יום העיון השמונה עשר
במנועי סילון וטורבינות גז

18th Israeli Symposium on Jet Engines and Gas Turbines

November 28 2019,
Faculty of Aerospace Engineering,
Technion, Haifa, Israel

BOOK OF ABSTRACTS

יום ה', ל' חשון ה'תש"פ, 28/11/2019 אודיטוריום 235, בניין הפקולטה
להנדסת אוירונוטיקה וחלל, טכניון, חיפה.

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בניין הפקולטה להנדסת אוירונוטיקה וחלל, טכניון, חיפה.

מפעל מנועי בית שמש	רפא"ל, הרשות לפתוח אמצעי לחימה	תעשייה אווירית	חיל האוויר ענף הנעה מחלקת מטוסים	ענף הנעה מפא"ת	הפקולטה להנדסת אוירונוטיקה וחלל הטכניון	הטכניון, מכון טכנולוגי לישראל

THE 18TH ISRAELI SYMPOSIUM ON JET ENGINES AND GAS TURBINES

Thursday, November 28 ,2019 (9:00-17:00),

Auditorium (235), Faculty of Aerospace Engineering, Technion, Haifa

This year, as in the previous 17 years, we plan to hold the Israeli Symposium on Jet Engines and Gas Turbines. There is a steady expansion of activities in Israel in jet propulsion. This includes the serial production of small engines, increased electricity generation using gas turbines fueled with Natural Gas (NG) as well as production of engines parts and maintenance work. Many companies and organizations are active in jet propulsion and gas turbine, including: MAFAT (MoD), IAF, Israel Navy, EL-AL, IAI, Bet Shemesh Engines, RAFAEL, TAAS, ORMAT, Israel Electric Corporation, R-Jet & Turbogen, the Technion and more.

Applied research, Improved engineering & technological innovations and new projects in Israel calls for continued professional meetings' for the exchange of information, for cross-pollination and for creating a fertile seedbed for cooperation. During the previous 17 symposia, in every one, more than hundred scientists and propulsion engineers met and presented their work from the various industries, the MoD and Academia. These symposia were a success, wetting the appetite for more such meetings.

The 18th symposium will include few invited lectures on selected subjects (from the US Air Force Research Laboratory and Purdue University) as well as 20 more lectures on large variety of topics, distributed over 6 sessions. The presentations are concerned with activities in different Israeli industrial firms, organizations and academia. A tour to the newly renovated Turbomachinery and Heat Transfer Laboratory will be conducted during the long lunch break.

The first half of the symposia (until lunchtime) will be held in English as well as most of the afternoon presentations.

Please note that the presentation from the 17th symposium can be seen in the following website: *https://jet-engine-lab.technion.ac.il/* . We shall upload the presentations (in full, or as a "censored" version), after the conference on the jet engine laboratory website (see below). Selected presentations will be published as archive publications in the "*INTERNATIONAL JOURNAL OF TURBO & JET ENGINES*"*:(https://www.degruyter.com/view/j/tjj)*

Looking forward for a fruitful and enjoyable symposium!

Professor Emeritus Yeshayahou Levy
Chairman of the symposium
Technion, Faculty of Aerospace Engineering,

e-mail: levyy@technion.ac.il,
http://jet-engine-lab.technion.ac.il

18th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES

TECHNICAL PROGRAM

	18th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES, NOVEMBER 28 2019 Auditorium (room 235), Faculty of Aerospace Building
08:30	(Registration) הרשמה
09:30	Opening: Professor Emeritus Yeshayahou Levy, Chairman, Turbo and Jet Engine Laboratory, Faculty of Aerospace Engineering, Technion.
	Professor Itzchak Frankel, Dean, Faculty of Aerospace Engineering, Technion.
	Major Yigal Ben-Shabat, Head, Propulsion Systems Branch, Aeronautical Division, MOD.
09:50	(Session First) מושב ראשון
	Session Chairman: Lt.Col. Avi Yosfan, Head of Propulsion Branch
A1	Prof. Guillermo Paniagua, Purdue Univ., USA, Turbine Research at Purdue from Innovation to Maturity
A2	Dr. John Clark, Air Force Research Laboratory, USA, Development of Cooled Vanes for the High Impact Technologies Research Turbine
	(and refreshments Break) הפסקה וכיבוד קל
A3	Prof. Levy Yeshayahou, Technion, Conversion of Jet Engine Combustor from Jet Fuel to Natural Gas
A4	Prof. Beni Cukurel, Technion, Development of Ultra-Compact Micro Gas Turbines with 400W Electric Power Output as a Battery Replacement in Drones
A5	Dr. David Lior, RJET & TURBOGEN, Small Recuperated Turbo-Fan conceptual design
13:10 **-** **14:40**	(Lunch) ארוחת צהריים Student Building – Transparent (Glass) Hall and tour at the laboratory

14:40 – 15:40	(Second Session) מושב שני		מושב שלישי (Third Session)		מושב רביעי (Forth Session)
	Auditorium – Room 235		Room 161		Room 241
	Session: Rotor dynamics and Vibrations		Session: Turbomachinery Optimization		Session: Production Technologies
	Session Chairman: Dr. Amiram Leitner, Rafael		Session Chairman: Dr. Shaul Eliahu Niv, IAI		Session Chairman: Ariel Cohen, Bet Shemesh Engines
B1	XU Dong and Yanfeng Zhang, University of Chinese Academy of Sciences, China, Numerical Investigation of Flutter Stability of a High-Speed Transonic Fan	C1	Shachar Balas, RAFAEL, Adjoint-Based CFD Optimization Method Demonstrated on a Test Bench Design	D1	Dr. Bernhard Bringmann, Starrag AG, Switzerland, Blisk Milling - From Component to Machine Design
B2	Afik Lifshitz, Eyal Setter, Shachar Tresser, RAFAEL, Estimation of Jet Engine Rotor Bearings Stiffness by Modal Testing	C2	Dr. Alexander Khrulev and Prof. Sergey Dmitriev, Ukraine, ICE Turbochargers Failures and Some Features of the Study of Their Causes Using the Fault Tree Analysis	D2	Yochanan Nachmana, Bet Shemesh Engine Ltd, Abradable coating in turbomachinery and plasma technology, Performance improvement
B3	Ori Kam, Bet Shemesh Engine Ltd., Spline-Coupling – Effective Stiffness Effect on Rotating System Dynamics	C3	Dvir Mendler, ORMAT, Unusual Challenges in Mixed-Flow Pump Design	D3	Shir Avrahami and Ori Kam, Bet Shemesh Engine Ltd, Single Crystal Casting Simulation
15:40 - 15:55	(Break and refreshments) הפסקה וכיבוד קל				

15:55 **-** **17:15**	(Fifth Session) מושב חמישי		(Sixth Session) מושב שישי
	Session: Control & Diagnostics		Session: Combustion
	Auditorium (room 235)		Room 161
	Session Chairman: Session Chairman: Dr. Amiram Leitner, Rafael		Session Chairman: Dr. Shaul Eliahu Niv, IAI
E1	Roman A. Varbanets, Odessa National Maritime University, Ukraine, Vibro-acoustic Diagnostics of Turbocharger	F1	Nikhil Balasubramanian and Prof. Danny Michaels, TECHNION, Combustion Instability in a Swirl Stabilized Combustor
E2	Shani Eitan, IAF, Measurement of Coating Thermal Properties via Induction Phase Radiometry	F2	Dr. Boris Chudnovsky, Alexander Lazenikov and Ilya Chatskiy, Israel Electric Company, Extended Operation Load Range of Gas Turbines As a Tool for Control Electricity Grid Equipped with Renewable Energy Suppliers.
E3	Giora Brandwine, Elcon Mamab Control Instruments Ltd., Temperature Measurements innovations in the Aerospace Industry	F3	Ariel Cohen, Bet Shemesh Engine Ltd, Lagrangian Simulation of a Slinger Combustor
E4	Dr. Michael Grebstein, RSL Electronics Ltd., Reliable, Comprehensive AI Powered Health Diagnostics and Prognostics of Turbo-Jet Engines and Gas Turbines through Fusion of Hybrid Methodologies	F4	Iker Laso, Natali Rozin, Joël van der Lee, Prof. Joseph Lefkowitz, Technion, A New Tunnel for Ignition Research

תודתנו נתונה לגופים ומוסדות אשר תמכו ביום העיון:
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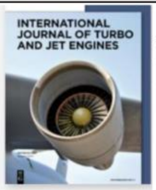
De Gruyter Publishing House	 INTERNATIONAL JOURNAL OF TURBO AND JET ENGINES DE G DE GRUYTER

LIST OF PRESENTERS				
Company	**Contact Person**	**Phone**	**E-mail**	**Web Site**
ATS	Orly Mashat – Marketing Manager Yoni Arieli - Engineering Manager	054-2588228 054-6171348	orlym@ats.co.il yonia@ats.co.il	www.ats.co.il
Colibri Spindles Ltd.	Oren Efrati – Product Manager	054-2326825	efrati@colibrispindles.com	www.colibrispindles.com
Elcon	Tal Dolev – Marketing Director	054-7435372	tal@elcon.co.il	www.elcon.co.il
Ham-let Group	Liat Pasternak – Product Marketing Eng. Benny Kaplan - Product Marketing Manager	052-6676873 054-7516370	Liat@ham-let.com	www.ham-let.com
Matechet Carmel	Shuki Dinman – Marketing Manager	052-2668834	shukid@m-carmel.com	www.matechet-carmel.co.il
Metalicone	Yanir Sharon – VP Marketing & Sales	054-2873615	yanir@Metalicone.com	www.metalicone.com
MotionTech	Ohad Mitrani – CTO	058-6468008	info@motiontech.co.il	www.motiontech.co.il
MRC Lab	Reuven Bookstein – Sales Manager	050-8822225	reuven@mrclab.com	www.mrclab.com
RTA Engineering Ltd.	Ronen Berman - Manager	052-5550955	ronen@rtaeng.com	www.rtaeng.com
Sharon Tuvia (1982) Ltd.	Gadi Lis - Marketing	054-7892263	gadi.l@sharon-tuvia.com	www.sharon-tuvia.com
TurboGen CHP Ltd.	Ori Beck – V.P. of Engineering	052-9216298	ori@turbogenchp.com	www.turbogenchp.com

A1

Turbine Research at Purdue from Innovation to Maturity

Professor Guillermo Paniagua

Mechanical Engineering at Purdue University, USA

In the absence of further measures, carbon dioxide emissions from aviation are estimated to almost triplicate by 2050 compared to current levels. Because similar trends are estimated in energy power generation based on fossil fuels, numerous alternative compact and distributed thermal power systems are explored. This presentation will describe some of the turbine challenges for future thermal turbines, from fundamental challenges such as flow separation in diffusing passages to applied problems such as the mitigation of secondary flows and tip leakage. Hence, aerothermal turbine research in small core turbines is not only essential to maximize the power extraction in thermal engines, but our research advances into flow control as well as in the identification of flow detachment and the unstarting phenomena in transonic passages.

Regarding pressure gain combustion, the harsh flow conditions delivered by the combustor require alternative designs. We will present several strategies we have developed during the past decade for both axial and radial turbines, with subsonic inlet, supersonic inlet. The axial turbines with subsonic inlet, and radial outflow turbines enable the highest efficiency. In parallel we also developed bladeless turbines to harness power from both high subsonic and supersonic flows, even without inlet swirl, allowing for power extraction from harsh environments with minimal maintenance costs.

To further advance thermal efficiency of conventional gas turbines the entire system should be optimized along the trajectory, which requires a global model of the engine. Optimal turbine shapes along the trajectory, which highlights the interconnection between optimization and engine modeling. Multi-objective optimization was performed using differential evolution strategy and Computational Fluid Dynamics software. During the past seven years our group has developed several strategies to optimize the turbine tip geometry, considering clearance variations, to improve the aerodynamic performance and reduce the thermal loads. Our research showed the strong impact of the over-tip coolant flows on the over-tip flow field. More recently we incorporated nature and bio-inspired shapes to redesign turbine airfoils and stator-rotor rim seal cavity. We incorporated wavy structures at the leading and trailing edges as well as the suction side mimicking design features of seal whiskers and tubercles of a whale. The airfoils were optimized to maximize the efficiency of a highly loaded high-pressure turbine at positive incidence.

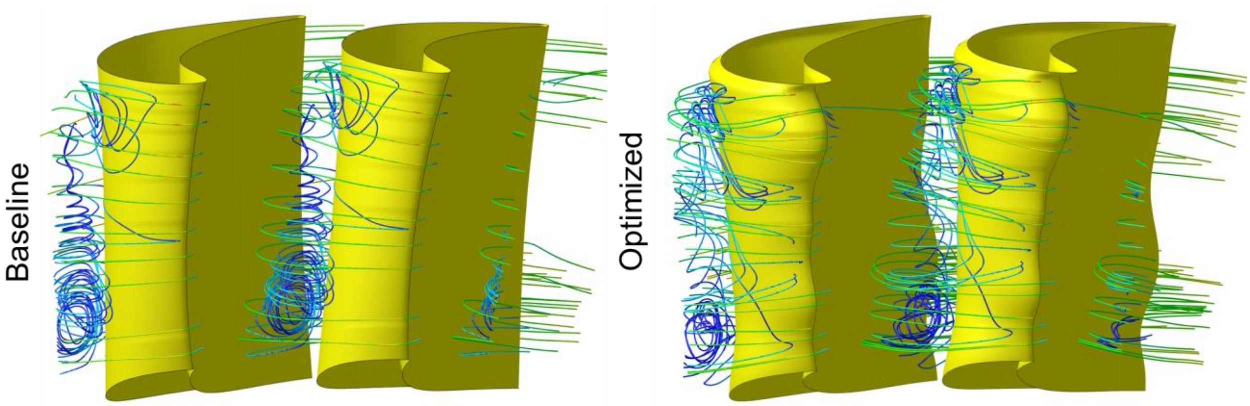


Fig. 1: Turbine optimized geometries

Our team integrates both experimental with computational work, including RANS/URANS solvers, as well as inhouse developed tools to run unsteady Euler simulations, Direct Navier Stokes simulations, and linear stability. Detailed experimental campaigns are performed at the Purdue Experimental Turbine Aerothermal Lab, illustrated in the figure below. This experimental tri sonic facility can operate continuously and also perform transients, suited for precise heat flux, performance, and optical measurement techniques. PETAL owns two aero-thermal modular wind tunnels, with two separate settling chambers and two sonic valves The two different wind tunnels have three different test sections LEAF (Linear Experimental Aerothermal Facility), BRASTA (Big Rig for Aerothermal Stationary Turbine Analysis), STARR (Small Turbine Aerothermal Rotating Rig) to service both fundamental and applied research. LEAF is completely transparent for optical imaging and detailed calibration of both intrusive and optical diagnostics, aimed at technology readiness levels (TRLs) of 1 to 2. BRASTA was designed with multiple optical access to perform proof of concepts as well as validation of turbine component performance for relevant non-dimensional parameters at TRLs of 3 to 4. STARR comprises a two-stage turbine module, specifically designed to ensure accurate efficiency measurements, with a direct drive (no gearbox) high speed AC electric motor, enabling engine representative transient operation. All the test sections can be connected to auxiliary systems which can provide multiple gases including N2, CO2, or dry air, providing injection coolant with a large variability of density ratios and blowing ratios. The test section inlet pressure can vary from 0.5 to 6 bar, while the temperature can vary from 270 to 700 K. Therefore, the resulting Reynolds number (Re) extends from 60,000 to 3,000,000, based on a characteristic length of 0.06 m. The adequate settings of the inlet mass flow and sonic valve position enables a very wide range of inlet Mach number, from Mach 0.1 to Mach 6.5, with mass-flows up to 30 kg/s.

The linear test section was delivered to PU in 2017 and commissioned in 2018. Since then, several experimental campaigns have been performed at subsonic and supersonic conditions. In this linear test section, cantilevered contractions were designed at the exit of the settling chamber to ensure flow homogeneity. A robot (KUKA) is used to change the pitch and yaw angles during the calibration procedure of different probes. Probe measurements can be performed in parallel with pressure sensitive paint, Stereo PIV, and/or molecular tagging velocimetry. The PETAL facility is equipped with femtosecond lasers and the fastest (kHz–MHz) cameras available on the market that will allow a highly-resolved thermo-aerodynamic characterization. The objective is to couple high spatial and temporal resolution diagnostics such as high-speed 3D PIV thin oil skin friction measurements. PU has also demonstrated temperature measurements with up to 100 kHz frequency with accuracies of 1% and resolution of 0.5 mm or better. Advances are being made to enable tracer-based gas-phase temperature imaging in a collaboration with the Department of Energy (USA). These diagnostics and the optical access afforded by the aforementioned facilities will enable unprecedented capability for characterizing performance under unsteady pulsation. In addition to the wind tunnels, the PU team has built and is currently testing a world-unique RDC test facility with full optical access to fuel/oxidizer inlet plenum, combustor, diffuser, and stator vane inlet. Detonations have been achieved with perfect reliability using non-premixed H_2 and air, which avoids any chance of flashback and is ideal for demonstrating the aforementioned combustor-diffuser-turbine integration tasks. Diagnostics thus far include kHz–MHz imaging of flame emission, Schlieren, and coherent anti-Stokes Raman scattering, with PIV molecular tagging also available.

