israel

As the power and thrust requirements from modern micro turbomachines increase, they pose new challenges on the thermal management of the units. As such, the turbines of these devices are operating in increasingly harsher thermal environments and as the micro turbine are currently mostly uncooled, new cooling paradigms have to be explored to further promote the state of the art. Therefore, we are using our turbine research facilities to develop effusion and skin cooling methods for micro gas turbines. Previously used only in their larger counterparts, the transition of these methods to smaller scales is not trivial and requires significant scientific and experimental inputs in order to provide viable cooling solution for micro turbines.

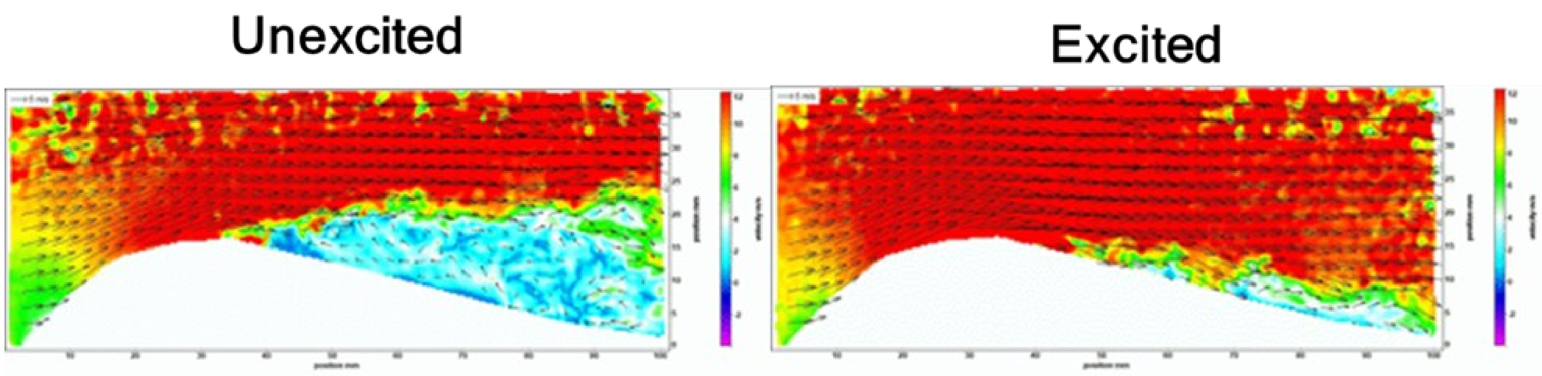


Application of Acoustic Flow Control Methodology to High Lift Airfoils

Acar Celik

Technion - Israel Institute of Technology, Israel

Turbine airfoils are known to suffer severe performance degradation at off-design conditions that can be mitigated by active flow control methodologies. In the present study, acoustic excitation is used to control the separation over such airfoils and different strategies are developed to determine flow and excitation parameters for optimum control of separation for varying airfoil shapes. These guidelines are developed based on detailed experimental campaign measuring surface pressure and velocity field around the airfoils. Experiments are performed using an in-house low speed acoustic wind tunnel facility equipped with laser diagnostic techniques (PIV) and other relevant instrumentation (static pressure probes, flow velocity meter and thermocouples). The excitation parameters (amplitude and frequency of global excitation), flow parameters (velocity) and shape of airfoils are individually varied. These experiments not only bring out the most favorable conditions but also enable us to uncover the flow mechanisms leading to desired modifications in airfoil performance.



Experimental and Numerical Study of Liner Film Cooling and Combustor Swirl Flow Interaction

Dr. Anil K. Tolpadi

General Electric Aviation, USA

Modern gas turbine combustors have high cooling efficiency demands making it necessary to have a good understanding of the interaction between hot gases and coolant flow. The aim of the present study is to experimentally characterize the flow and measure the liner heat transfer coefficient in a combustor chamber having an axial swirler and a liner slot for cooling.

The test rig geometry comprises of a linear three sector chamber fed by an open loop blower. Swirling main stream flow is achieved with an injector that produces flow structures that interacts with film cooling flow delivered by a simplified slot at the inner wall of the liner. The injector flow rate and the slot cooling flow rates are independently varied to study their interaction.

A 2-D Particle Image Velocimetry (PIV) setup is employed to measure the test section flow field in two different planes. Heat transfer measurements are made using a Thermochromic Liquid Crystals (TLC) steady state technique with a thin Inconel heating foil fed by two Copper bus bars.

Results obtained indicate a significant role of film cooling flow on both swirler aerodynamics and liner heat transfer. With increased slot cooling flow, the peak heat transfer coefficient gradually decreases. This is because of a reduction in the swirling jet expansion with higher slot cooling that also affects the amount of flow recirculation due to vortex breakdown. The geometry has also been modeled numerically using CFD and the calculated flow field has been compared with the measurements.

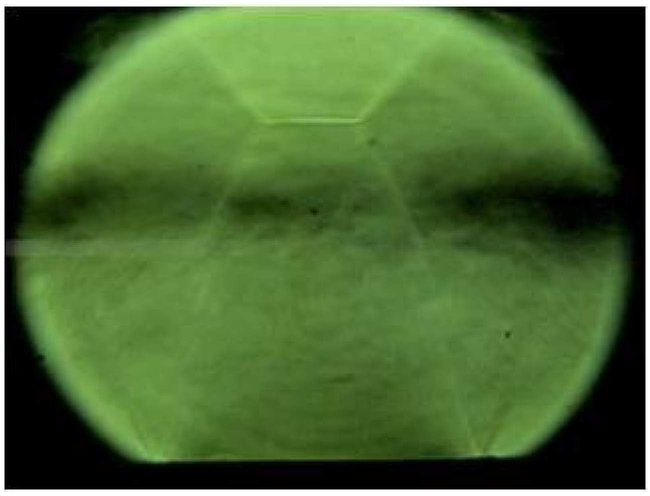
Schlieren Visualization of Detonating Combustion

Dr. Ionut Porumbel

INCDT COMOTI, Romania

Pulsed detonation engines are propulsion systems that carry out the combustion of the fuel through detonation waves. In contrast with deflagration, detonation propagates at supersonic velocity with respect to the unburned conditions. Therefore, the combustion generated pressure waves coalesce into a leading shock wave, behind which the reaction front immediately follows, and combustion may be approximated as occurring at constant volume. The coupling of the shock and combustion waves represents the detonation wave travelling at the local speed of sound, but supersonic with respect to the unburned mixture conditions. The leading shock wave rises the pressure along a Hugoniot curve and creates conditions for heat release along a Rayleigh line in the combustion wave. The combustion process is much more violent, and the engine thrust and cycle efficiency are increased. In terms of specific impulse, they exhibit superior performance to conventional liquid, hybrid or solid rocket engines, and represent an interesting and challenging alternative for space propulsion. Compared to classic turbine engines, if a detonation wave is used instead of a regular flame to burn the combustible mixture, the speed of the burning process increases by several orders of magnitude and the thermal efficiency further increases. A semi-empirical comparative study of the detonation vs. Brayton cycle efficiency carried out by our research team and relying on detonation experimental data showed a 15% increase in theoretical cycle efficiency over the Brayton cycle, while more than doubling the cycle averaged power for the same amount of burned fuel. In addition, the pressure gain combustion offers the advantage of lowering the required injection pressure, thus potentially benefiting from an overall reduction in system mass. Because of this, pulsed detonation engines can potentially simplify and reduce the weight of the current propulsion systems. Although the research on pulsed detonation engines started more than half a century ago, the current modelling capabilities and technology justify revisiting this concept. Such work is currently ongoing at the Romanian National Institute for Gas Turbines COMOTI aiming for the development of a Hydrogen fueled thruster for space propulsion, under contract with the European Space Agency. The pulsed detonation chamber for the thruster is designed for valveless operation, at a frequency of 100 Hz. The aerodynamic valve regulating the admission of fuel inside the combustor is controlled by means of high amplitude oscillating vortices captured and amplified by Hartmann resonators. The combustible mixture is ignited by a spark plug working at a frequency finely tuned with the aerodynamics of the combustor. A step, created by abruptly changing the diameter of the flow channel downstream of the spark plug is initiating the detonation wave that further propagates through an exhaust pipe to the atmosphere. The overall length of the pulsed detonation chamber is below 0.5 m.