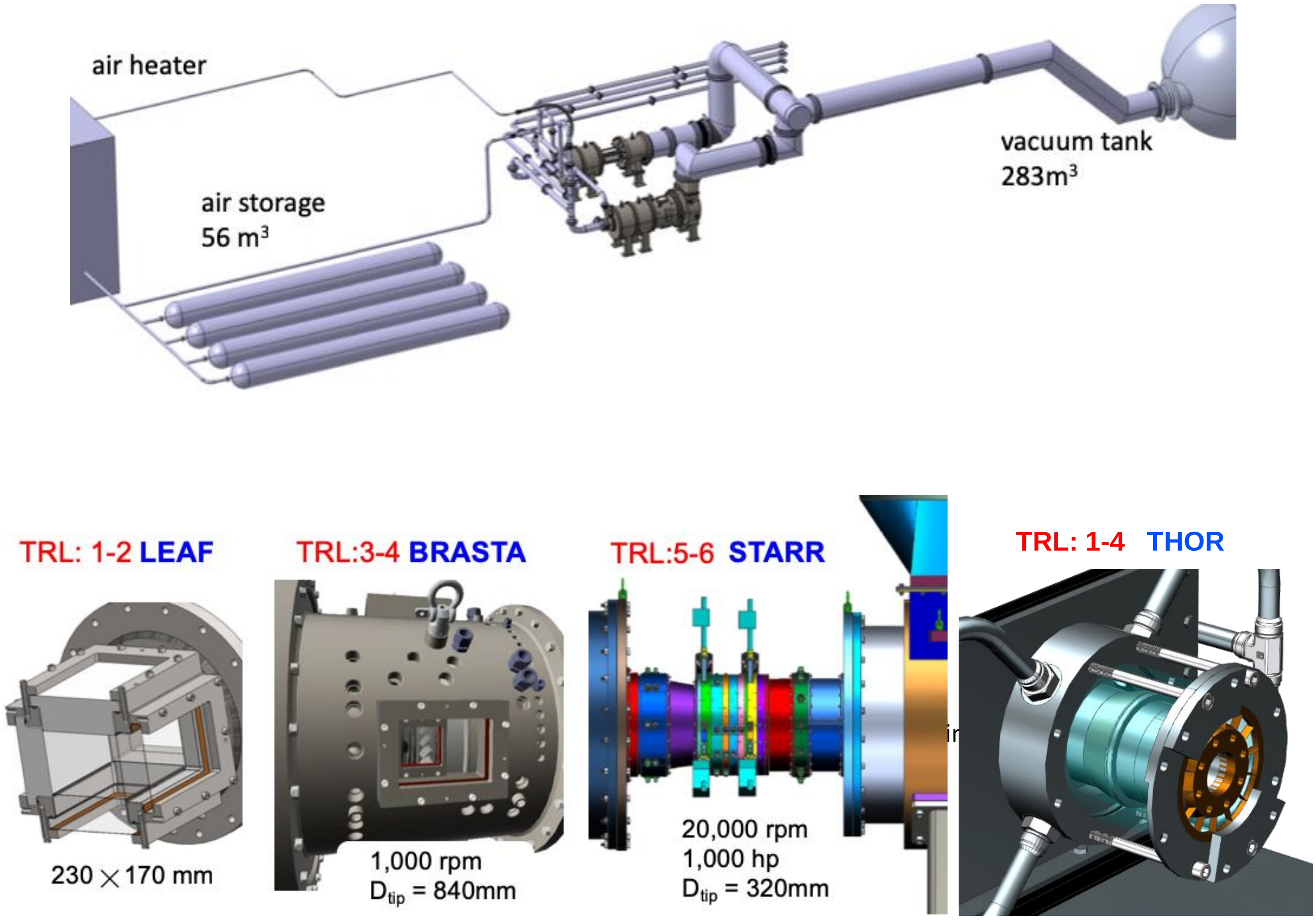


Fig. 2: PETAL wind tunnels for characterization, development of new models and testing optimized designs

A2

Development of Cooled Vanes for the High Impact Technologies Research Turbine

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

For future gas turbine engines, it is desirable both to increase performance and to reduce operating costs. While turbine performance increases are achievable through increases in turbine inlet temperature, this often results in decreased turbine durability. Since designers often rely on an experience- and correlation-based approach, there is a durability margin that is built into the design of turbine components. Consequently, component life estimates can either be over-predicted or under-predicted. If part life is over-predicted, then turbine components are using more than the optimum amount of cooling, and the performance of the overall system is reduced perforce. However, if part life is under-predicted, then the system requires more frequent inspection coupled with possible repairs and/or part replacements. This inevitably results in increased life-cycle costs. Accordingly, it is apparent that advances in component durability for future systems require a decreased reliance on empiricism in the overall design process

Recently, the stage-and-one-half High Impact Technologies (HIT) Research Turbine (See Fig. 1) was developed at the Air Force Research Laboratory (AFRL) in part as an effort to foster improvements in turbine cooling design, analysis, and validation. Initial experiments with the turbine indicated that the fully cooled heat transfer distribution on the upstream vane could be well predicted using Conjugate Heat Transfer (CHT) analysis. So, this gave credence to efforts to improve the cooled performance of a turbine nozzle guide vane using more advanced analysis than the correlation-based methods typically applied in durability design.

Two means to improve the durability of a turbine vane were ultimately investigated and demonstrated. In the first instance, heat transfer analysis was brought into the aerodynamic analysis of a turbine vane in order to reduce the heat load to the part at the same time an efficient aerodynamic design was defined. In the second investigation, the cooling flow to the vane and the vane geometry were both considered fixed, and the distribution of the available flow was altered both to reduce the maximum surface temperature on the vane and to reduce the surface temperature gradients. For both demonstrations, optimization techniques were used in conjunction with Reynolds-Averaged Navier Stokes analysis to achieve the design improvements. Additionally, a number of experimental facilities were used to validate the improved designs, and these were guided by appropriate flowfield simulations at every stage of validation, including Conjugate Heat Transfer analysis. These validation studies included a fully-cooled flat experiment, a transonic cascade in a reflected-shock tunnel, and a full-scale annular cascade in a blow-down facility. Ultimately, the design studies were successful in achieving the targeted improvements. However, it became clear through these efforts that further facility instrumentation improvements are required to enable the discernment of design effects in local areas of the turbine vane.

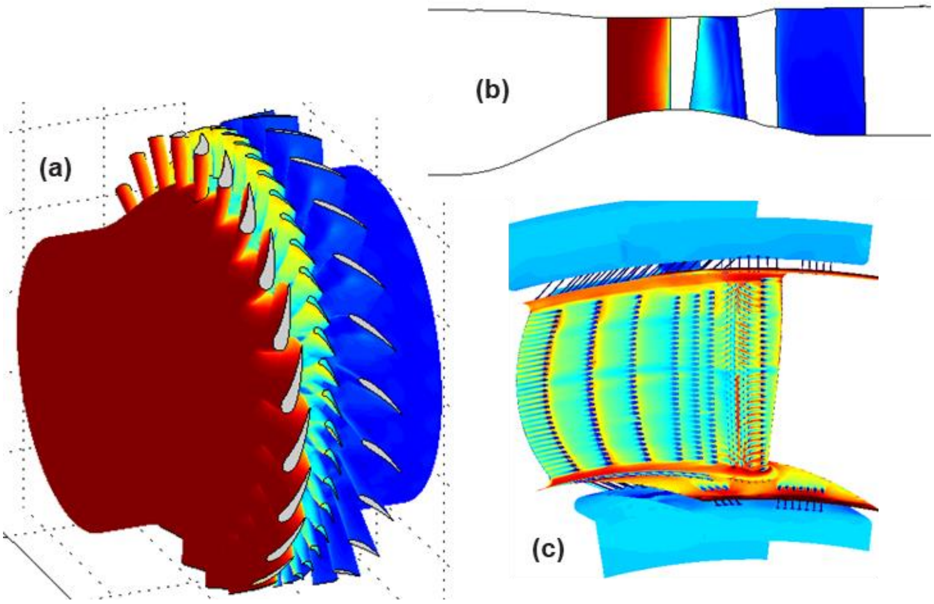


Fig. 1. The AFRL High Impact Technologies (HIT) Research Turbine: (a) oblique view, (b) flowpath, and (c) vane pressure side heat flux from a Conjugate Heat Transfer (CHT) analysis

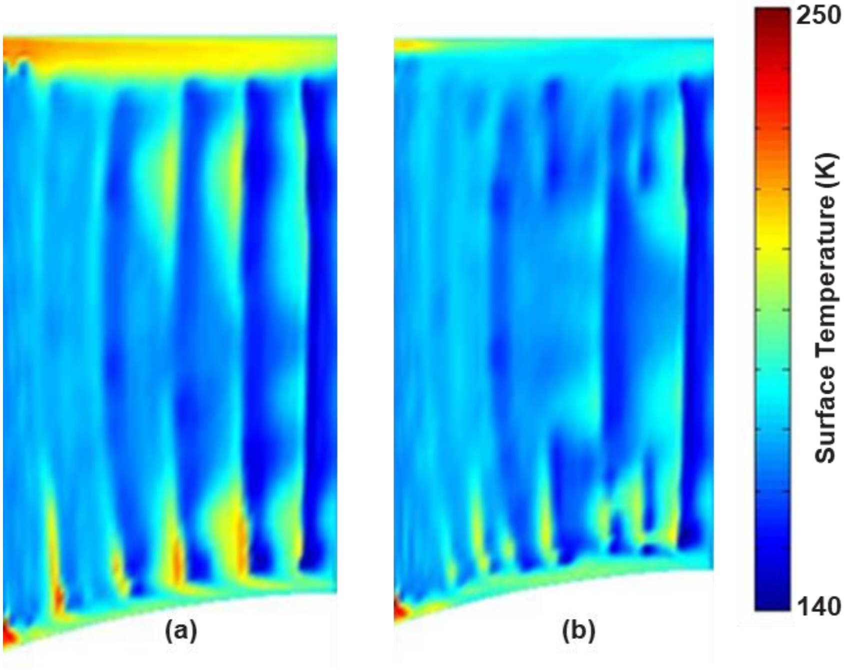


Fig. 2. HIT Research Turbine vane pressure-side surface temperatures with (a) baseline and (b) optimized cooling distributions

A3

Conversion of Jet Engine Combustor from Jet Fuel to Natural Gas.

Levy Yeshayahou, Sherbaum Valery, Zackai Matan, Roizman Alex, Eerenburg Vladimir, Technion, Harari Ofir, Israel Aircraft Industry

Heavy-Duty gas turbines are dominant players in the power-generation market, however, there has been a steady growth in the use of aero-derivative gas turbines for electricity generation. The development of aero-derivative gas turbines has historically been achieved by converting existing aviation jet engines to suit the needs of the customer while working under restrictions imposed by governmental agencies for land-based power generation units. The current study focus on the modifications required for the combustor, to change the fuel from jet (kerosene) fuel to natural Gag (NG, methane). This is further complicated by the need to stick to stringent pollutant emissions restrictions that are imposed on land-based gas turbine power generation units, thus assuring its CO and NOx emissions not to exceed their limiting levels and maintain stable combustion performance. The restrictions imposed on this study enabled to modify only the fuel nozzle without any further modifications in the geometry of the combustor

The work was conducted in four main stages:

1. Numerical simulation of the original combustor, shown in Figure 2, fueled with jet fuel.
2. Design a new fuel nozzle for injecting natural gas and verify through CFD simulations its performance
3. Perform an experimental campaign to validate the results of the numerical simulations. Using kerosene fuel
4. Perform an experimental campaign to validate the results of the numerical simulations. Using the modified fuel nozzle and methane fuel.

Due to the limitations of the available infrastructure at the Jet Engine Laboratory at the Technion, the tests were designed to be perform in a 54º sector of the combustor (with 3 fuel nozzles out of the 20 in the actual combustor) and at atmospheric pressure with limited preheating upstream of the combustor. For the experiments, the air mass flow rate is reduced accordingly to maintain similar air velocities at the entrance to the combustor as in the actual conditions. Following the reduction of the airflow rates, similarly, we reduced the fuel flow rate accordingly to maintain the required fuel to airflow ratio.

Finally, upon a successful comparison between the results of the numerical predictions at atmospheric pressure and the experimental results, one could consider the validity of the CFD to serve as a useful tool for evaluating the combustion performance at real operational conditions.

We performed CFD simulations using the original combustor configuration with kerosene fuel as reference data, furthermore we also performed the simulations with kerosene fuel at atmospheric conditions. Thereafter, we developed a new concept for the fuel nozzle for the methane fuel, for equivalent thermal power, while complying with the geometrical restrictions. We designed several methane fuel nozzle and selected the optimal one through its simulated performance.

The CFD simulations have indicated that the global performance of the combustor, while operating with methane fuel and under steady-state conditions, are at least as good as while operating on kerosene fuel. This includes combustion efficiency, low emissions, and lower wall temperatures. The experiments have demonstrated the ability of the combustor to operate on methane fuel with the newly designed fuel nozzles. The combustion tests also demonstrated the ease of ignition (while using the original igniters) and its stable operation. Additional tests are required to find the global stable operational envelope of the combustor.

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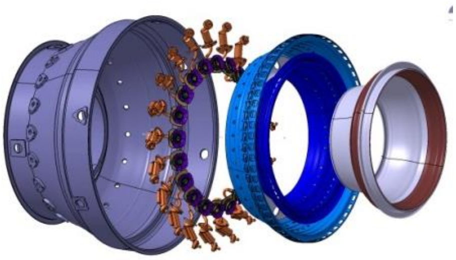
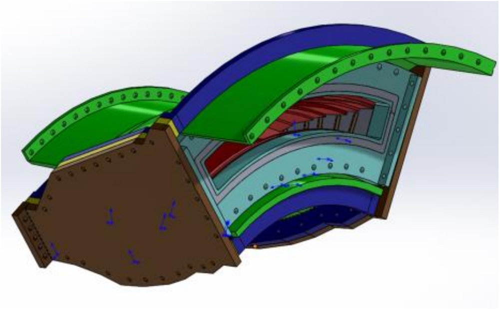
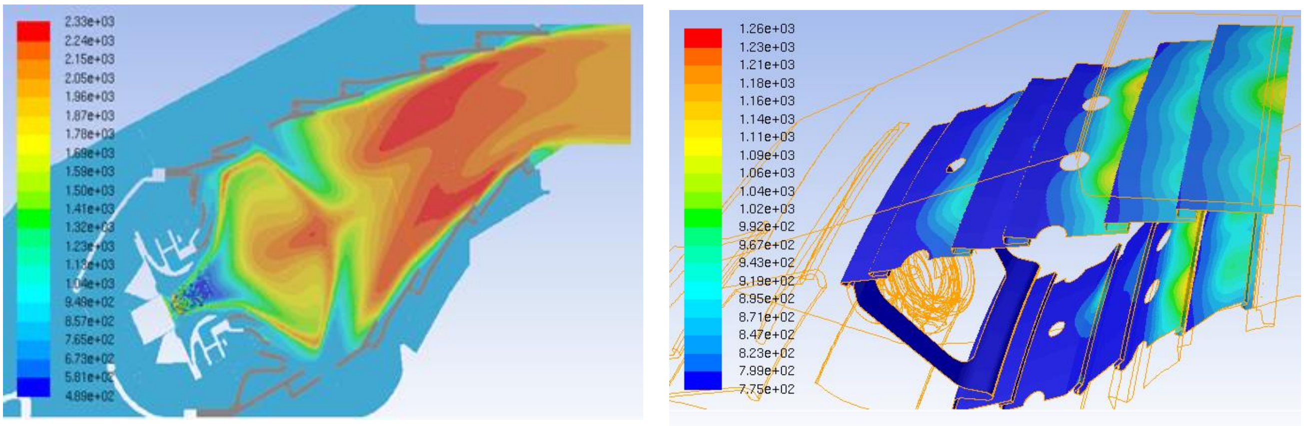




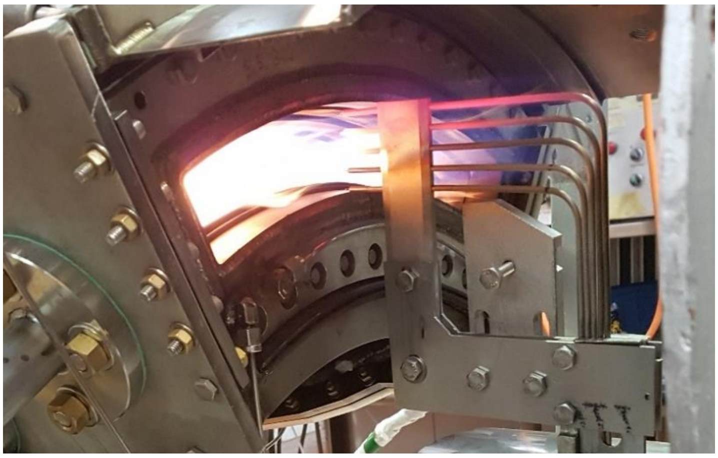
Combustor assembly

Sector for laboratory tests



Temperature distributions across the combustor and its liner walls

Combustor test rig



Combustor operating with kerosene

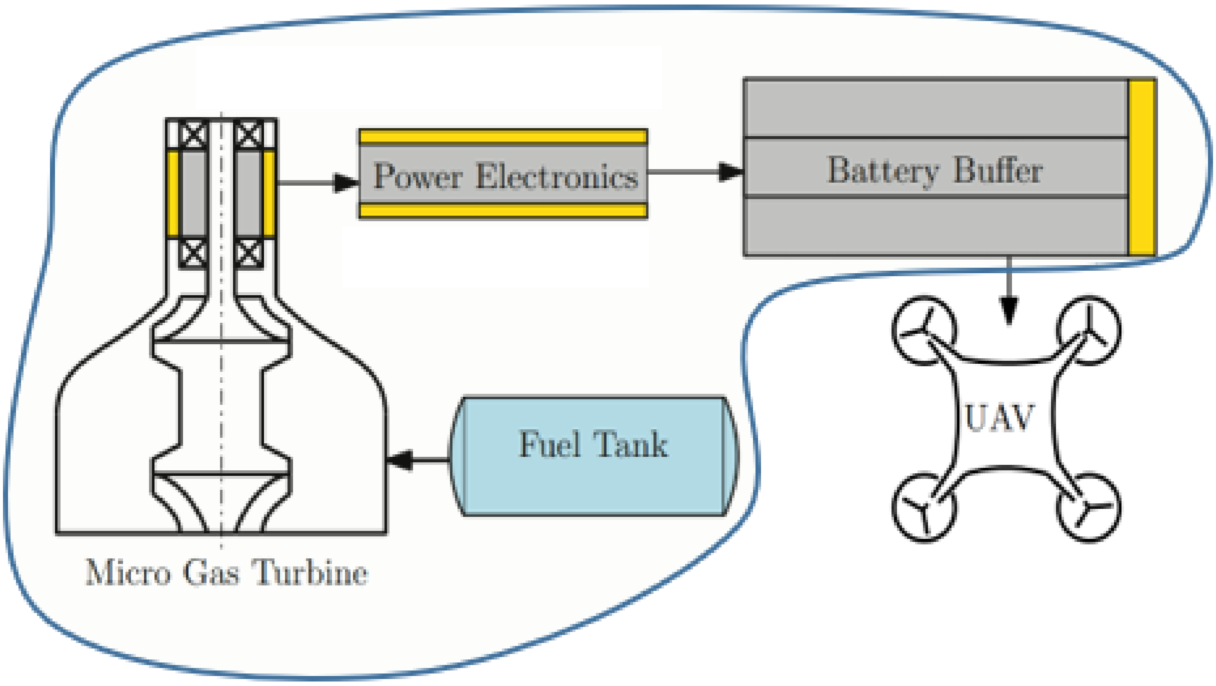
Combustor operating with methane fuel

A4

Development of Ultra - Compact Micro Gas Turbines with 400W Electric Power Output as a Battery Replacement in Drones

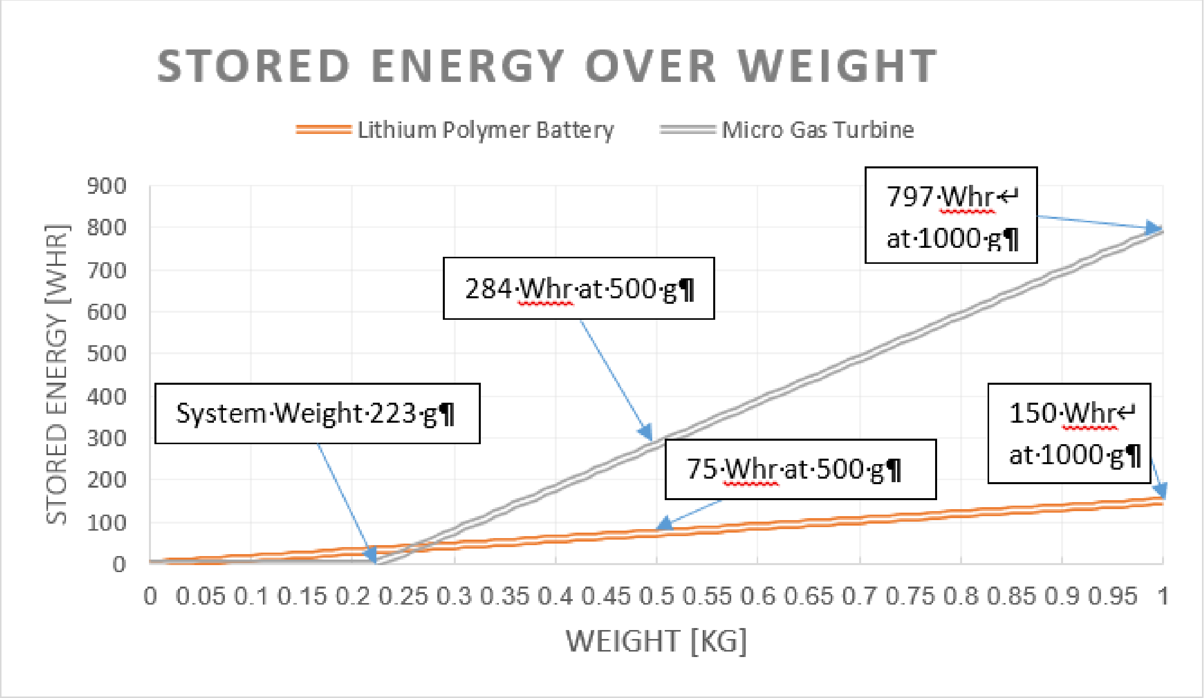
Lukas Badum, Assoc. Prof. Beni Cukurel
Turbomachinery and Heat Transfer Laboratory, Technion - IIT

Micro unmanned aerial vehicles (MAV) flight time is highly dependent on achievable electric energy density. Therefore, the development of a 400W 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, this effort 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 is established to evaluate multiple engine configurations, leading to a highly redundant development process that will result in a multi-parameter optimized UMGT prototype.



Hybrid UAV Power Supply System

This research focuses on a hybrid energy supply system that converts the chemical energy of kerosene into electric power output that is then stored in a battery buffer. This electric energy is then transferred to the UAV system. For small UAVs, the electric energy can be directly used for thrust by electric motors. For larger UAVs that already are equipped with piston engines or gas turbines to provide thrust, the proposed generator system serves to supply the on-board systems with sufficient electric power. The battery buffer together with the power electronic system allows the gas turbine to operate always at optimum system speed and efficiency. The main advantage of this system in comparison with Lithium-Ion batteries is its high energy density. The factor of energy density depends on the overall system mass. If a system mass of 500 g including fuel is chosen, the energy density of Lithium Ion batteries is outperformed by factor 3.8. For a 1000 g system, the enhancement factor is 5.3.



Stored Energy Progression

Research on UMGTs started in the 90-ies and was conducted by different research groups. Short overview of the most important research projects in the field of UMGTs is summarized in the table:

Research Group	Approach	Bearings Type	Power Output [W]	Design Speed [krpm]	Reached Speed [krpm]	Reasons for Failure
MIT 1995-2006	Silicon Lithography (2D)	Aerodynamic/Aero-static	60	2400	15 (0.6%)	Manufacturing, heat transfer, cycle efficiency, bearings
Tohoku 2001-2007	CNC Milling (3D, Inconel)	Hydro-Inertia	130	870	360 (41%)	Bearing instability
Leuven 2003-2008	CNC Milling & EDM (3D, Ti-Alloy, Silicon Nitride)	Aero-dynamic/ Aero-static	1000	500	261 (52%)	Bearing instability and rotor-dynamics
Stanford 2003	Ceramic Gel Casting (3D)	Ball Bearings	200	800	420 (53%)	Rotor-dynamics
KIMM 2011-2013	CNC Milling (3D, Inconel)	Air Foil Bearings	500	400	280 (70%)	Unbalance response
Xi'an 2010-2017	CNC Milling (2D)	Air Foil Bearings	50	930	360 (39%)	Bearing instability, manufacturing

Review of Different UMGT Research Projects

A5

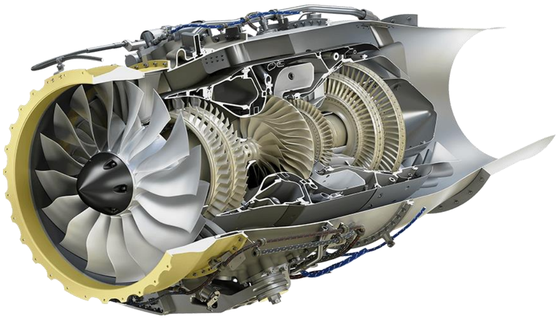
Small Recuperated Turbo-Fan conceptual design

David Lior

RJET & TURBOGEN

Turbofans are the most efficient engines used for most of military and commercial aviation. High by-pass ratio is applied to decrease fuel consumption but still most of the fuel energy is lost in the hot exhaust flow.(fig.1 shows such a turbofan recently introduced in business aircraft) .

In recent aero-engine core concept development, heat exchangers have been seriously considered as a key technology for higher energy efficiency, particularly in the form of intercooler and recuperator components. Low overall pressure ratio (OPR) turbofans can benefit from the use of recuperators, by recovering waste heat from the exhaust gas, and intercoolers provide a way to significant high OPRs. Furthermore, the studies of the combination of both techniques have showed persistent advantages of thermal efficiency for a wide OPR range.



B.P.R	**2.9**
O.P.R.	24
Thrust	9.1 KN at S.L
Weight	211 Kg

Fig.1-GE HONDA Turbofan –none recuperated

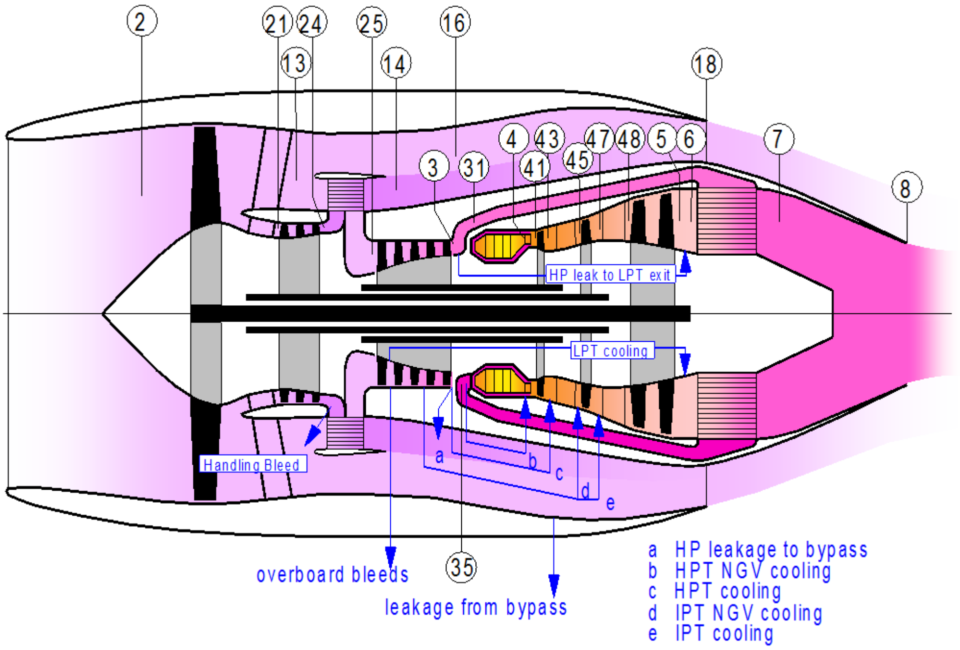


Fig 2- Recuperated Turbofan concept

Recuperated Turbofan aero engines design has been evaluated by IRA European program in 2005-2016 .Several recuperator designs have been presented in which the recuperator is placed in the engine exhaust flow heating the compressor exit air flow thus reducing fuel consumption (fig.2,3). The recuperator is justified if the reduced fuel consumption is higher than its added weight.

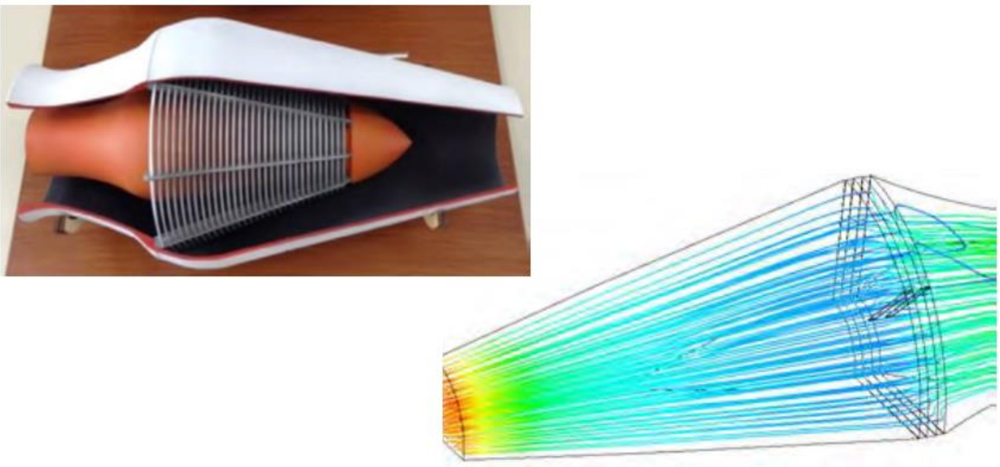


FIG.3-Conic Recuperator design

Further investigation of the recuperated fan engine cycle reveals that the overall engine pressure ratio (currently between 30-50 in modern engines) may be reduced to lower values (between 6-15) when installing the recuperator, while keeping the same fuel consumption. (FIG.4)

The low Overall core Pressure Ratio (OPR) reduces the engine weight and cost. These low OPR recuperated engines have thus a potential to improve aircraft performance and cost. The main engineering challenge is reducing the recuperator system weight while achieving a high effectiveness.

A preliminary recuperated small turbofan design is presented (see fig 5) in which the recuperator design is optimized for high altitude of 12000m and a Mach No. of 0.8. The recuperator is split into 2 heat exchangers one at the exhaust and the second at combustor inletת, both connected by a none evaporated fluid flow transferring heat energy between them. This design results in low gas turbine weight and TSFC for small O.P.R turbofans.

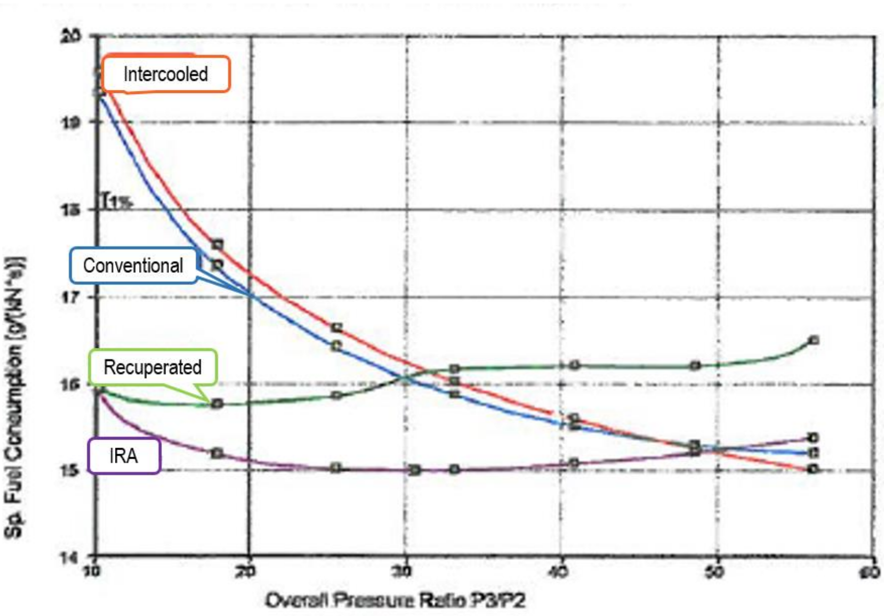


Fig 4: T.S.F.C As function of O.P.R
Alt 12000m Mach0.8

Design results at 12000 m

Thrust -0.66KN
Fuel flow-10.1 gr/sec {without recuperator 16.6 gr/sec}
Fuel weight gain per hour=19.8 kg/hr.
T.S.F.C-15.3gr/KN*s
Spool speed-69000 rpm
Fan spool speed-23000 rpm
B.P.R-6
O.P.R-7.5
TURBINE INLET temp-1334k
Recuperator weight-steel-40kg
Engine weight-35kg
Total weight-75 kg
Conclusion:
Recuperator is beneficial after 2 hours of flight.
It will save 200 kg of fuel after 12 hours of flight.