The presentation will include Schlieren visualizations of the reactive flow in a pulsed detonation chamber model, focusing on the effect of changing the oxidizer from air to pure Oxygen in the same geometrical configuration.



On Nanosecond-Pulsed High-Frequency Plasma Ignition Regimes in Flowing Reactive Mixtures

Dr. Si Shen

Technion - Israel Institute of Technology, Israel

Nanosecond Pulsed High-Frequency Discharge (NPHFD) plasmas have shown promising results as an ignition method in high-velocity applications. Three inter-pulse coupling regimes are found for different ranges of inter-pulse times (IPT): fully-coupled regime: at short IPT, ignition probability is found to be the highest, and local quenching of ignition kernels is negligible. Partially-coupled regime: At intermediate IPT, the ignition probability drops to near zero, possibly due to destructive interaction between flame kernels formed after each discharge pulse, and the local quenching is amplified. Decoupled regime: at long IPT, the ignition probability becomes a function of the number of pulses and the single pulse discharge probability. This is because individual kernels do not interact with each other until far downstream from the discharge site. The relative IPT range of the inter-pulse coupling regimes, as well as the ignition probability and flame kernel growth rate within each regime, was found to be a function of the parameters mentioned above.

This study tests different electrode gap distances (d) across a wide range of IPT. The partially coupled regime is reduced as d increased but never disappeared. The ignition probabilities also increase with increasing d in the decoupled regime, except when d = 5 mm due to inconsistent discharges. As for the effects on the flame kernel growth, the small d cases influenced by heat loss to the electrodes create small flame kernels. In addition, the kernel growth rate increases with increasing d. The infrared study also shows an increasing average temperature of the flame kernel at large d. The minimum ignition power (MIP) also drops with increasing d.

Two discharge regimes are also observed, the toroidal regime at small d and the diffusive regime at large d. Such discharge regimes were studied by Professor Laux's group [1] in the air. This study expands the understanding of those discharge regimes for flowing fuel-gas mixtures. The change of the discharge regimes is detected near d = 3.5 mm. It significantly affects ignition probabilities, MIP, and kernel growth.

Moreover, elongation of discharge is also observed. It is most prominent at large d and IPT between the fully-coupled and partially-coupled regimes. Such elongation shows significant influence over ignition probabilities under experimental conditions. However, further study is needed to understand its full effects. In conclusion, an optimal electrode gap distance should exist for a high ignition probability and large kernel growth.

References

[1] Dumitrache, C., Gallant, A., Minesi, N., Stepanyan, S., Stancu, G. D., & Laux, C. O. (2019). Hydrodynamic regimes induced by nanosecond pulsed discharges in air: mechanism of vorticity generation. Journal of Physics D: Applied Physics, 52(36), 364001.

Well-Stirred Reactor with Homogeneous Plasma for Development of Chemical Kinetic Model of Plasma, Ammonia and Air

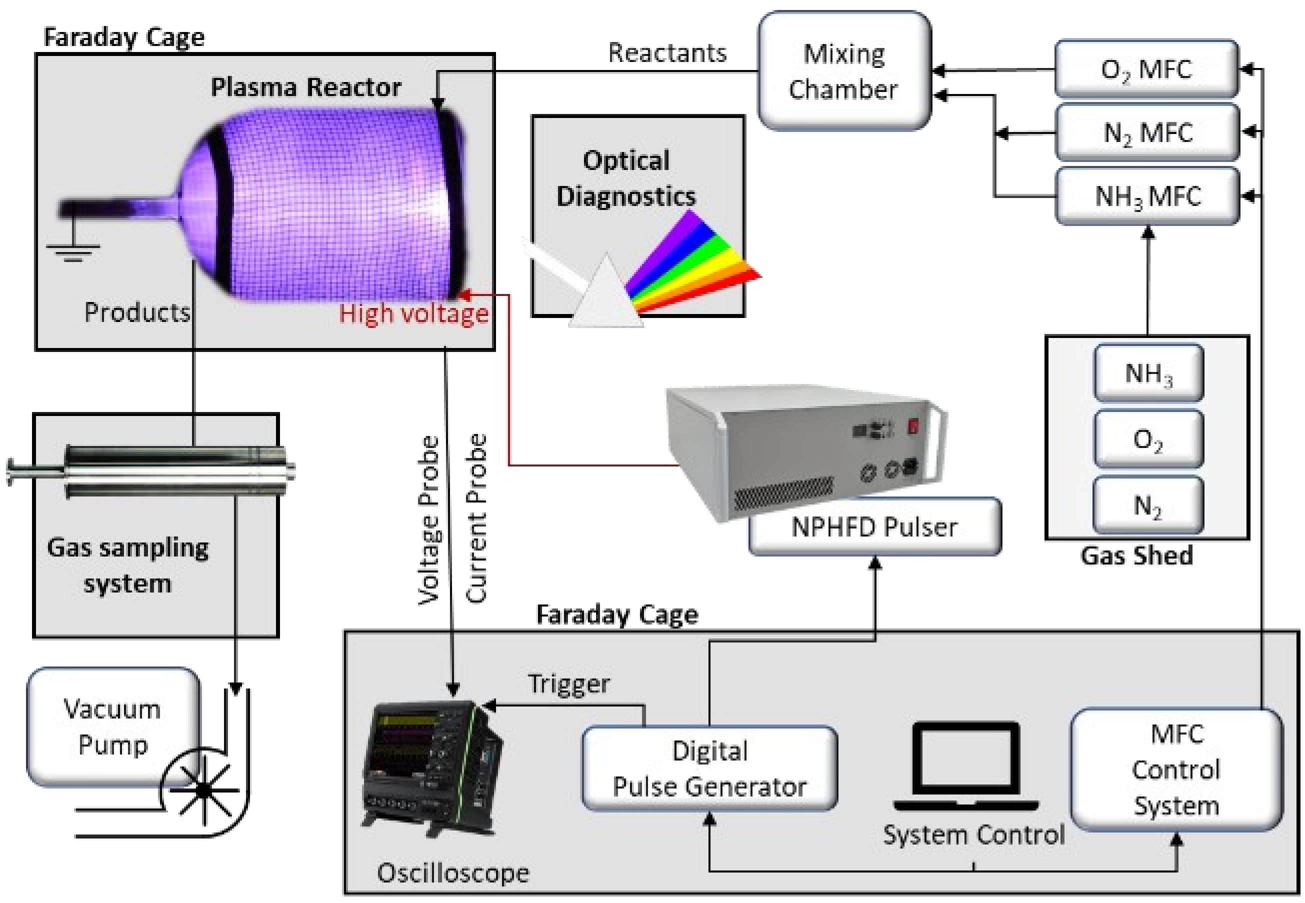
Galia Faingold

Technion - Israel Institute of Technology, Israel

Adaptation of existing infrastructure is key for meeting the green-house gas emission targets of the Paris Climate Accords. Using plasma-assisted reforming, ammonia can be modified to be compatible with current engine technology with only minor alterations. Based on our initial modeling work, plasma chemical processes initiated by high-frequency nanosecond-duration pulsed energy deposition can dissociate ammonia efficiently and selectively produce hydrogen and amino radicals, and when used in conjunction with oxidizer, can also produce nitrous oxide, among other combustion enhancing species. In this study, we present progress on evaluation and validation of the chemical kinetic mechanism for ammonia and air in a dielectric barrier discharge reactor.