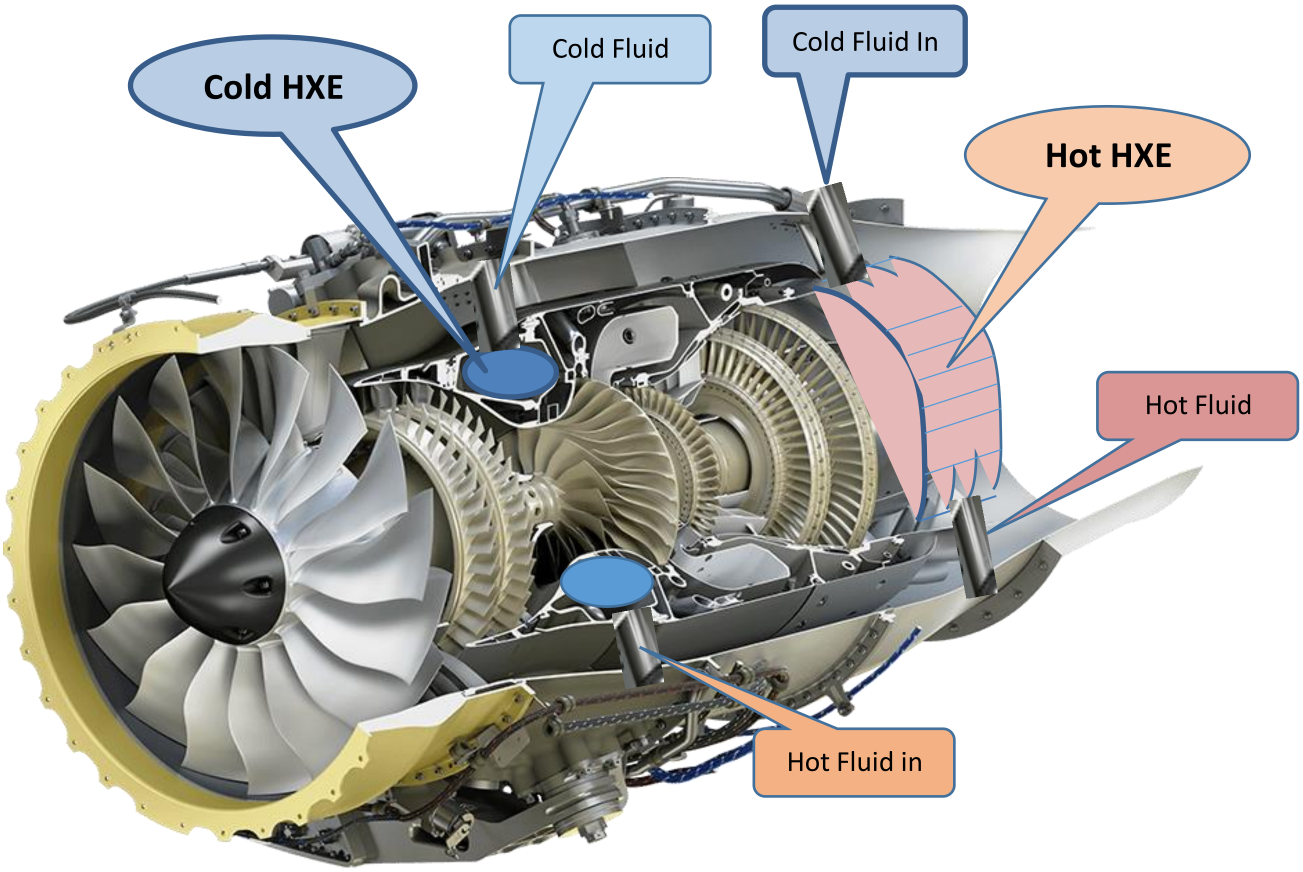


Fig 5: Split Recuperator Design

B1

Numerical Investigation of Flutter Stability of a High-Speed Transonic Fan

Xu Dong and Yanfeng Zhang
Institute of Engineering Thermophysics, Chinese Academy of Sciences
University of Chinese Academy of Sciences

Modern fan and compressor designs are moving toward higher pressure ratio, better aerodynamic performance and lighter weight, which enhance the interaction between the blade and the surrounding fluid and increase the risk of aeroelastic instability, such as flutter. Flutter is a self-excited aeroelastic instability phenomenon and the unsteady aerodynamic pressure acting on the blade surface is derived from the motion of the blade itself. Flutter can cause material fatigue even blade failure in a short time. Therefore, it is very important to predict the flutter stability of the compression system.

In this presentation, the first bending mode flutter behavior of a high-speed transonic fan under different operating points at 100% rotation speed are analyzed by a unidirectional Fluid-Structural Simulation (FSI) method, the energy method. To model the traveling wave propagation during flutter, two different methods are used in this work: the traveling wave method(TWM)and the influence coefficient method (ICM). The former method direct simulates traveling wave that all blades oscillate with a certain phase angle, which means various numbers of passages are needed to simulated different IBPA, so as to make the flows in the computational domain show periodic changes (the traveling wave). The influence coefficient method means only one blade (the reference blade) need to oscillate with several passages, and the unsteady pressure and aerodynamic damping on the blade surface at different IBPA are calculated according to the superposition principle.

In order to find a computational domain that saves simulation time as much as possible and get a reliable result. Different computational domains with various blade passages were compared when using the influence coefficient method. Fig. 1 shows that the results obtained by 9 passages computational domain is more consistent with that by TWM. However, if we just want to determine the most unstable IBPA, the five passages computational domain can meet the requirements, which can save nearly half of the computing resources.

The distribution of aerodynamic damping is closely related to the flow structure near the blade surface. At the near stall point, separation caused by the interaction of shock wave and boundary layer exists in area above 50% span on the suction side, which corresponds to negative aerodynamic damping when IBPA=0, which is presented in Fig. 2, that is, the flutter stability of the blade is reduced. On the other hand, the shock wave vibration on the blade suction side causes high pressure fluctuation and produces positive aerodynamic damping region. It should be noted that with the change of IBPA, the effect of the shock wave and separation on flutter stability also be changed.

Another area with a high aerodynamic damping value is the suction side where near the tip and leading edge and over 85%-100% span. The unsteady pressure here is caused by the change of passage area in response to blade motion, which is also different from the shock wave and separation. No matter how the IBPA changes, the aerodynamic damping value in this region is positive.

Understanding the influence of flow structure on aerodynamic damping on blade surface can provide an idea of active flutter control, like bleed, and at the design stage, take the “flutter free” into consideration.

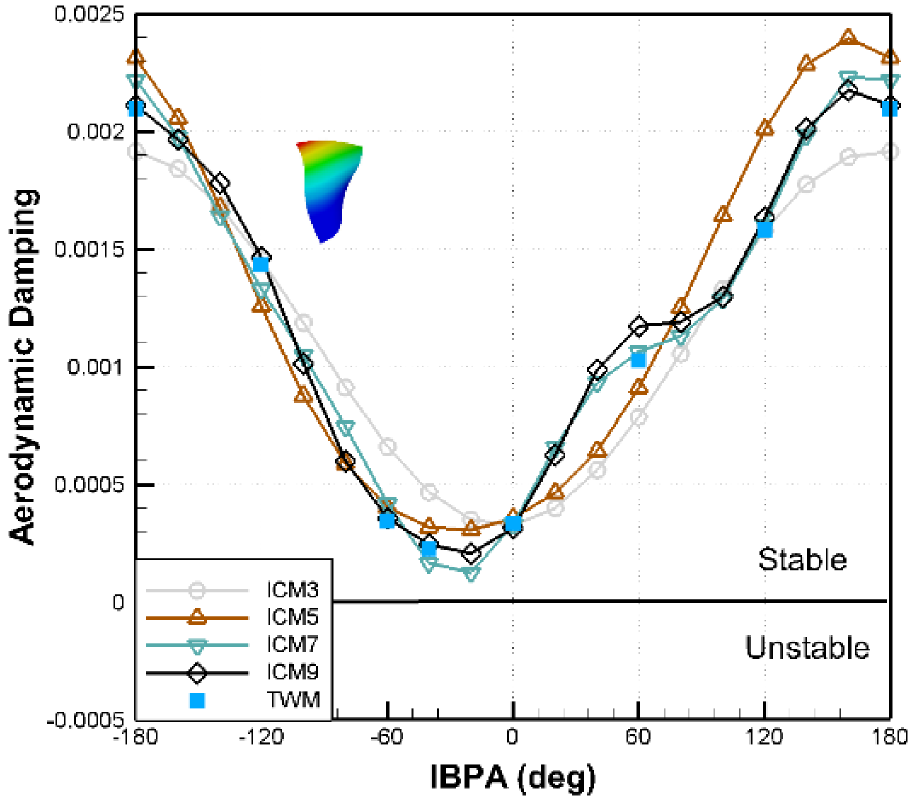


Fig. 1Aerodynamic damping obtained by TWM and ICM

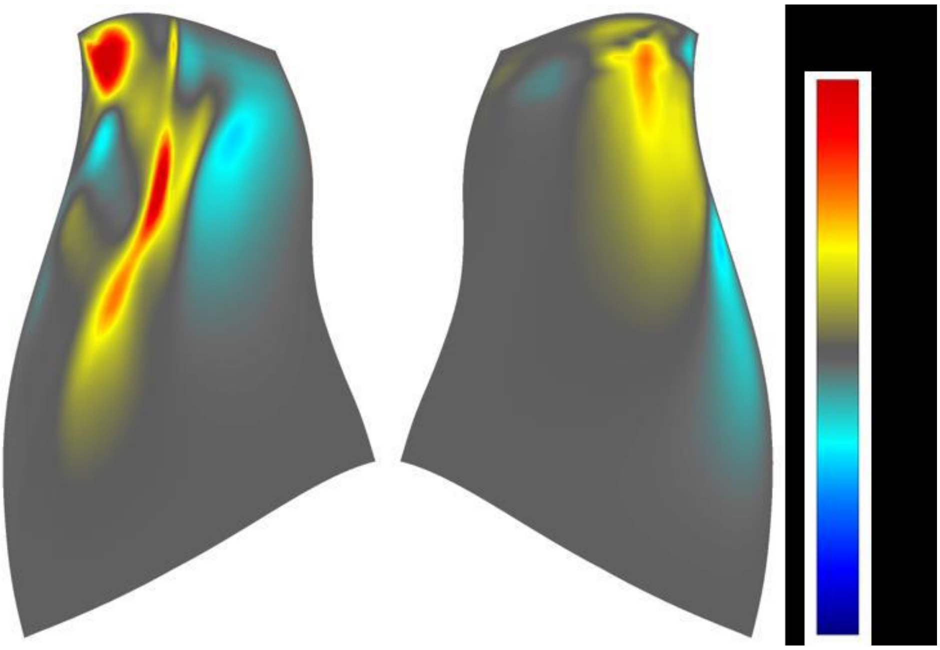


Fig.2 Aerodynamic damping distribution at near stall point, IBPA=0, the left on is SS

B2

Estimation of Jet Engine Rotor Bearings Stiffness by Modal Testing

Afik Lifshitz, Eyal Setter, Shachar Tresser,
Rafael

A proper rotor-dynamical design of the rotor in jet engines, while avoiding critical speeds within the range of operation, is necessary to protect the structural integrity of the engine and the long-term smoothness of its operation. The radial stiffness of bearings has a crucial influence on the dynamical behavior of the rotor, in particular on their natural frequencies and mode shapes. Poor estimation of the bearings stiffness may lead to critical speeds within the working speed range of the machine, which may induce strong vibration levels causing damage to the system.

In general, a precise estimation of the bearing stiffness takes into account parameters such as the axial load, radial load, speed of rotation etc. The stiffness of angular contact bearings, which often finds use in small jet engines, is significantly influenced by the axial preload, which sets the angle of the force acting between the balls and the race of the bearing.

This work presents a method to estimate the radial stiffness of angular contact bearings and the influence of the axial load on their radial stiffness. The method is based on experimental modal analysis of a shaft supported by two identical bearings, which are axially loaded by a controlled force. By extracting the Eigen frequencies of the system for different loading values, and comparing the results to finite element analysis, it is possible to get the relation between axial load and the radial stiffness of the bearings. Numeric and experimental results received during study are shown in Figure 1.

תכנון רוטור-דינמי נכון של הרוטור הסובב במנועי סילון תוך הימנעות ממהירויות קריטיות בתחום העבודה ,הכרחי לשמירה על שלמות המנוע ותפקודו התקין לאורך זמן. לקשיחות הרדיאלית של מיסבים קיימת השפעה מכרעת על הדינמיקה של גופים סובבים ובפרט על התדרים העצמיים ואופני התנודה שלהם. הערכה שגויה של הקשיחות עלולה להביא להתעוררות מהירויות קריטיות בקרבת מהירות העבודה ולנזק למנוע ו/או לפלטפורמה.

באופן כללי ,הערכה מדויקת של קשיחות המיסבים לוקחת בחשבון מספר גורמי השפעה אפשריים: עומס צירי על המיסב , עומס רדיאלי ,מהירות הסיבוב ועוד. במיסבי angular contact, המשמשים רבות במנועי סילון זעירים, יש השפעה גדולה במיוחד לעומס הצירי אשר מכתיב את זווית הכוח בין הכדורים למסילה.

בעבודה זו מתוארת שיטה להערכת הקשיחות הרדיאלית של מיסבי angular contact ולמידה בה היא מושפעת מהעומס הצירי הפועל במיסב. השיטה מבוססת על אנליזה מודלית ניסויית ,המתבצעת על גל הנתמך בשני מיסבי angular contactונתון לעומס צירי מבוקר. חילוץ התדרים העצמיים של המערכת עבור עומסים שונים ,והשוואת התוצאות לאנליזות אלמנטים סופיים ,מאפשרים לקבל קשר בין העומס הצירי לקשיחות הרדיאלית של המיסבים.

תוצאות סימולציות וניסויים שבוצעו לאורך הפעילות מופיעות באיור 1 להלן.

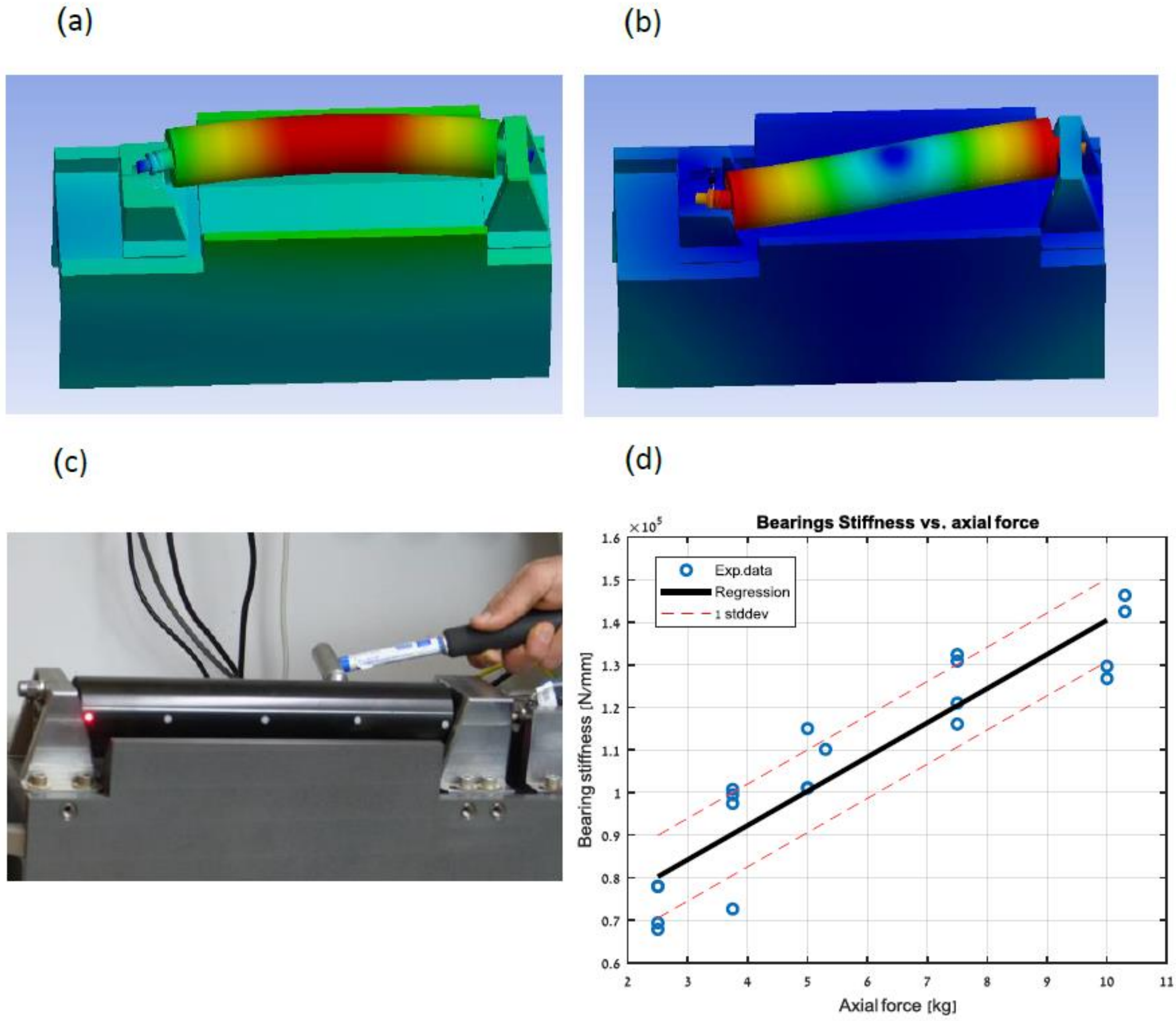


Figure 1: Results of bearings stiffness estimation work

(a),(b) Simulative results for mode shapes of the system;

(c) Experimental system during modal analysis; (d) Resultant bearing stiffness vs. axial preload

B3

Spline-Coupling – Effective Stiffness Effect on Rotating System Dynamics

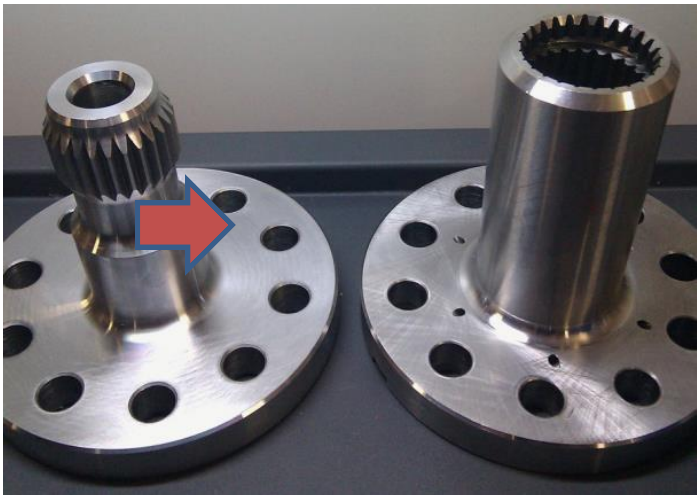
Ori Kam – Bet Shemesh Engines Ltd

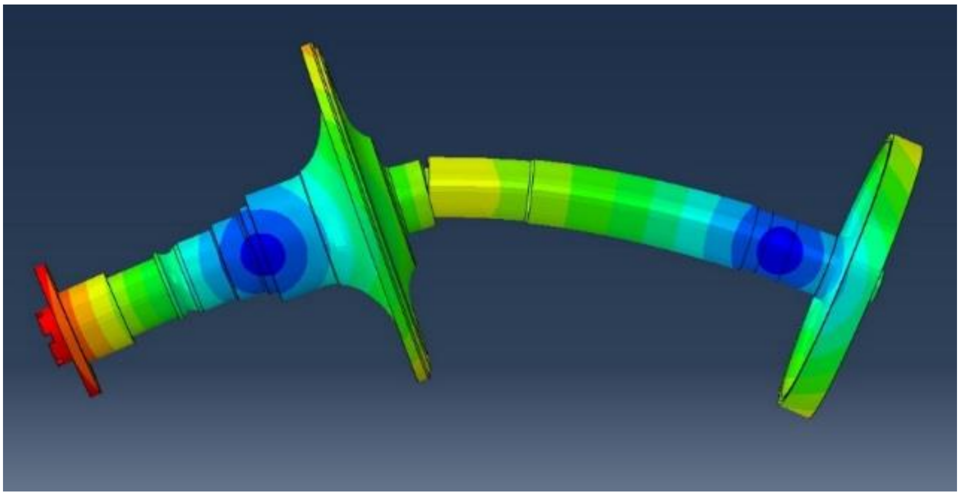
For the purposes of rotordynamic analyses, the spline-coupling is often assumed to be a rigid connector but the accuracy of this assumption depends on the mechanical parameters of the system. The influence of torque on the spline-coupling stiffness is widely treated in the literature.

It can be concluded that for large torques, the spline-coupling stiffnesses approach those of rigid connectors. On the other hand, the splines stiffnesses - in all its DOFs – are found to be highly sensitive and influential when loaded by small torque forces. The latter circumstance is of relevance to small and medium sized jet engines.

As such, the effective spline's stiffnesses should be considered while choosing an appropriate connector during small jet engine shaft design and in performing rotordynamic analyses of the latter. Furthermore, in order to achieve accurate results, finite-element calculations of the effective stiffness values must be performed.

The feasibility of a spline coupling connector integration in the BS175A rotor was investigated through rotordynamic calculations. An extrapolation of the published data for spline stiffnesses VS torque was used to address the BS175A loads. Modal simulation of the whole rotor was performed under a range of spline stiffnesses in all of its DOFs. Comparison with the current rigid connector yielded significant deviations from the rotor's natural frequencies.





C1

Adjoint-based CFD Optimization Method Demonstrated on a Test Bench Design

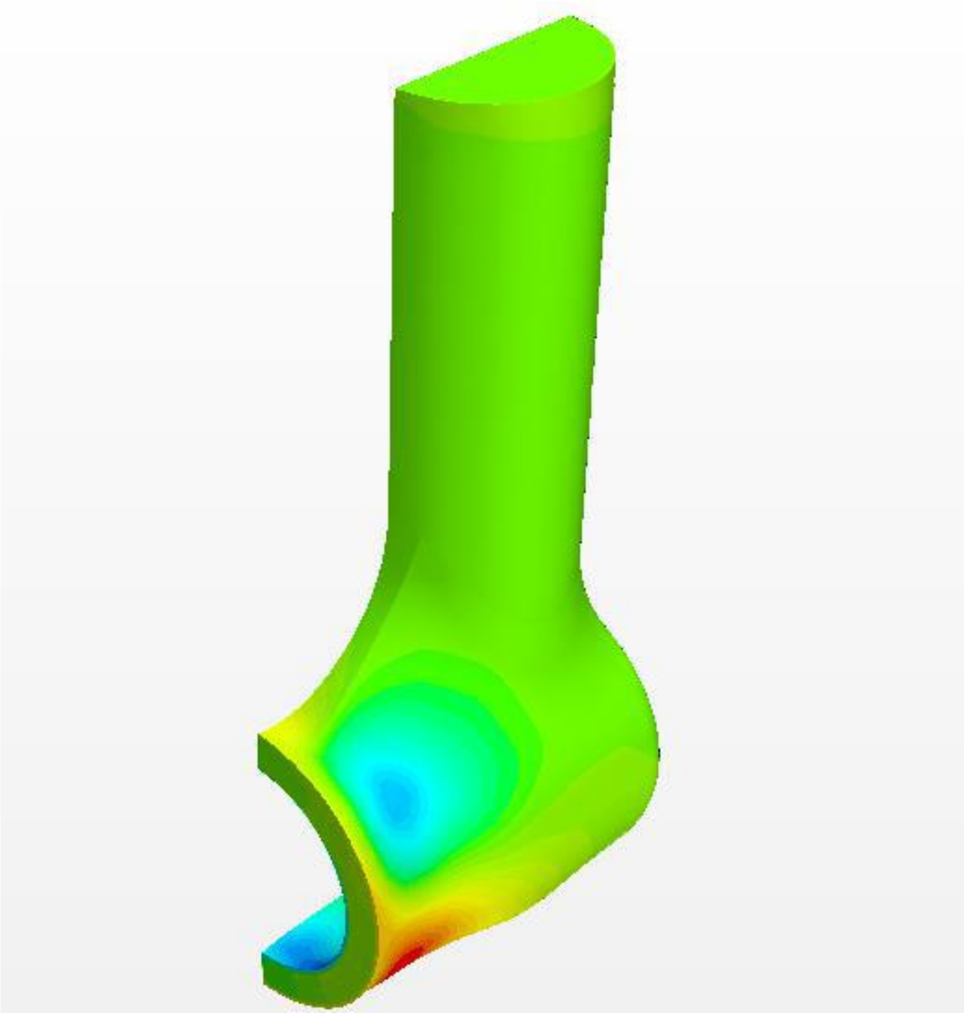
Balas S.,
Rafael Advanced Defense Systems

Optimization is an increasing subject of interest as computing capabilities increase. The motivation for optimization is clear since it can reduce time and costs of the design processes, maximize the performance and enhance innovation.

There are several methods used for optimizations; each has its advantages and disadvantages, and each is suitable for a different kind of problem. Therefore, one should wisely choose the appropriate method. In the case of an aerodynamic local shape optimization, the gradient method is found to be suitable and obtaining the gradients becomes a challenge.

The adjoint method enables obtaining the gradients of the mesh deformation, with respect to the cost function defined by the designer, in a relatively quick procedure.

The presentation demonstrates how to use the gradient method for optimization of a test bench part design and to how to calculate the gradients using the adjoint method.



C2

ICE Turbochargers Failures and Some Features of the Study of Their Causes Using the Fault Tree Analysis

Alexander Khrulev and Sergey Dmitriev
Aerospace Institute, National Aviation University
Kyiv, Ukraine

Despite significant advances in research and design of turbochargers for internal combustion engines, there is a large number of them failing in operation, the failures being caused both by operation and by errors in engine maintenance, and occasionally by manufacturing defects.

As the studies show, there are few sources that contain data on determining the causes of faults in turbochargers, and the information in them is not always helpful to the consumer. Existing methods for identifying the causes of faults give dozens of possible causes, as a result of which their use in practice requires so much laboriousness that it is actually inefficient - in a large amount of cases, in operation, consumers find it difficult to determine the cause of failures and therefore prefer to simply replace the turbocharger with a new one. However, this approach often leads to the repeated failure if the cause of it was not related to the turbocharger itself, but was triggered by external causes, for example, a malfunction of the engine and its systems. As a result, the cost of repairing a vehicle significantly increases, sometimes even multiplies, and this problem becomes more and more acute as turbocharging becomes more widespread in engines of various vehicles, and its complexity and costs are increasing.

On the other hand, when assessing the reliability of aggregates, logical-probabilistic models are widely used, describing the causal relationships of failures of the entire system with failures of individual elements and other events (impacts), including the well-known method of the fault tree analysis (FTA). However, this method, which is used in practice for calculating probabilistic characteristics and risks of failures, does not quite correspond to the problems of finding the causes of the faults.

In the present study, an attempt has been made to develop a relatively simple logical method for determining the causes of failures of turbochargers, relying on existing experience in their operation and maintenance, on the one hand, and on the fault tree analysis, on the other. For this purpose the turbocharger was presented as a simple unit that consists of four blocks (fig.1) with the links between them and the engine.

In this case the determination of the cause of the turbocharger failure can be made based on the analysis of the modified (reversed) fault tree, which allows the analysis to be performed in the direction opposite to the generally accepted direction - from the failure of the system up to the basic events that initiate the failures in its individual elements (fig.2).

Verification of the proposed method built on the specified principles using the experience of the studying faults of turbochargers in the real cases of failures showed that determining the cause of failure can be done with sufficient accuracy for practice as well as minimal time consumption.

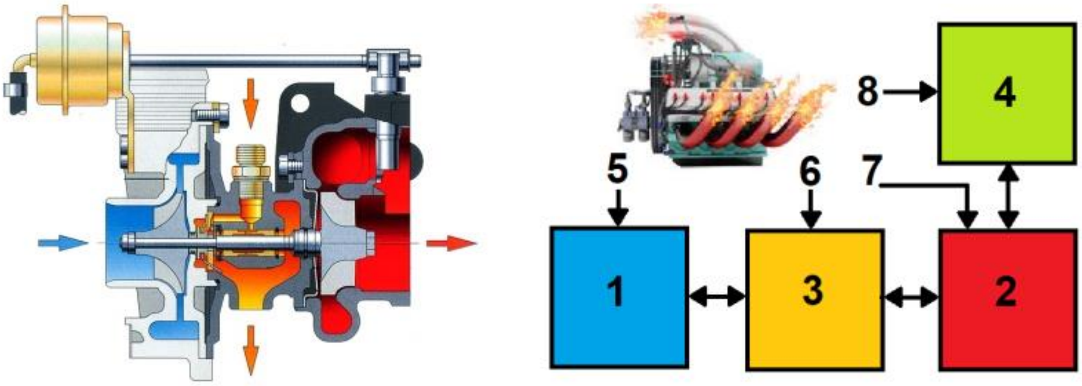
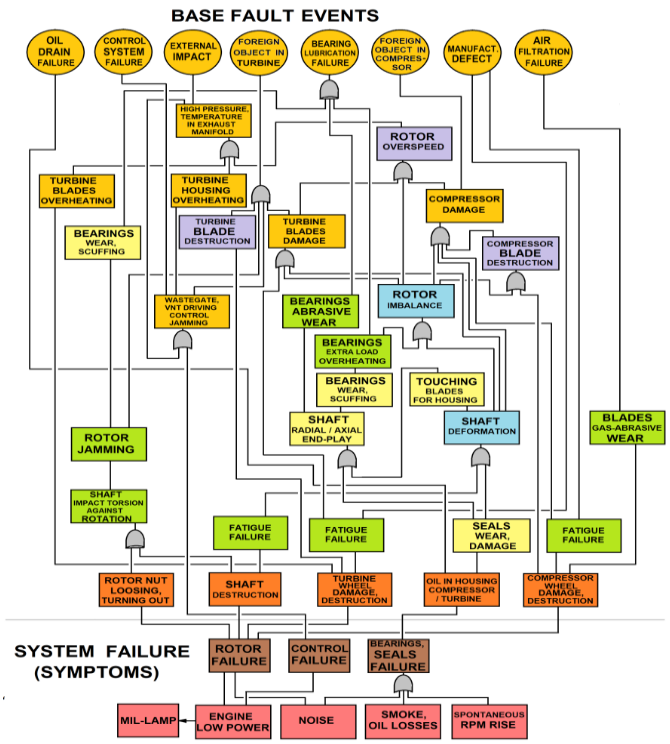


Fig.1. Turbocharger (left) and its block diagram (right):

1- compressor, 2- turbine, 3- bearing unit, 4- control system (Wastegate valve, variable nozzle turbine or other, with driving mechanism and control unit), external impacts on the turbocharger (from the internal combustion engine), including: 5- intake system of ICE, 6- ICE oil system and crankcase, 7- ICE cylinder and exhaust manifold, 8- engine control system.



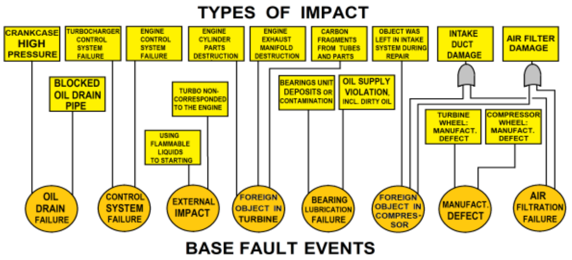


Fig.2. A general view of modified (reversed) fault tree of turbocharger presented as a diagram with the links between basic events causing failures and fault symptoms (left). On the right - the diagram with the link between basic events and types of impact as causes of failures.