A constant pressure, optically accessible well-stirred reactor with a homogeneous plasma discharge is devised (Figure 1). The reactor body is a fused silica tube with 4 cm outer diameter. An electrode configuration of an inner rod surrounded by an alumina dielectric tube, and outer mesh electrode wrapped around the outside of the fused silica tubular reactor creates a homogenous double dielectric barrier discharge. The inlet streams are arranged to create an environment with fast mixing of the reactants with the gases present in the reactor. In this way, the fresh mixture encounters electrons, excited species, and radicals immediately upon entry into the reactor, maximizing the conversion rate according to stirred-reactor theory. The discharge is created by nanosecond duration pulsed power. The benefit of this discharge type is that the plasma is maintained in a non-equilibrium state despite high electric fields in the gas, allowing a significant portion of the energy to be transferred to excitation of electronic states and dissociation of molecules.

Experimental results are used to construct and evaluate a chemical kinetic model, with which we simulate and replicate the plasma conditions in a 0D modeling framework. For a reformed stoichiometric mixture, it is possible to achieve a reduction of two orders of magnitude in ignition delay time. This reduction, however, comes at the cost of lost enthalpy, as ammonia reacts with oxygen to create water. Performing a sensitivity analysis on the influence of reformate composition on ignition delay time, the two most important species in the reformate were H2 and NH2. The presence of NH2 in high concentration also resulted in lower concentrations of NO after ignition, compared to the unreformed mixture. When reforming pure ammonia, the same number of pulses and energy as in the stoichiometric reforming case reduce ignition by one order of magnitude (compared to the unreformed mixture). This is less efficient than the stoichiometric reforming case. A higher reduction is possible for the pure ammonia case with more pulses (unlike the stoichiometric reforming case in which ignition is reached during the reforming process, limiting total energy deposition) and with no loss of enthalpy due to oxidation. At 200 kHz, a reduction of two orders of magnitude is possible after 1500 pulses.



An Experimental System for Blade Tip Timing Measurements

Shachar Tresser

Rafael Advanced Defense Systems, Israel

Vibrations of rotating blades is one of the main causes of failure in turbo machinery, and may be caused due to engine order forced response, acoustic resonance, rotating stall or flutter. Measurement of blade vibration is crucial to understand the stress level of blades, to understand failure mechanisms and to reduce design time. There are several methods to measure vibrations of rotating blades, however the only applicable one in jet engines is Blade Tip Timing (BTT), due to harsh conditions and lack of line of sight.

Since commercial BTT systems are very expensive, an experimental system was built to develop this method in-house, as a step towards performing BTT measurements of compressors and turbines of jet engines. The presented work describes the design of the experimental test rig, and the validation of the measurement method and algorithm.

Acoustic Analysis of Engine Operation and Events

Yohanan Nahmana, Michael Vrono

Bet Shemesh Engines, Israel

Each and every jet engine has an acoustic signature which can be analyzed. The presentation will describe samples of such analyses, detecting evidence for mechanical events during engine operation.

Aircraft Engine Technology Award Lecture

Maj. Shani Eitan

Israeli Air Force, Israel

Gas turbine engines typically contain hot section parts which must endure high levels of temperatures to maintain duty cycle loads. Engines hot section parts are usually made of super alloys, such as Inconel, and coated by various Thermal Barrier Coatings (TBC), such as Yttria-Stabilized Zirconia (YSZ). The purpose of TBC is to protect the part from prolonged exposure to high temperatures, which could result in thermal fatigue and oxidation. Thus, thermal properties of TBC play crucial role in determining the level of engine durability. Current techniques being used to measure thermal properties of TBC are complex and are unable to be performed in-situ with sufficient accuracy. This research introduces a novel technique together with a methodology and analytical approach solution to perform simple and more accurate measurement of TBC thermal properties by generating internal heat inside the parent material via induction. In following, the external temperature of the coating is continuously recorded, and analyzed. Phase between external temperature and internal induction power is used to calculate thermal properties. Direct phase expression was developed using 1D unsteady heat conduction equations to recover properties by decoupling the relationship between surface temperature phase and TBC properties. Diffusivity and thickness recovery optimization methodology is numerically tested using synthetic data which yields 1-5% error between synthetic specimen properties to predicted results. In addition, noise analysis is conducted by adding artificial errors to synthetic properties and solving consequent error in the recovered properties. Relations between several types of input errors such as proportional bias and Gaussian bias and their corresponded output errors are presented. It is found that same magnitude of order of error is maintained for the suggested methodology, and that temperature measurement accuracy has more influence over frequency generator errors. Infrastructure for constructing experimental setup for validation, together with exact solution for temperature evolution and numerical simulation is also in the framework of this research.

Radiometric Measurements of Small Jet Engine and its Plume

Ohad Ophir

IARD Sensing Solutions, Israel

Radiometric measurement is a nondestructive testing method that yields unique information. IARD Sensing Solutions has conducted radiometric measurements of a small turbo jet engine (the engine body and the exhaust pipe) and its plume during a static run test. The radiometric plume measurements included also a soot load characterization in the combustion products during the continuous operation of the engine at high RPM.

Equipment included the following:

- The engine body and plume radiance maps were measured by three MWIR imaging radiometers with the following spectral filters: 3.8-4.1 µm, 3.4-4.2 µm (aerosol emission) and 4.5-4.9 µm (CO_2 emission).
- The plume transmittance was measured by two CMOS cameras operating at 390 and 525 nm.
- The body/exhaust pipe reflectivity and BRDF in the IR spectral range was measured by field reflectometer SOC-410 in four spectral bands.
- Engine body and exhaust surface temperatures were measured by attached thermocouples.
- Additional engine characteristics were measured by testbed sensors (EGT, RPM, thrust, air and fuel mass-flows).

Test Process

Two IR imaging radiometers were positioned perpendicular to the engine and measured the body and the exhaust, while the third was positioned to look into the exhaust pipe (failed after three seconds). The CMOS cameras were positioned to look at the plume on sky background. The IR reflectance of the engine body and exhaust pipe was measured prior to the engine operation. The jet engine was operated with varying its RPM from idle to max and back to idle.

Analysis

The radiance of the exhaust pipe measured by two of the IR cameras was compared to values calculated from the exhaust surface temperature measured by the thermocouples. This comparison yielded the emissivity of engine body and exhaust pipe. From CMOS cameras the plume transparency was measured. It was compared to a plume transparency model based on Mie theory. From this comparison the soot content in the plume was estimated.