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C3
Unusual Challenges in Mixed-Flow Pumps Design

Dvir Mendler,

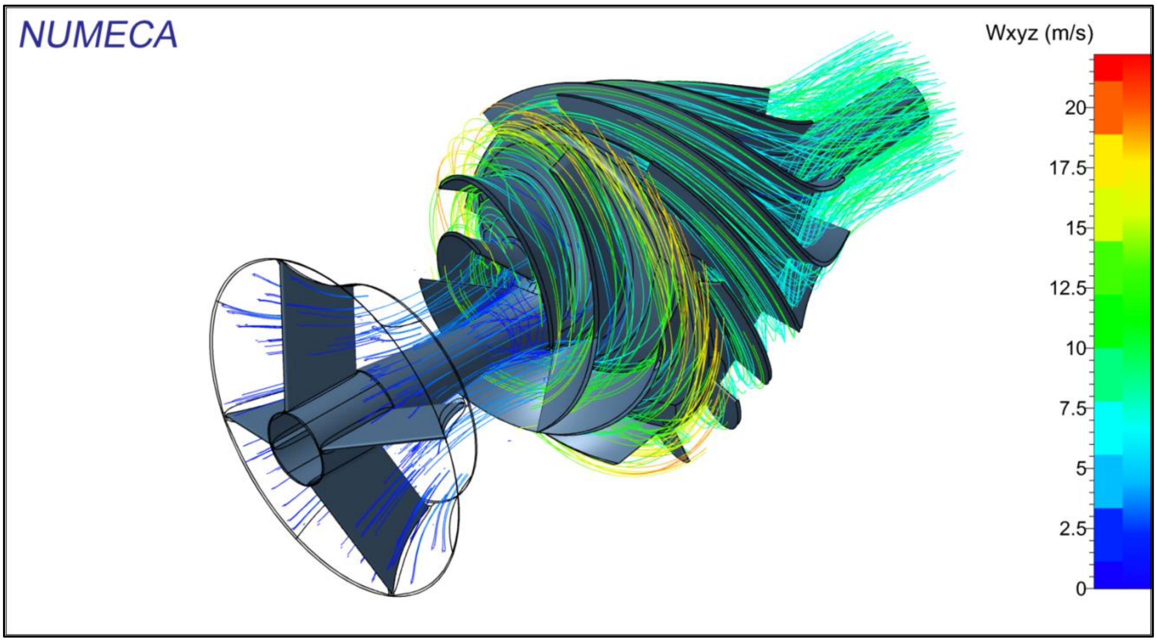
ORMAT

Ormat uses different kinds of pumps for its ORC geothermal power plants. In this study two kinds of pumps will be addressed. Production pumps, which elevate hot geothermal fluid (brine) from deep wells to the surface. And cycle pumps, which rise the pressure of the organic motive fluid. Both kinds of pumps are mixed-flow pumps, and each has its own design challenges. Pump lifetime has crucial importance, especially for a production pump, since each failure leads to a large loss of income. Flow field design issues that directly affect pump lifetime and reliability were investigated using CFD and are presented in this study.

A failure of a deep well production pump, after respectively a short period of time, was linked to hydro-abrasive wear due to sand particles in the geothermal fluid. In order to increase the lifetime of the replacement pump, a flow field research was conducted using CFD. Two pump models were compared for the specific operating point, and potential concerns regarding the flow field were examined. Considering the flow field investigation, a different kind of pump model was chosen. The chosen pump passed the running time of its previous and it is still running.

Hot fluid of up to 200 C and well depths of up to 700 m make the installation and startup of production pumps difficult. Hot fluid temperature causes transient thermal expansion, while high head causes high axial thrust force. Low axial thrust has high priority in the design of new production pumps. Different parameters that impact axial thrust were examined using CFD and compared to tests. Results from the study contributed to the reduction of axial thrust of new designs.

Saturated fluid that leaves the condenser enters the cycle pump and might cause cavitation. In order to design first stage with low NPSHr, CFD is implemented in the design process. A CFD analysis using "Numeca- Fine/Turbo" cavitation feature for a suction bell and an impeller was compared to data sheet and presented in this study.



D1

Blisk Milling – From Components to Machine Design

Dr. Bernhard Bringmann, Richard Bacon, Bernhard Güntert,

Starrag AG

From a manufacturer's perspective, the machining of Blisks is posing a significant challenge. Current developments are leading to more difficult geometries (e. g. leading edges of blades with elliptical forms, higher complexity in blade shapes, thinner blades and limited accessibility between blades), higher requirements for surface finish to avoid any manual polishing process, more difficult to cut materials due to the use of Blisk technology in hotter sections of the compressor. In addition to these technological developments, with the spread of Blisk technology in jet turbine design, the price sensitivity of the OEMs about the manufacturing cost is rising.

This forces manufacturers to find process solutions that consistently achieve all requirements in a cost competitive manner.

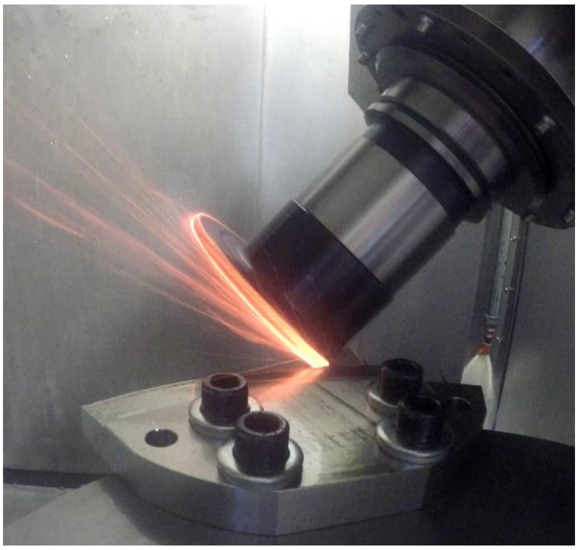


Figure 1: Example for new roughing strategies on Blisk segment demonstrator: ceramic disk cutter for slot opening

Every development must aim at increasing process reliability and productivity in order to follow the general trends described above. There are new innovations in machining strategies (e. g. disk cutters for slot opening, see Figure 1, or barrel cutters for finishing), in cutting tools (e. g. geometries for suppressing vibrations, edge preparations and coatings to extent tool life), in CAM software (e. g. optimal path generation, blending motions to avoid step overs) as well as in other regions to achieve these goals.

Starrag AG
Seebleichestrasse 61, 9404 Rorschacherberg, Schweiz, T +41 71 858 81 11, F +41 71 858 81
info@starrag.com, www.starrag.com

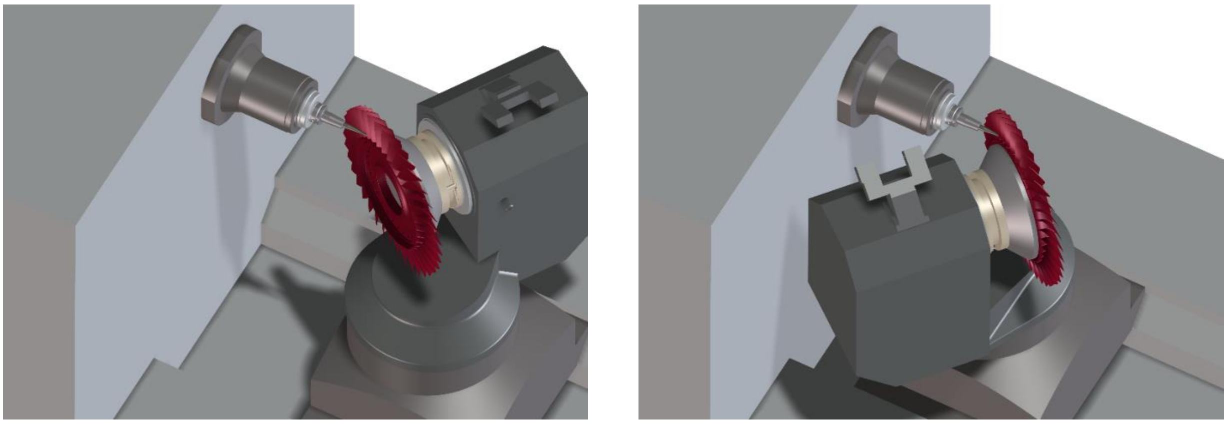


Figure 2: Evaluation of accessibility for Blisk machining processes

The machine tool acts basically as the integrator to implement the optimal process (i. e. highest process reliability and productivity).

In this presentation a systematic approach is shown for the design phase of a Blisk milling machine starting from the desired machining process to the optimal implementation, quantifying the effect of changes in design parameters.

The evaluation aspects presented here are starting from basic the accessibility to the part with the optimal machining strategies (see Figure 2), then going to the required cutting stability for roughing and the dynamic behavior in 5-axis motion around the airfoils. The achievable acceleration gradient in process while achieving the quality requirements for geometry and surface can be determined when simulating the dynamic behavior of machine structure and control.

The results of this systematic design method are presented are discussed.

D2

Abradable Coating in Turbomachinery and Plasma Technology, Performance improvement

Yochanan Nachmana,

Bet Shemesh Engine Ltd,

רקע

ביצועי מנוע עיקריים הינם תצרוכת דלק ודחף בתנאי טיסה ,להם נלווים פרמטרים נוספים כגון רעש ,תוצרי פליטה ועוד. חברות התעופה משקיעות מאמצים גדולים לשיפור הביצועים באמצעות שיפורי ם בתכן המנוע. על הביצועים משפיעים בין השאר מרווחי קצה הלהב טורבינה ומדחס) וטמפרטורת הפעולה.

כללי

במסגרת ההרצאה יוצגו עקרונות מקובלים ביישום ציפוים שחיקים ללא בקרה פעילה כאמצעי לצמצום מרוחים בין חלק סובב למבנה הסטאטי ופרמטרים הנדסיים משפיעים על צפויים מסוג זה.

כמו גם תהליך שיפור ביצועי מנוע סילון באמצעות שינוי תזוזות על קו הפעולה והתרומה לתצרוכת הדלק.

סקירה

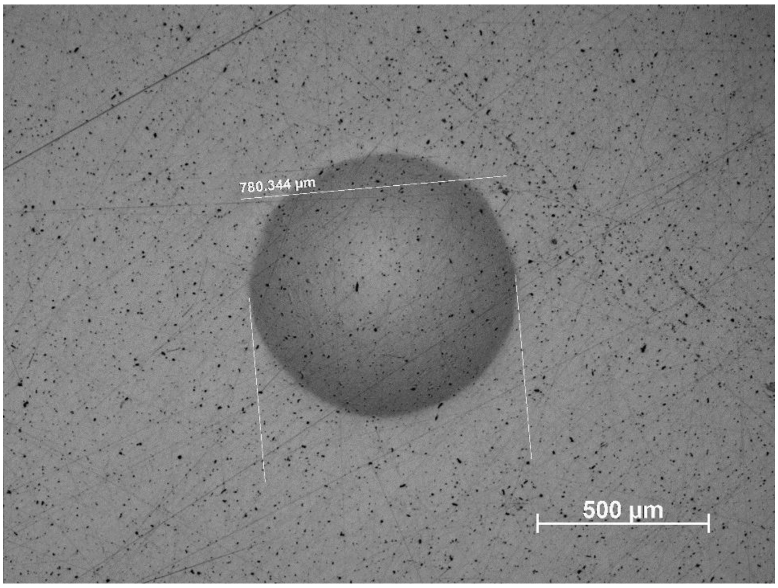
ציפויים שחיקים משמשים לצמצום המרווח המתקבל בעבודה בין חלק סובב למבנה הסטאטי ומאפשרים מרווח מינימאלי במצב פעולה ,עד כדי אפשרות שלהב תיצור מגע עם המעטה . במקרה זה כמה אופני כשל אפשריים ויישום נכון של הציפוי יאפשר במקרה של מגע התאמה של המרווח ללא כשל של הלהב.

פרמטרים כגון קשי הציפוי ,תכונותיו המכאניות, גודל החלקיקים וחוזק ההדבקה משפיעים על עמידות ותוצאות המגע בינו לבין הלהב ועל כן תתרום לחסכון בדלק, המשמעותי למנועים מסחריים, יותר מהזזת נקודת העבודה על קו הפעולה שתתרום לדחף בנקודת המקסימום על חשבון דרישה לעמידות בטמפרטורת עבודה גבוהה יותר.

סיכום

מספר פרמטרים משפיעים על ציפוי שחיק שתרומתו בשיפור נצילות הדרגה ועל כן בתצרוכת הדלק.

שפור ביצועים במנוע ניתן לקבל ע"י הזזת נקודת העבודה על קו הפעולה אך שנוי מסוג זה לא תורם משמעותית לחסכון בדלק ודורש בדיקות והערכות שביצועם המוצלח נותן תוצאות משמעותיות.



D3

Single Crystal (SC) Casting Simulation

Shir Avrahami & Ori Kam

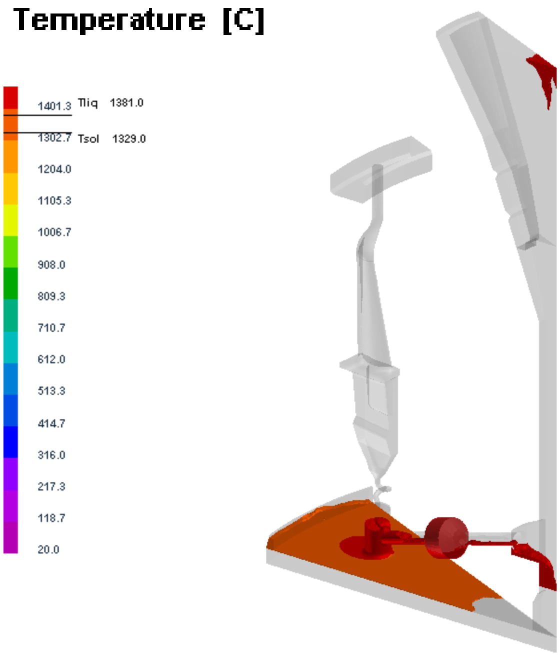
ProCAST is a FE-based software package which enables the simulation of the casting process, including heat transfer, view factors, fluid flow modeling (CFD), thermomechanics, and the modeling of microstructure formation.

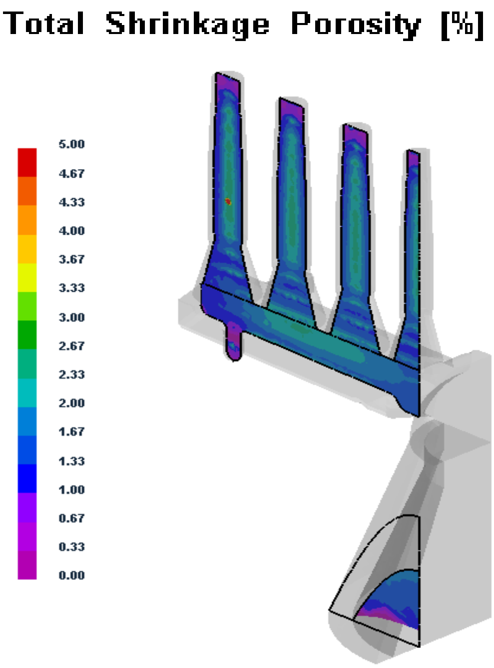
Several issues can arise during the casting processes, including porosity and non-filling of thin walled regions. The ProCAST software is capable of simulating and predicting these and other phenomena. The following investigations were performed using the software and will be presented:

- In SC castings, the ceramic mold is open from the bottom and without proper treatment there is a risk of alloy leakage. The pouring rate of the alloy is investigated to determine its influence on the leak risk and to find the optimum rate to avoid such issues.

- As a preparatory step to performing detailed investigations of various cases using the software, simulations we carried out to determine the physical parameters with the greatest influence on the result. Once identified, precise values for these parameters should be measured in laboratory tests.

- A test casting was performed in order to provide a baseline for calibration of the boundary conditions and physical parameters in the software. An initial comparison between the casting results and the simulation results will be presented.





ProCAST הינה תכנה המבוססת על שיטת אלמנטים סופיים. התכנה מאפשרת מידול מלא של מעבר חום, שימוש ב- View-Factor , מידול זרימת נוזלים כולל מילוי של תבניות (CFD) , מידול מאמצים בצימוד לאנליזה התרמית (Thermomechanics) ומידול של היווצרות מיקרו-מבנים.

ישנן מספר בעיות שיכולות להתרחש בתהליך היציקה וההתמצקות: פורוזיביות, אי מילוי ובעיות נוספות. מטרת התוכנה בין היתר לחזות בעיות אלו.

בהרצאה יוצגו מספר עבודות שנעשו בתוכנה:

- ביציקות SC , תבנית הקרמיקה פתוחה מלמטה. במידה והספיקה לא אידיאלית עלולה להיות דליפה. בפרויקט מידלנו את התהליך במטרה למצוא את אופטימום הספיקה ובכך למנוע את הבעיה.
- ישנם פרמטרים שישנה חוסר ודאות לגבי ערכם ועלולים להשפיע על התוצאות בתוכנה. לכן נערכה בדיקת כיול התוכנה במטרה לבדוק מהם הפרמטרים הקריטיים שמשפיעים על התוצאות ואותם רצוי לבדוק במעבדה.
- בוצעה יציקה הזהה בפרמטרים לסימולציה בתוכנה במטרה להשוות את התוצאות. התוצאות יוצגו בהרצאה.