Results

1. A decrease of more than 50% in the exhaust emissivity (from ~0.55 to ~0.2) was observed as exhaust pipe temperature rose from ambient to ~800 °C.
2. A soot load of 0.0015% was measured during continuous operation at high RPM.

Development of a 45 kW Recuperated Turboshaft Gas Turbine Core

Fred Frigerio

UAV Turbines, USA

UAV Turbines Monarch family of engines ranges in power from 7 kW to 180 kW. The Monarch 5, a 45 kW SLSD rated gas turbine core was developed as the best balance of weight, size, and performance anchoring the modular compact design intended for applications where fuel efficiency, reliability, size, and weight were critical requirements. As such we will review the different concepts, cycles, and component architectures that were evaluated and, in some cases, manufactured culminating on the current Monarch architecture.

Additively Manufactured Pre-Assembled Turbojet Engine (APE) for Unmanned Aerial Vehicles

Michael Palman

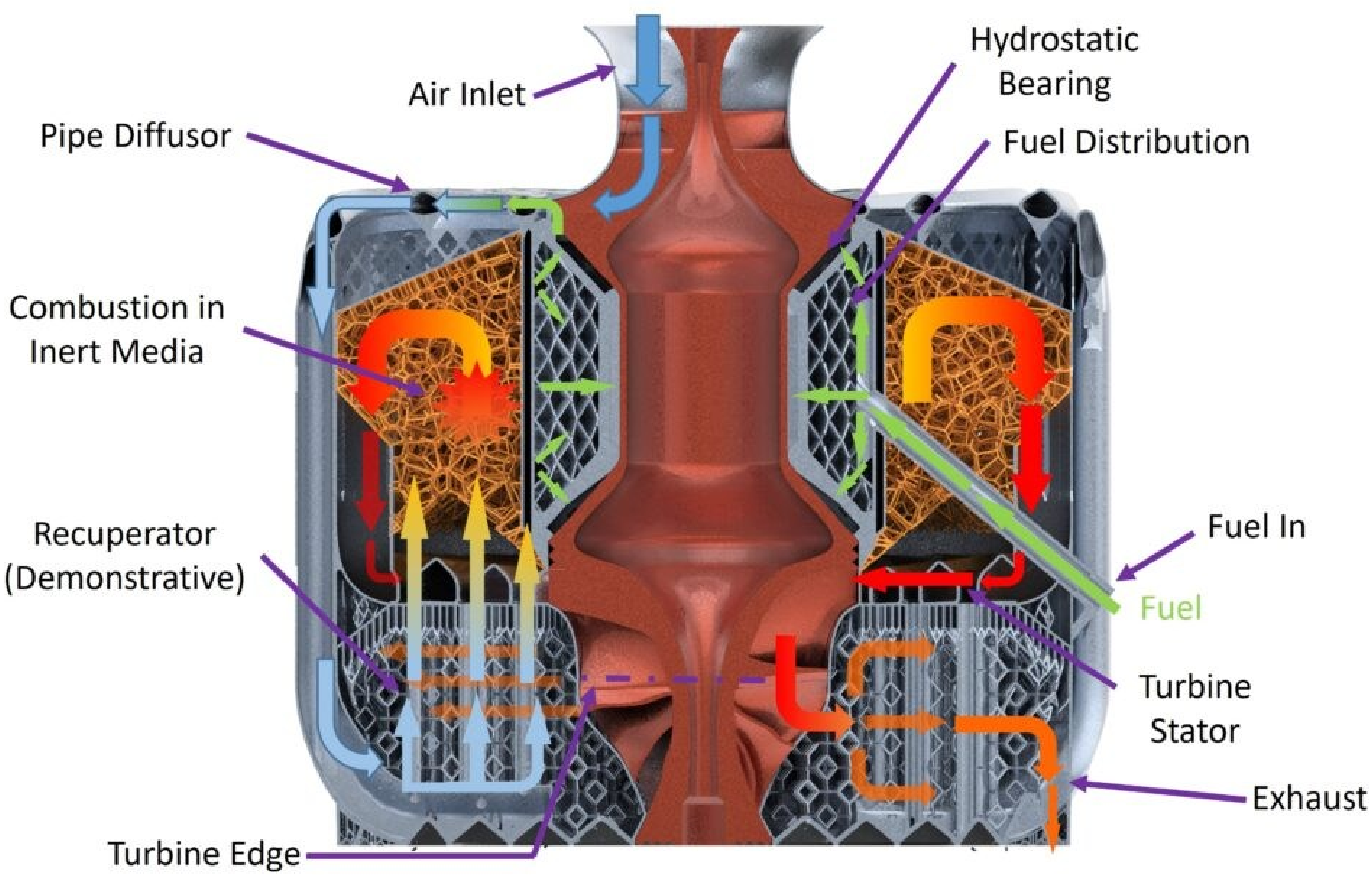
Technion - Israel Institute of Technology, Israel

In the modern world, unmanned aerial vehicles (UAV) capture an ever-increasing part of our daily operations. This is especially true for small scale UAVs, which are commonly powered by micro-gas turbines. These micro jet engines have thrust rating below 1 kN and have disproportionate cost that varies between 30,000 to 150,000 USD. For both disposable and re-usable platforms, this inflates the system cost dramatically. Moreover, in multi-mission platforms, significant efforts are invested towards prolonging the service life of these small yet expensive engines, and maintenance becomes an important subject, which involves long chain of suppliers and overall work expenditures that have the potential to even surpass the base price of the engine.

Instead of relying on these paradigms, extremely cheap limited-life micro-jet engines have the potential to eliminate supply chains, warehousing of replacement parts, maintenance procedures, and all expenses associated with it. However, despite the relatively simple design of a conventional micro-turbojet engine, its manufacturing involves long and costly processes due to presence of numerous parts, different manufacturing methods, logistics of various subcontractors and collaboration of different departments that assemble and qualify the product. Instead of relying on this conventional process, the proposed concept here entails development of a non-conventional engine design that can be additively manufactured in its final topology through a single uninterrupted print that encompasses both the rotating and stationary components. Requiring only a metal printer and an operator, the cost of the engine will be diminished to capital equipment depreciation and raw material, with an expected cost reduced merely to a small fraction of the current engine market prices.

Considering the print volume of the currently available metal 3D printers, the target engine design will have a diameter of up to 30 cm, thrust rating of 650 N and air mass flow rate of about 1.4 kg/s. The proposed manufacturing method also mandates a reduction in number of components. Thus, the engine will include only two major parts – static casing with embedded combustion chamber and a rotating shell structure. This rotating part will include compressor and turbine impellers connected by a thick hollow shaft that will enhance the rotordynamic performance. The hollow shaft connecting the compressor and the turbine will also serve as a fuel driven hydrostatic bearing. The fuel will subsequently evacuate through perforated media towards compressor-diffuser region and mix as an aerosol with incoming air flow. In a pursuit to reduce engine size, porous media combustor will be used to burn the premixed fuel-air mixture. The rotating component of the engine is designed to be balanced after the manufacturing process only through external ad hoc removal of mass from the surfaces.

This project involves sophisticated multidisciplinary optimization of aerodynamics, thermodynamics, heat transfer, rotordynamics and stresses for turbomachinery and hydro-static/dynamic bearing components under 3D manufacturing limitations. Although the performance of the final design is anticipated to be inferior to state-of-the-art micro-turbojets in terms of both thrust to weight ratio and thrust specific fuel consumption due to design constraints associated with incessant printing, the expected disruptive change in cost and availability is expected to create a market for such products.