E1

Vibroacoustic Diagnostics of Turbocharger

Roman A. Varbanets

Odessa National Maritime University, Mechnikov str. 34, 65029, Ukraine, e-mail:
roman.varbanets@gmail.com
IMES GmbH consultant

During operation of marine diesel engines, the exhaust manifolds become clogged with products of incomplete combustion. As a result, the throughput of the exhaust manifolds and the nature of the internal flow of gases before the blades of the turbocharger impeller can vary. In this case, the appearance of pulsations is possible which leads to rotor oscillation. The increased level of rotor oscillation creates additional loads on the turbocharger bearings and reduces their life.

The experiments on marine diesel engines in laboratory and in sea conditions have revealed that the turbocharger compressor blades generate oscillations which are always present in the overall vibration spectrum, regardless of the technical condition of the turbocharger. Acoustic emission of compressor wheel is caused by air pressure pulsation at every blade (figure 1).

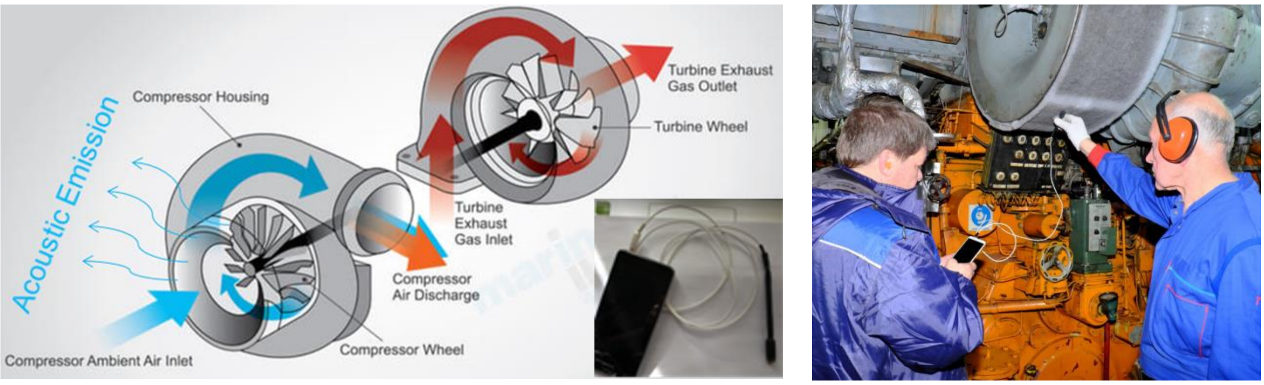


Fig. 1. Recording the vibration of turbocharger using the broadband microphone

The spectral analysis of the turbocharger vibration has shown that the compressor blades generate a vibroacoustic signal with a frequency equal to the speed of the turbocharger rotor multiplied by the number of air blades

$\upsilon_b = n_b \times RPM_{TUR} / 60$, [Hz]

where υ_b – turbocharger compressor's blade frequency, Hz; n_b – the number of compressor air blades, RPM_{TUR} – the speed of the turbocharger rotor, $\min^{-1}$.

Figure 2 shows the vibration spectrum of the turbocharger VTR 564-31. The spectrum contains many multiple harmonics and subharmonics. The frequency of the compressor blade's harmonic is between the limits L_1 and L_2 (figure 2)

$L_1 = n_b \times RPM_{TURmin} / 60$, [Hz],

$L_2 = n_b \times RPM_{TURmax} / 60$, [Hz],

where $RPM_{TUR\ min,\ max}$ – the minimum and maximum possible speed of the turbocharger rotor, $\min^{-1}$. These values are selected from the data of factory tests of the turbocharger (shop or sea trials).

Thus, we can calculate the compressor blade's frequency and the main speed of the turbocharger (figure 2):

$RPM_{TUR} = 60 \times \upsilon_b / n_b = 60 \times 2948\ \text{Hz} / 20 = 8844\ RPM,$

$\upsilon_{turbocharger} = \upsilon_b / n_b = 2948\ \text{Hz} / 20 = 147{,}4\ \text{Hz}$

Spectral analysis of a vibroacoustic signal recorded in 'wav' format at a frequency of 44,1 kHz makes it possible to analyze harmonics in steps of less than 1 Hz at a recorded signal frequency up to 20 kHz. The blade frequency of the turbocharger compressor is significantly lower. Thus, an RPM_{TUR}'s error less than 1 RPM can be reasonably obtained. Such accuracy is much higher than the accuracy of the standard tachometers, which makes it possible to use the blade frequency of the turbocharger compressor in accurate calculations of the main rotational speed of the turbocharger and the subsequent estimation of the diesel engine power. After that we can analyze the harmonic amplitude (Δ) at the main speed of the turbocharger ($\upsilon_{turbocharger}$). It is evident that a significant increase in harmonic amplitude at the turbocharger speed indicates an increase in rotor vibration. The MAN MC diesel engines experiments have shown that raising of the main frequency harmonic amplitude to more than 3 times above the average level of the adjacent harmonics (± 40Hz) characterizes dangerous vibration of turbocharger rotor. Figure 2 shows a slight increase in the amplitude Δ (less than 1.3 times), which characterizes the permissible vibration level of the turbocharger rotor

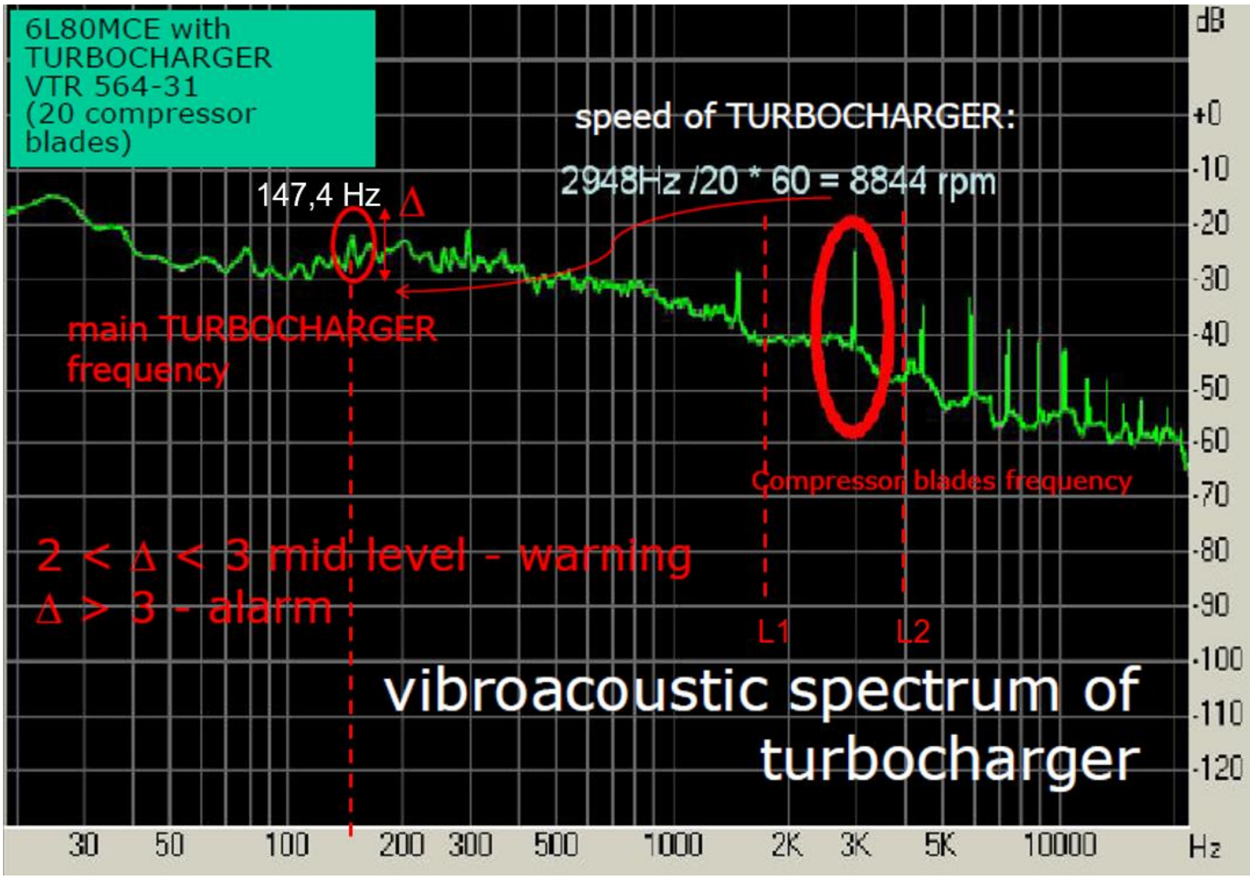


Figure 2. Vibroacoustic spectrum of turbocharger VTR 564-31

The discrete spectrum “leakage effect” eliminating (LEE algorithm). This effect is a consequence of the finiteness of the analyzed time series and its discrete representation. This effect distorts the amplitude up to 40% and frequency of the main harmonic in the spectrum. It must be fixed before amplitude Δ analysis. We make suggestion that the frequency *m*, the phase φ, and the amplitude A of the original signal from the values of two maximum harmonics in the spectrum close to Δ: X_k, X_{k+1} should be specified. For these harmonics, it is proposed to compose a system of equations, the solution of which will give the signal frequency and the amplitude Δ with the eliminated leakage effect:

$$\left\{\begin{matrix} \left|E(m,\phi)_k / E(m,\phi)_{k+1}\right| = \left|X_k / X_{k+1}\right| \\ \operatorname{Arg}(E(m,\phi)_k) = \operatorname{Arg}(X_k) \end{matrix}\right\}, \text{ where } E(m,\phi)_k = e^{j\phi}\frac{e^{2\pi j(m-k)}-1}{e^{\frac{2\pi j(m-k)}{N}}-1} + e^{-j\phi}\frac{e^{-2\pi j(m+k)}-1}{e^{\frac{-2\pi j(m+k)}{N}}-1},$$

k-th harmonic parameters: $X_k = \mathrm{Re}_k + j\,\mathrm{Im}_k$; $X_k = NA_k e^{j\varphi_k}$, $A_k = \frac{1}{N}\sqrt{\mathrm{Re}^2{}_k + \mathrm{Im}^2{}_k}$, $\phi_k = \mathrm{arctg}(\frac{\mathrm{Im}_k}{\mathrm{Re}_k}) = \operatorname{Arg}(X_k)\cdot$

The harmonic coefficients can be represented in the form $X_k = (A_k / 2)E(m,\phi)_k$, where $E(m,\phi)_k$ is a complex function independent of the amplitude, but dependent on the frequency and phase.

Conclusions and solution. The proposed method allows to determine the turbocharger rotor speed and level of the vibration by stabilizing harmonics amplitude of vibroacoustic spectrum using LEE algorithm. The presented algorithm can be implemented in a continuous monitoring system of a turbocharger (figure 3).

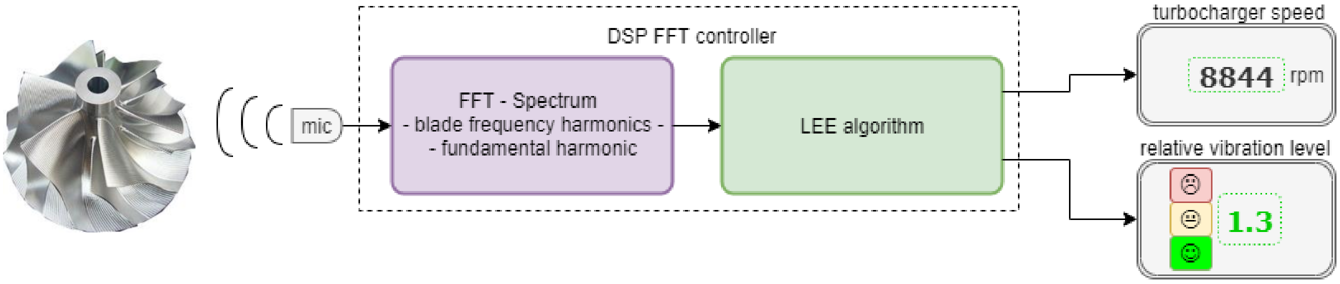


Fig. 3. Block diagram of a turbocharger vibroacoustic continuous monitoring system

Expected features of the proposed system:

- continuous monitoring of RPM and rotor vibration level;
- reliability and ease of installation, as the sensor is in a low temperature zone;
- low cost of the system;
- high accuracy RPM control, which makes it possible to monitor the total engine load.

In order to better define the limits of normal rotor vibration levels for various types of turbochargers, further research is needed. It may be noted that the vibroacoustic spectrum analysis of turbocharger can be quickly made under the operating conditions and does not require significant expenses.

E2

Measurement of Coating Thermal Properties via Induction Phase Radiometry.

Eitan Shani(I) and Beni Cukurel (II)
(I)IAF & (II)Technion

The 18th Israeli Symposium On Jet Engines

Gas turbine engines typically contain hot section parts which must endure high levels of temperatures in order to maintain the duty cycle loads. The hot section parts are usually made from 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, the thermal properties of TBC play crucial role in determining the level of engine durability. Current techniques that are used to measure the thermal properties of TBC are complex and are unable to perform in-situ inspections with sufficient accuracy. A comparison between other measurement techniques was conducted with emphasis on accurate in-situ TBC inspections.

This research introduces a novel technique to perform simple measurement of the 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 the thermal properties are calculated using an analytic heat conduction model.

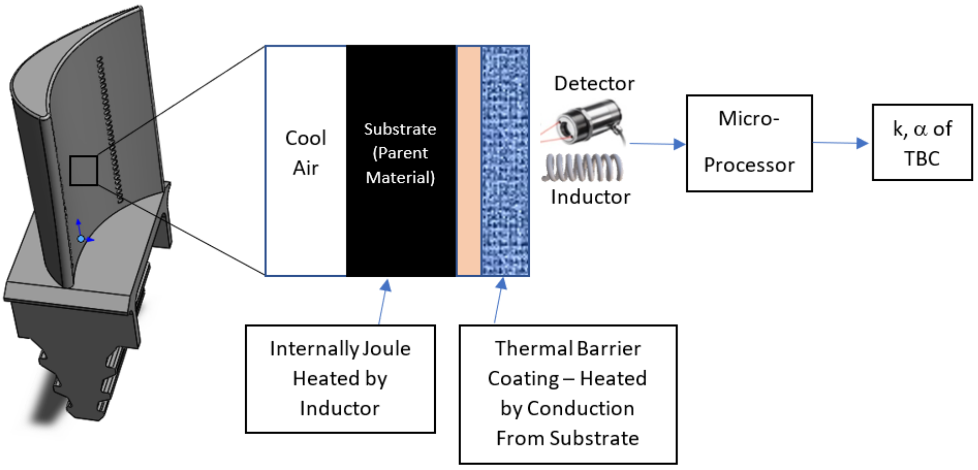


Figure 1 - General Diagram of the Research Concept - Measurement of TBC Thermal Properties by Induction Radiometry

In order to evaluate introduced technique model, a non-homogenous heat transfer problem is posed including a double layer continuum and a transient heat generation term to simulate induction heating signal. Heat generation term simulates electrical energy signal with modulated frequencies to thermally excite the measured specimen. In addition, it captures skin effect which is a dominating phenomena of induction heating process.

Heat transfer equations were developed, using Greens functions approach, to solve temperature response and to decouple the relationship between induction parameters, surface temperature and TBC properties. Full analytical solution of the temperature evolution was completed to create a simulation tool. Simple analytical expressions were derived, using Fourier Transform to capture direct relationship between signal phase and thermal properties, to enable thermal properties recovery from measurements.

Also, in the scope of this work, finite elements model is being developed to serve as another verification method for this technique. Finally, research plan has an experimental stage, including an electrical circuit design with induction coil set to verify analytical model and results. This process will additionally include noise filtration and optimization process.