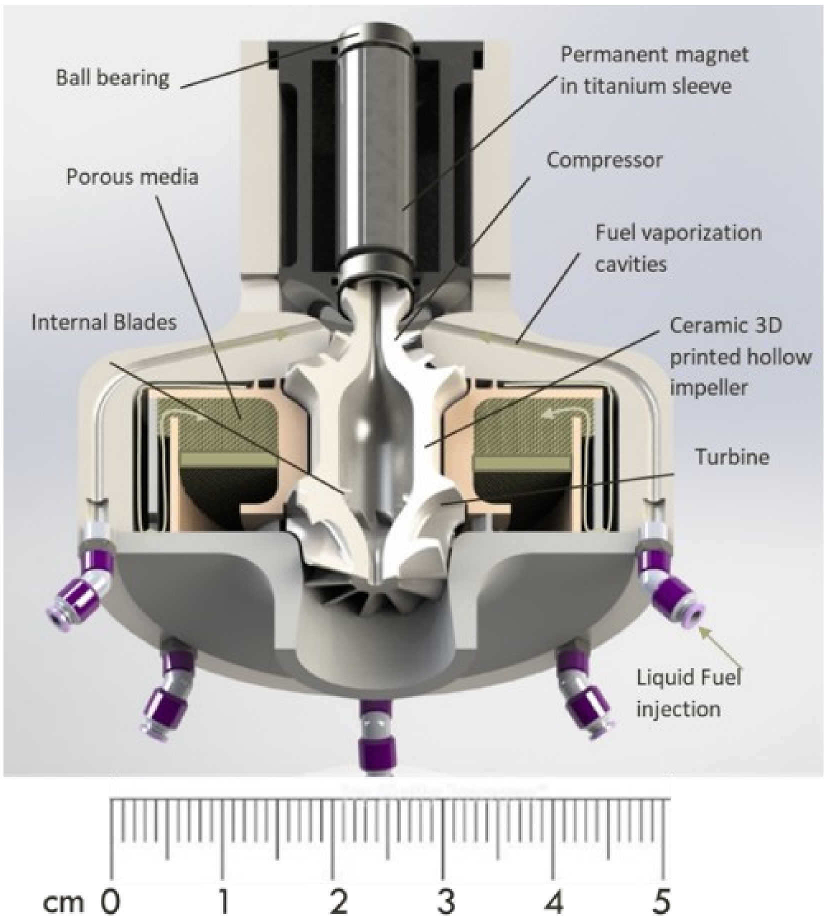


Development of Additively Manufactured Ultra Micro Gas Turbine Generator

Lukas Badum

Technion - Israel Institute of Technology, Israel

Electronic military equipment weight as well as MAV flight time is highly dependent on achievable electric energy density. Therefore, the development of a 300W kerosene driven Ultra Micro Gas Turbine (UMGT) prototype is proposed, which is foreseen to triple energy density compared to current Li-Ion batteries. UMGT developments of previous research projects did not achieve useful electric power output due to manufacturing limitations and unstable air bearings. To encounter these shortcomings, the proposed project will facilitate an additive ceramic manufacturing approach, allowing outstanding design flexibility and material properties. As current high-end ball bearing technology is suitable for the demanding operating conditions of UMGTs, ceramic hybrid bearings will lead to reliable operation of the turbine rotor. In accordance with experimental tests, an analytic engine model will be established to evaluate multiple engine configurations, leading to a highly redundant development process that will result in a multi-parameter optimized UMGT prototype.



Thrust Vectoring and After Burner System for Increasing Survivability of Micro-Jet UAVs

Dor Shitrit

Technion - Israel Institute of Technology, Israel

A major current threat on Unmanned Aerial Vehicles (UAVs) and Air-to-Surface Missiles (ASM) is being intercepted by Surface-to-Air Missiles (SAMs) with maneuvering capabilities. There are many methods to increase the survivability of such UAV and ASM while the challenge is keeping them cost-effective and relevant to the modern battlefield.

One of the ways to increase survivability is by improving agility. Agility of an aircraft can be improved by using thrust vectoring (TV) and activation of an after burner (AB). It enables the platform to accelerate by operating the aft burner while vectorizing the thrust, thus “breaking lock” from the potential threat.

This study aims to investigate such integration in micro turbo jet UAVs. It includes dynamic simulation of the after burner as well as the vectoring nozzle systems and their effect on the aircraft overall performance. A total of 3 engine power configurations (basic with constant nozzle, adjustable nozzle, adjustable nozzle with aft burner) and 2 vectoring configurations (with, without) are examined.

For this purpose, "Do-DT-45" UAV and "SA7-Strella" SAM are chosen as target and interceptor demonstrators. Complete engine decks are created including designing engine control system to withstand the engine limitations during the transient state. Drag polar, stability & control derivations of the target and interceptor main characteristics are estimated. Evasive maneuvers are characterized, and a dedicated aircraft control system is implemented to support it. Finally, a quantitative analysis for the joint contribution of thrust vectoring and after burner to the survivability of the aircraft is introduced by implementation of interception simulation.

The main results indicate that TV & AB systems have the potential for increasing miss distances thus survivability, and integration of both produce the most significant improvement in miss distance. Priority for TV or AB can vary depending on certain interception conditions. Moreover, there can be engagements in which these capabilities will not succeed to save the aircraft from hit. Therefore, implementation of TV or AB capability is recommended conditioned by detailed analysis as well as pre-known knowledge about the target and potential interceptor, optimal evasive maneuvers, and overall playground.

Design of a Radial Compressor for Additive Manufacturing

Prof. Tom Vestreate

von Karman Institute for Fluid Dynamics, Belgium

In this work we present a design methodology for a radial compressor specifically aiming additive manufacturing. Typical constraints such as limitations in overhang are directly considered, leading to a design with lower performance.

Investigation of Splittered Tandem Stators for Highly-Loaded Low-Aspect-Ratio Transonic Fan Stage for a Small-Scale Turbofan Under Some Mechanical Design Constraints

Modern fans and compressors require high pressure ratios and therefore demanding diffusers to straighten the flow. Tandem stators have been long considered for such cases in order to supply momentum to especially near-stagnant suction side close to the trailing edge. Therefore, corner separation can be suppressed, which, otherwise, would prevent diffusion. Along these lines, this study considers an atypical transonic bypass fan stage of a small geared UAV turbofan engine. This engine is hypothetically supposed to drive a jet-powered UAV which can fly both at loiter and fly-fast modes, therefore requiring variable-cycle operation. The results of the ongoing research are previously published in several articles. The concept uniquely considers higher pressure ratio for the hub of the fan relative to its tip, resembling a missing booster stage. This requires high aerodynamic loading in the stator near the hub region. However, small sizes of the engine (~20cm in diameter) requires wide-chord and low-aspect-ratio blading as well as an inherently reduced Reynolds number. This viscous dominance undermines the diffusion capability of the stator at the hub. Applying lean to the stators are restricted by the fact that screws or ducts should pass through the stators, making them effectively radially-stacked. Therefore, splitter blades are added which feature bow lean to suppress hub suction-side corner separation. Moreover, a tandem configuration is applied such that there are both front and rear main and splitter blades. The number of main and splitter blades are both determined as 6 based on resonance considerations using Campbell Diagram. Therefore there are 12 blades at the front and 12 blades at the rear.

Previously validated ANSYS CFX solver with implicit laminar-turbulent transition modeling in SST framework is employed to predict the flow field. The final tandem design is achieved after careful adjustment of axial and tangential gaps between the rear and front main and splitter blades. This tandem design is compared with a more traditional baseline stator with the same low aspect ratio. It is shown that the tandem arrangement significantly helps minimizing the corner separation, which cannot be easily achieved with design modifications of the baseline stator. In this regards, its effects are major. However, total pressure loss is still high. An automated design optimization seems unlikely to change this dramatically. It is concluded that the tandem design is a powerful tool that enables operation at higher loadings in stators. However, its benefit is still limited by low aspect ratios.

Comparison Between Different CFD Methods Simulating Stator Rows with Non-Equal Number of Vanes

Tom Regev, Ariel Cohen

Bet Shemesh Engines, Israel

Turbomachine designs often require two consecutive stator rows, In CFD analysis of these components it is often desired to generate as few blade passages as possible-usually one passage per blade row. CFD solvers account for the different periodicity using rotor-stator interfaces which guarantee a conservation of the fluxes on both sides of the interface. While these interfaces tend to give decent accuracy between rotor and stator rows, their use between adjacent stator rows of different periodicity leads to a loss of information of the row interaction. This work compares several methods of modelling multi-stage stators.

Efficient High-Speed Compressors in Aircraft Engines

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Pratt & Whitney Canada, Canada

In the general aviation world, a fuel-efficient compact high-pressure ratio compressor design is the key for a successful aircraft engine (turbo fan, turboprop and turboshaft engine). This lecture presents on the research and development trend and successful examples in high-speed (both transonic and subsonic) compressors. A wide range of compressor configurations will be highlighted and compared.

Fast progresses in computational fluid dynamics (CFD), both commercial codes and in-house developed codes, have a strong impact on the recent compressor designs. Now it is possible to capture real hardware geometry details such as blade tip, filets, the gaps, bleed slot, seal geometry etc. Rapid advances in turbulence modelling such as large eddy simulation (LES) and detached eddy simulation (DES) improve the understanding of the complex flow structures in high-speed compressors. Multi-blade row models such as the “mixing plane” model make it possible to simulate the whole compressor. The improvements in true geometry model and turbulence modelling enable compressor designer to predict compressor performance and operability more accurately.

General design considerations and challenges for high-speed compressors are outlined in this lecture. The compressor operability limits (stall or surge) are discussed in detail. The recent advances in stability enhancement designs such as casing treatment are reviewed. A multi-discipline compressor design optimization system, which includes aerodynamic, structures and vibrations, is used in the advance compressor design.

New measurement techniques in high-speed compressor are used in the compressor rig validation. These techniques include high frequency despondence transducers, 3D printed blade leading edge probes and Laser Doppler Anemometry (LDA).

With the aid of the advanced CFD, a new multi-discipline design optimization system, the latest measurement techniques and the expert design know-how, a few families of high-pressure compressor were successful developed and introduced our engine products. Some examples of axial and centrifugal compressor are presented in this lecture.

Analytical Investigation of a Slinger Injector

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An analysis of the flow inside a slinger injector hole is performed, leading to interesting conclusions regarding the atomization performance of such injectors.

Multipurpose Combustion Chamber for Testing Facilities of Airbreathing Engines

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Testing of airbreathing engines often requires preheating of the incoming air in order to simulate various flight conditions. A combustor is being designed and developed for this purpose, capable of operating at wide range of operating conditions and producing low levels of soot and other emissions.

The design incorporates a triple-channel swirler with air-assist atomization using simplex atomizers. The design of mechanical structure of this combustor was strongly influenced by requirements of versatility of inlet and outlet flow properties.

The flow field and chemical species production within the combustion chamber were solved numerically. The computations showed that recirculating combustion zone and acceptable emissions can be achieved using aforementioned swirler at required range of operating conditions.

Effect of N_2 Dilution on H_2 and H_2 Enriched CH_4 Flame in Swirl Stabilized Premixed Combustor

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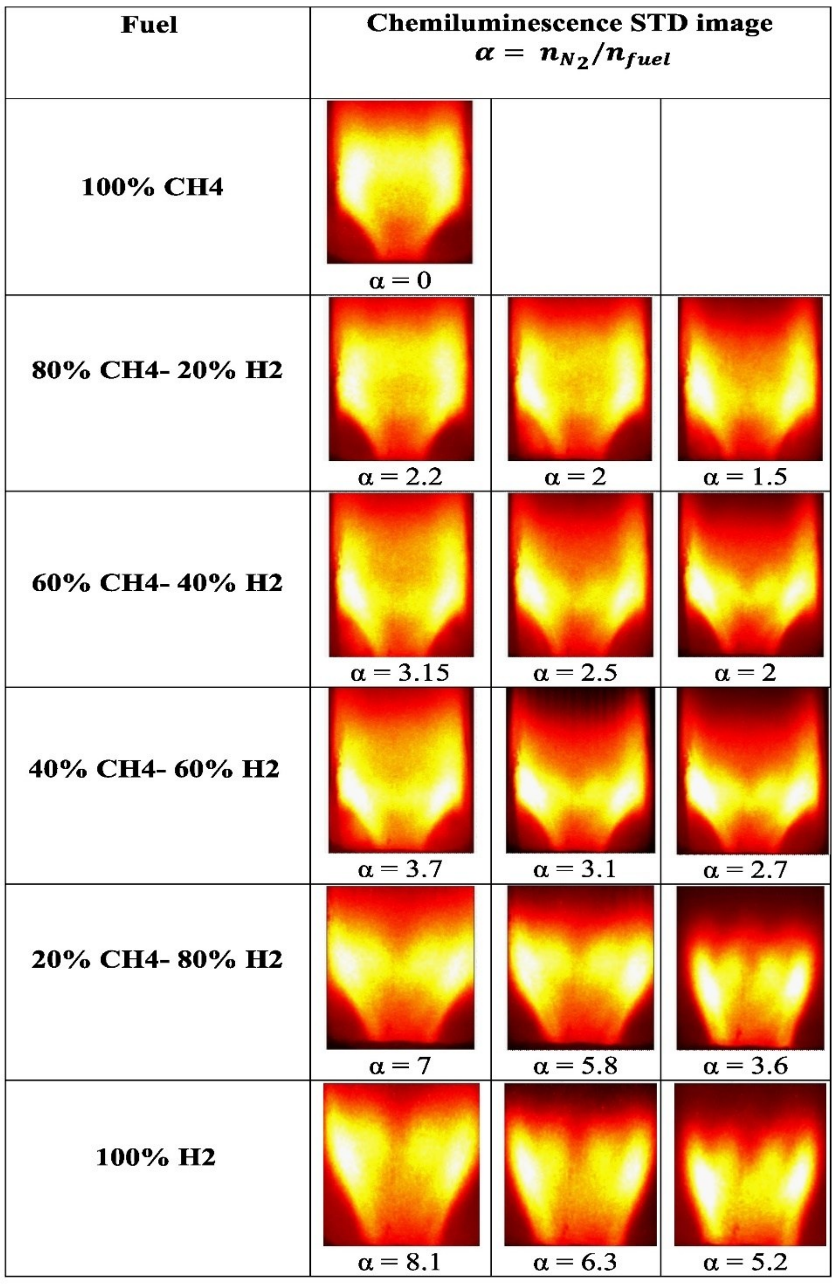
Hydrogen (H2) is looked as an attractive fuel to power and propulsion gas turbines. However, the different chemical properties of H2 present major challenges to combustor design. The combustion of H2/Air and H2/CH4/Air mixture even at slight lean conditions is highly prone to flashback because of its higher flame speed and flame temperature. These two properties also make the flame to stabilize differently with different lengths and combustion dynamics. The high flame temperature produces high nitrogen oxides (NOx) compare to its corresponding fossil fuels. In order to achieve low NOx emissions and prevent flashback, combustion of H2/Air and H2/CH4/Air mixture were diluted with nitrogen (N2) in this study. The idea here is to match the flame shape of methane by keeping constant the power output (19.5 kW) of swirl stabilized combustor. In this work, H2/Air and H2/CH4/Air mixture with H2 volume fractions up to 100% at different N2 dilutions were investigated using OH* chemiluminescence imaging and acoustic pressure measurements. The preliminary results suggest that there is flame topology transition (up to 60% H2 enrichment) in a particular fuel mixture with change in the N2 dilution. With decreasing N2 dilution, the flame changes from "V" shape to "M" shape. For higher H2 enrichment (80 and 100%) cases, the flame always remains "V" shape stabilized in inner shear layer (ISL) and appears to be shortened in length with decreasing dilution. Figure 1 represents the flame shape transition with different N2 dilutions for H2 and H2 enriched fuels at constant power output (19.5 kW). Generally, a V-flame refers to a flame that attaches to ISL, sustained by hot exhaust of inner recirculation zone (IRZ). Therefore, the stabilization of "V" shape flame in ISL in higher H2 enrichment (80 and 100%) cases is mainly because of the resulting fast chemistry and increased extinction strain rate of H2. The strong diffusion of hydrogen from swirling jet to IRZ increases the local equivalence ratio which provides local flame pockets and hence the flame stabilization in ISL. In addition to this, the level of pollutant emissions (CO2 and NOx) was also measured during experiments. The results suggest that, as expected, to get half the reduction in CO2 compared to methane requires at least 80% H2 enrichment to methane. On the other hand, the production of NOx mainly depends on temperature; therefore, the addition of H2 to methane or 100% H2 obviously increases NO emission. However, dilution with N2 decreases the overall flame temperature, which results in a significant reduction in NOx emission. For a typical "V" shape flame, a reduction in NOx emission ranges from 48-91% for H2 enrichment 40-

100% were measured for corresponding N2 dilution. Considering "V" shape flame in 20% H2 enrichment case, the effect of N2 dilution on NOx emission is insignificant.



Assessment of Methanol as an Alternative Fuel for Micro Gas Turbine

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The world is experiencing an accelerated shift towards alternative non-petroleum-based fuels. The aviation sector despite being one of the largest polluters still has no valuable alternative to fossil fuels. Considering the difficulty of implementing electric propulsion for long-distance air travel, alternative combustion-based sources have to be further evaluated. One additional new age frontier for research has been micro gas turbine, and high amount of resources are dedicated on identifying propulsion sources for such engines. The most promising new age carbon-neutral fuels in space are H - hydrogen and CH3OH - Methanol. With micro gas turbines, the compact design constrains limits the potential to use hydrogen as power source. The conversion of jet engines into a hydrogen-based combustor requires a massive engineering overhaul and as a result, it has been postulated that methanol can operate as a bridging mechanism for jet engines. Methanol proves to be a sustainable “medium-density” energy source with properties similar to existing fuels. But for any practical application of methanol, a better understanding of its combustion characteristics is required. This warrants additional importance as methanol is known to produce carcinogenic pollutants like formaldehyde. The operational traits of methanol oxidation can be gauged by studying methanol chemical mechanisms.

An opposed jet combustor, a well-known combustor design was employed to examine the combustion behavior of methanol. This opposed jet system was employed to study the suitability of existing chemical kinetic models in predicting methanol (CH3OH) oxidation while simultaneously investigating the formation and consumption of formaldehyde (CH2O). Experimental thermal and emission data were correlated against simulations from different chemical kinetic models. Considering that highly used mechanism like GRI Mech 3.0 has a sub-path for methanol, it is important that their suitability is studied for methanol oxidation.

Based upon experimental results, it is observed that the NUI Galway Mech15.34 model was most accurate in predicting methanol combustion behavior but is seen to under predict some species. The work showcased the difficulty of igniting vaporized methanol, thereby suggesting the need to modify the existing design by incorporating a fuel vaporizer. Finally, simulations with water-diluted methanol were carried out. Such water in methanol configuration is known to have a certain advantage in terms of reduced stress corrosion cracking in some titanium-based alloys. The results here illustrate a marginal reduction in formaldehyde formation while maintaining a similar peak combustion temperature. Theses new operational zones of reduced formaldehyde formation were then modelled on LM2500 engine using GasTurb software.

Configuration Adaptation of 3D AM Bearing Housing – Conclusions

Matan Zakai, Yohanan Nahmana

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In 2018 we presented the design of a 3D printed bearing housing. This presentation will describe design changes made during the development process as well as fundamentals of QA inspection and functional testing of the part.

Ansys Turbomachinery Modelling with Aeromechanics Focus

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ANSYS, Israel

The flow within turbomachinery is transient in nature, leading to a steadily growing demand for accurate steady state performance predictions to solving more transient simulations. Capturing transient phenomena close to the stability limits, accounting for rotor/stator interaction effects and prediction of aeromechanics are becoming more common.

The presentation showcases the key advances made in Ansys turbomachinery modelling from efficient performance predictions to aeromechanics simulations. The topics covered include:

- Turbomachinery workflows for parametric blade generation, meshing and map generation
- Process integration and design optimization
- Faster transient simulation using Transient bladerow methods and Harmonic Analysis
- Efficiently run Aeromechanics for flutter and forced response, using Harmonic methods

The Effect of Dynamic Stiffness on Small Engine Rotordynamics

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For small turbojets, where the static structure stiffness is relatively higher than that of the rotating structure, it is generally assumed that the dynamic stiffness of the static structure can be neglected. This presentation will describe simulations performed on an engine which, though small, is sufficiently large such that the effect must be accounted for.

High Fidelity CFD Simulations of Hydrostatic Bearings

Over the past years the importance of hybrid (combination hydrostatic and hydrodynamic) journal and thrust bearing has significantly grown in turbomachinery applications. Low wear, high shaft speeds, heavy loading capabilities, large range of operating temperatures, high stiffness and damping, absence of friction at zero speed are examples of why hybrid bearings are widely used. Hydrostatic journal or thrust bearings are a type of bearings that separate sliding surfaces using pressurized fluid in contrast with hydrodynamic bearings, where the separation of the sliding surfaces occurs naturally due to relative motion of the surfaces and their geometry. Journal bearings are used to support radial loads, while axial loads are supported by thrust bearings. Hydrostatic bearings have two main parts – the pad and the hydraulic circle. The bearing pad contains one or more than one pockets to ensure there is sufficient area to lift the bearing load. The pressurized fluid flows into the pockets through the orifices. A continuous pressurized fluid forms a fluid film around the shaft, preventing the contact of rotating and stationary surfaces and the lubricant leaves the bearing at the outlet.

In this paper, high fidelity CFD simulations of hydrostatic bearing which was designed for NATO SPS G5939 project are presented. This hydrostatic bearing has cylindrical and conical geometries, cylindrical structure in the middle and 2 conical structures at the ends. It is aimed to directly use the engine fuel as a bearing lubrication fluid. In order to accomplish this, the bearing leakage flow should have sufficiently high mass flow rate and pressure in order to mix with the compressor outlet flow upstream of the combustion chamber.

Firstly, steady-state 3D Reynolds-averaged Navier-Stokes (RANS) CFD simulations were performed for radially-loaded part of the hydrostatic bearing to see the initial data and make a general estimation by looking at outputs such as lift force, cavitation, pressure distribution, mass flow rate etc. The simulations were performed at various supply pressure and clearances using kerosene as bearing fluid. The realizable K-Epsilon Model with Enhanced Wall Treatment Function was set and Zwart-Gerber-Belamri cavitation model was implemented to detect whether there is cavitation or not. It was seen that according to results, even if hydrostatic bearing architecture is used, hydrodynamic effects are still as important for small nominal clearances and when the clearance increases, cavitation may become a serious problem at high shaft speeds.

The hydrostatic bearing has both radial and axial sections and therefore each bearing type has been validated separately. For hydrodynamic validation, papers of Raimondi and Boyd [1] were used. They obtained famous diagrams about hydrodynamic bearings which are still used even today.

For hydrostatic/hybrid validation Guo's [2] paper was used. In that study CFD simulation was conducted by using CFX-TASCflow. Maximum pocket inlet pressure difference was about % 2 and load capacity difference was below % 1. Difference of mass flow rate is about %7. For hydrostatic thrust bearing validation, experimental data and simulation data were compared and validation was completed with approximate values. After the success in this validation case, the K-Epsilon Realizable model with Enhanced Wall Function was also used in the main case.

In order to justify accuracy of CFD simulations, check on mesh independence was conducted for 0,5 eccentricity and 10 bar pressure difference on different mesh sizes. The K-Epsilon Realizable turbulence model was used for the validation of both thrust and radial hydrostatic bearings. This model was also used in the main hydrostatic bearing analysis. Time dependent simulations will be made in which the shaft is fully dynamic.

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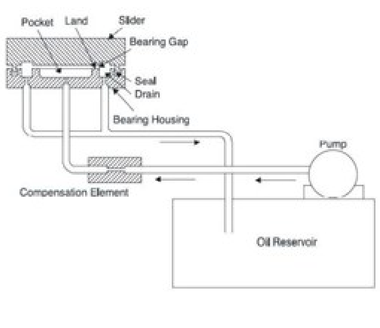

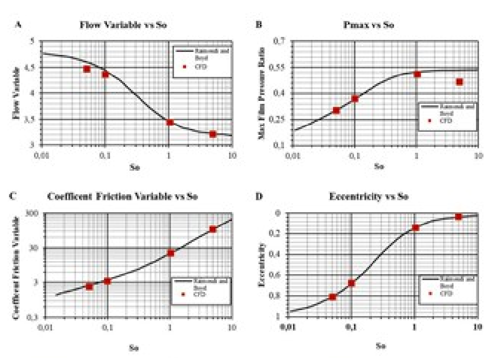

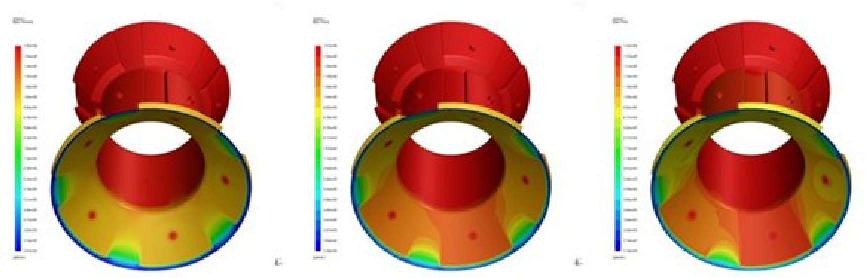

Development of a Modular Plant Model for Real Time Testing of a Recuperated Engine FADEC

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UAV Turbines, USA

During the development of UAV Turbines' Monarch 5, 50 HP recuperated microturbine, a series of technology gaps were identified. One of the more significant gaps was the lack of a modern electronic engine control unit. A survey of existing off the shelf units identified potential solutions, however, during more in-depth review, these systems were lacking in flexibility (were mostly for unrecuperated turbojets or APUs). During an effort to modify a unit from a leading APU manufacturer, the effort resulted in a large, heavy unit lacking critical capabilities that couldn't be implemented without a complete FADEC redesign. UAVT, therefore, kick started an ambitious program to develop a modular control system running on a modern controller with the objective of having a low-risk path to a FADEC capable of being used in an FAA/EASA certified propulsion system or APU.

The first critical step was the development of an engine plant model capable of simulating the transient and steady state engine response during Hardware-in-the-Loop (HIL) testing of the resulting hardware and software through the engine operating envelope, and out-of-design conditions with a real-time high-fidelity simulation. This paper will address the process, the modeling and the lessons learned in creating a modular plant model that can simulate the range of engine configurations in the Monarch family of engines, from simple-cycle to recuperated-cycle, with a high-speed generator or a turboprop.

Control of Micro Gas Turbine via DSpace

Dr. Arkady Lichtsinder

Rafael Advanced Defense Systems / Technion - Israel Institute of Technology, Israel

TBD

Minimum Measured Parameters Required to Develop a Jet Engine Dynamic Model

Dr. Michael Lichtsinder

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Turbojet dynamic model make it possible to evaluate behavior during transient and to design the engine control in a manner to prevent dangerous as compressor stall, turbine over-temperature, rich and wear flameout in the combustor; the engine diagnostics, prognostics; sensor fault detection and prevention. To solve these problems on-line, a sufficiently large number of engine models are required that are capable of performing real-time calculations. For example, a bank of engine models exceeding the sensor number can only be used for the sensor fault detection and isolation. Simple exact empirical engine models built on the basis of experimental data are often used. One of the main questions in this model development is: what is the minimum number of parameters that must be measured to develop an empirical transient algebraic engine model?

The presentation formulates the rule for determining the minimum number of measured parameters required to develop the algebraic dynamic model of jet engine. The main factors in this rule are the following:

a) The engine geometry (variable or constant the nozzle area and/or blade rotation angles);
b) Thermodynamic state of the nozzle (choked or unchoked);
c) Number of the ordinary differential equations in the Virtual Thermodynamic Engine Model Prototype (VTEMP):
    - the motor spool dynamics equations including the rotor moment-of-inertia,
    - the second order transient phenomena equations: volume dynamics, heat soakage, ignition lag.

In the simplest case, a VTEMP with constant geometry is considered, and second-order transients are neglected. A larger number of an engine axes corresponds to a larger number of parameters in the empirical model. Inclusion of the volume dynamics and/or the heat soakage in the VTEMP increases the number of parameters in the empirical model by one respectively.

Examples of algebraic dynamic models, block diagrams for single-spool and two-spool engine DECKs, and dynamic models for control of engine Olympus are given in the presentation.

The method discussed in this presentation can be useful to develop minimal jet engine models for on-line simulations, control, engine diagnostics and sensor fault detection. This method makes it possible to prevent cases where some empirical engine models include an insufficient number of variables, and therefore these models do not accurately represent processes in the entire dynamic range of the engine.

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