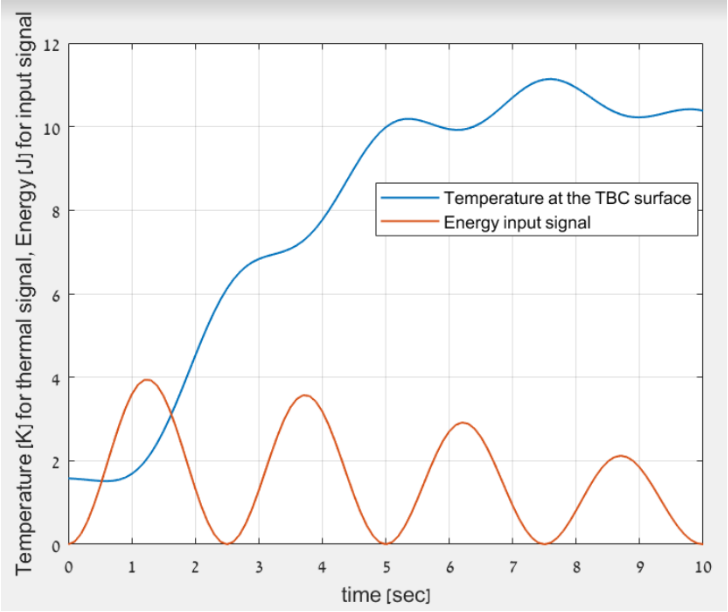


Figure 2 – Temprature response of a modulated indcution heating energy signal

E3

הדור הבא (צמדים טרמיים) למדידת טמפרטורה –Stabilized תרמוקפלים

Giora Brandwine,

Elcon Mamab Control Instruments Ltd.

חדשנות בתעשייה ופיתוחים של טכנולוגיות ישנות הפכו לעניין שבשגרה, אנו חיים בעולם טכנולוגי שבו אם לא נעקוב אחרי המתרחש נישאר מאחור ותיפגע התייעלותנו, גם בעולם המדידות הבסיסיות אנחנו שומעים מדי שנה על פיתוחים וחידושים טכנולוגים אשר נותנים מענה לבעיות שונות בתעשייה. בכתבה זו נספר על הפיתוח האחרון בתחום מדידות הטמפרטורה, דור חדש של תרמוקפלים אשר נקראים תרמוקפלים יציבים – Stabilized. לפני שנציג את הטכנולוגיה החדשה, נסביר על אמצעי מדידת טמפרטורה השונים.

סוגי אמצעי מדידת טמפרטורה במגע עם התהליך:

במדידת טמפרטורה ישנן שתי שיטות עיקריות : מגע / CONTACT ו- ללא מגע/ NONCONTACT .

מגע- מדידת טמפרטורה במגע פיזי עם החומר הנמדד כגון: מוצקים ,נוזלים וגזים. במדידה ללא מגע מתבצעת המדידה בשיטת אינפרא-רד ומתאימה לנוזלים ומוצקים בלבד.

היום מיוצרים רוב אמצעי החישה במגע (גששי טמפרטורה) במבנה המבוסס על שינוי סיגנל חשמלי, מתח או התנגדות ,ביניהם : תרמוקפלים-צמדים תרמים, טרמיסטורים ונגדים משתנים כמו-PT100,PT1000, NTC ו PTC

תרמוקפלים הינם אמצעי מדידת טמפרטורה הנפוצים בתעשייה ונרצה להתמיד בהם בכתבה.

מהם תרמוקפלים - צמדים תרמיים

השיטה הנפוצה ביותר היום למדידה של טמפרטורה הינה באמצעות תרמוקפל. תרמוקפל הינו צמד מתכות שונות זו מזו המחוברות בנקודת המדידה (צומת חמה) ויוצרות מתח חשמלי EMF אשר משתנה ביחס לטמפרטורה בנקודת המדידה.

עיקרון התרמוקפל מבוסס על אפקט סיבק-פלטייה המתאר יחס בין חום למתח חשמלי בהינתן צמד מתכות שונות זו מזו.

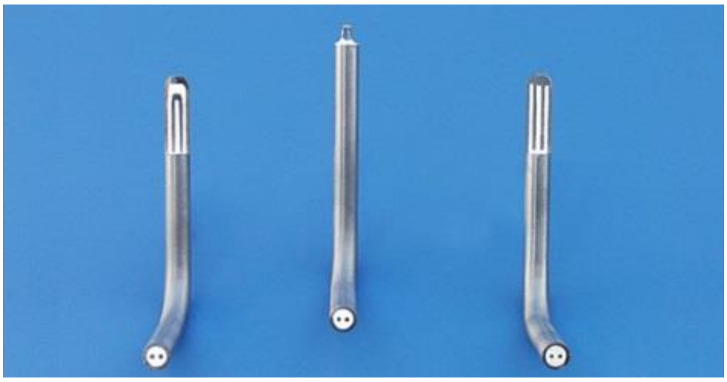
שיטה מדידה זו היא בעלת תחום המדידה הרחב ביותר ואף מעולה למדידה בתחומי הטמפרטורה הגבוהים.

יתרונה של השיטה אף במדידה של מקומות קטנים ,ובמקומות עם ויברציות גבוהות. זמן התגובה שלו הוא המהיר מכל החיישנים.

לתרמוקפלים יש סדרת תקנים מארצות שונות המאחדות אותם תחת שינוי מ- MV לטמפרטורה.

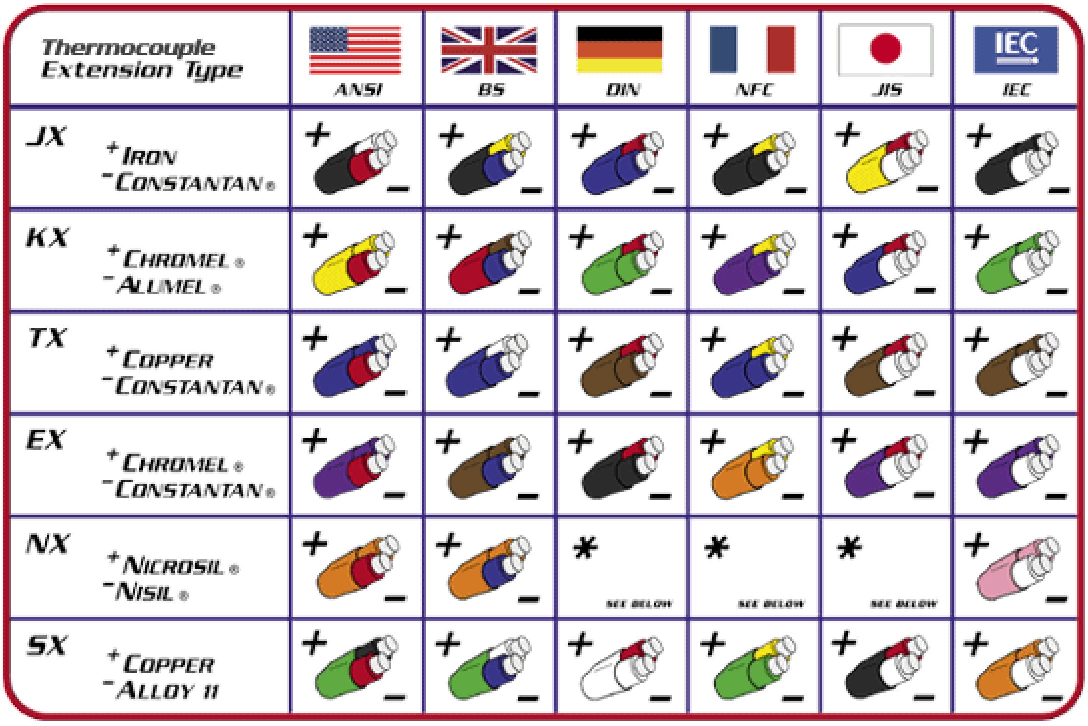
הצומת החמה אשר מבצעת את המדידה קובעת את זמן התגובה ורגישות החיישן .

ככל שהחיישן דק יותר והצומת קרובה לחומר הנמדד הרגישות תהיה גבוהה יותר. (לכן חשוב אם הצומת תהיה גלויה, מאורקת או מבודדת).



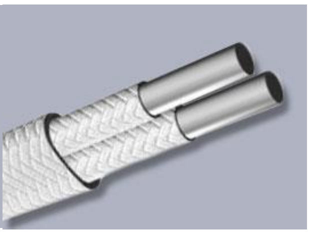
מאורק גלוי מבודד

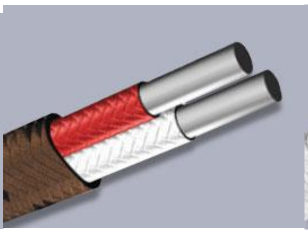
הצלבה בין התרמוקפלים השונים שימוש בכבל לא מתאים יגרום בוודאות לשגיאה בקריאה.
(טבלת צבעי זיהוי של תרמוקפלים)

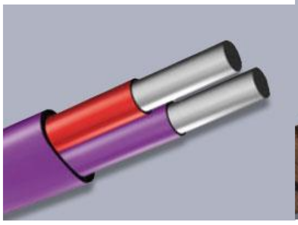


Thermocouple Extension Type	ANSI	BS	DIN	NFC	JIS	IEC
JX +Iron −Constantan®	+ −	+ −	+ −	+ −	+ −	+ −
KX +Chromel® −Alumel®	+ −	+ −	+ −	+ −	+ −	+ −
TX +Copper −Constantan®	+ −	+ −	+ −	+ −	+ −	+ −
EX +Chromel® −Constantan®	+ −	+ −	+ −	+ −	+ −	+ −
NX +Nicrosil® −Nisil®	+ −	+ −	* SEE BELOW	* SEE BELOW	* SEE BELOW	+ −
SX +Copper −Alloy 11	+ −	+ −	+ −	+ −	+ −	+ −

<u>כבלי תרמוקפלים למדידת טמפרטורה וכבלי הארכה -</u>
מספר דגמי הייצור של כבלי תרמוקפלים הוא רב, וכל יצרן מפתח דגמים שונים בהתאם לתהליך מניסיונו האישי. בנוסף לסוגי התרמוקפלים ,המעטפת המבודדת את החוטים הגלויים מהווה חלק חשוב במוצר , סוגי המעטפת יכול להיות מ כבלי פי.וי.סי ,טפלון, סיליקון, סיבי זכוכית שונים ,בידוד קרמי ושילוב בניהם עד לטמפרטורות 1316 מעלות צלסיוס.

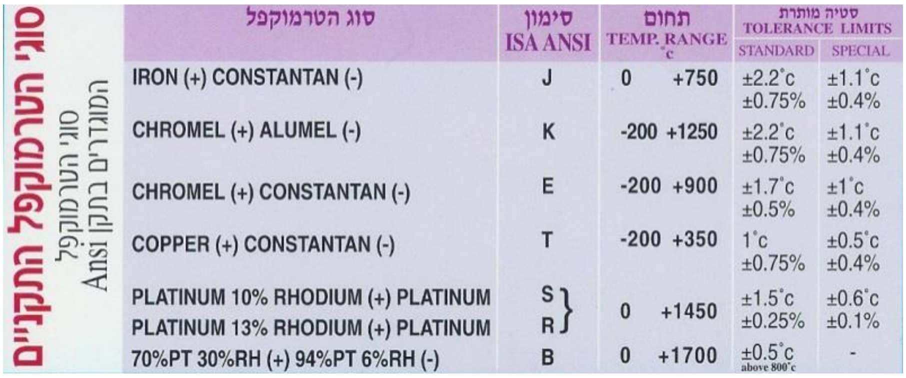

מחומרי פלסטיק


סיבי זכוכית


בידוד קרמי

<u>כבלי תרמוקפלים בטכנולוגיות ב -Mineral Insulated metal sheathed :</u>
כיום מרבית גששי טמפרטורה (תרמוקפלים ו PT100)
מיוצרים בשיטה זו. שיטה זו אידיאלית למדידה בתעשייה ובמעבדות מחקר.
שיטה זו מבוססת על מעטפת ממתכות שונות המכילה מגנזיום אוקסיד(MgO) המצטיינת בבידוד חשמלי גבוהה ומוליכות טרמית טובה. ובתוכם מוליכי תרמוקפל או מוליכי ניקל , נחושת עבור PT100מספר המוליכים יכול להשתנות בהתאם ליישום.
השיטה טובה לשימוש בנוזלים, מוצקים וגזים. מבחר סוגי המעטפת גדול מאוד וכתוצאה מזה היכולת להתאים לכל תהליך את סוג המעטפת המתאימה לו.
להלן מספר יתרונות של השיטה:
חיים ארוכים ,בידוד גבוהה, אטום ומוגן בפני השפעות של קורוזיה וחמצון ,ניתן לעיבוד ,ריתוך והלחמה, זמן תגובה מהיר, עמידות מכנית גבוהה, מידות קטנות, קל להתקנה.

<u>דיוק ותחומי עבודה של תרמוקפלים :</u>
מצורפת טבלה המציינת את הדיוק ותחומי העבודה של הטרמוקפלים



סוגי הטרמוקפל התקניים

סוגי הטרמוקפל המוגדרים בתקן Ansi

סוג הטרמוקפל	סימון ISA ANSI	תחום TEMP. RANGE °c	סטיה מותרת TOLERANCE LIMITS STANDARD	 SPECIAL
IRON (+) CONSTANTAN (-)	J	0 +750	±2.2°c ±0.75%	±1.1°c ±0.4%
CHROMEL (+) ALUMEL (-)	K	-200 +1250	±2.2°c ±0.75%	±1.1°c ±0.4%
CHROMEL (+) CONSTANTAN (-)	E	-200 +900	±1.7°c ±0.5%	±1°c ±0.4%
COPPER (+) CONSTANTAN (-)	T	-200 +350	1°c ±0.75%	±0.5°c ±0.4%
PLATINUM 10% RHODIUM (+) PLATINUM	S	0 +1450	±1.5°c ±0.25%	±0.6°c ±0.1%
PLATINUM 13% RHODIUM (+) PLATINUM	R			
70%PT 30%RH (+) 94%PT 6%RH (-)	B	0 +1700	±0.5°c above 800°c	-

החידושים בטכנולוגיה הוותיקה

תעשיית כבלי התרמוקפלים אינה גדולה כמו חוטי הנחושת או חוטי חשמל, אבל זה עדין מרגש לראות איך טכנולוגיה מוכחת זו מיושמת לדור הבא של הטכנולוגיה. ניתן למצוא תרמוקפלים במגוון רחב של יישומים - ממחקרים מדעיים בטמפרטורות נמוכות מאוד ועד ליישומים תעשייתיים במטלורגיה - הדורשים טמפרטורות גבוהות.

TC Stabilize

התרמוקפל היציב – Stabilize, זהה בתכונות שלו לתרמוקפל המסורתי, מה שמבדיל אותו הוא השינוי בתכונות שלו המיוחס לסדר האטומים במתכות. חברת TEW&C שחברתנו הנציגים שלה רכשה את הידע הנ"ל מאוניברסיטת קיימברידג' ופיתחה תהליך ייצור ייחודי המבוסס על עשרות שנות ניסיון אשר פותר את בעיית הדריפט. התרמוקפל הזה נקרא TC-K Stabilized. שיטה זו מאופשרת גם עבור כבלי תרמוקפל וגם עבור Mineral Insulation.

בעיית הסחיפה ("דריפט")

כאשר מבצעים סקר טמפרטורה לתנור, משתמשים בכמה תרמוקפלים הפרוסים ברחבי התנור. אחרי מספר חשיפות של תרמוקפל K לתחומי טמפ' 343-593c, קיים דריפט חיובי של + 3c בטמפ' 538c וב +5c בטמפ' 1093c.
כלומר, טמפ' התנור נמוכה ב 3-5c מהערך הרצוי ולמספר הזה צריך להוסיף את הסטייה המותרת ע"פ תקן הדיוק של התרמוקפל.
השינוי בתכונות התרמוקפל מיוחסות לסדר האטומים במתכות.
כאשר נעשה שימוש בתחומי הטמפ' של 538c ומעלה, חלק מהאטומים של ה+ מארגנים את עצמם ממצב רנדומלי למצב מסודר Ordered state. סידור האטומים מחדש גורם לכך שהמתח (mV) של המוליך החיובי יהיה גבוה מהטמפ' האמיתית. כל שגיאה הנובעת מדריפט מתווספת לשגיאה המותרת ע"פ הסטנדרט.
לדוגמא: הרצת תנור ב 1093c ושימוש בתרמוקפל בסטנדרט רגיל יכול לגרום לסטייה של 13.2c המורכבת מסטייה מותרת של 8.2c ועוד 5c סטייה בתוצאה מדריפט.
סטיות אלו בטמפרטורה כתוצאה מה Drift עלולות להזיק בתהליכי הייצור.

עמידה בתקני NEDCAP

ניטור טמפרטורה באמצעות תרמוקלים מסוג stabilize מתאים לתקני הNEDCAP המקובל בתחום המוצרים התעופתיים בו יש חשיבות מרובה לתוצאות נכונות ויציבות של מדידת טמפרטורה.
למידע נוסף ניתן לפנות למחבר.

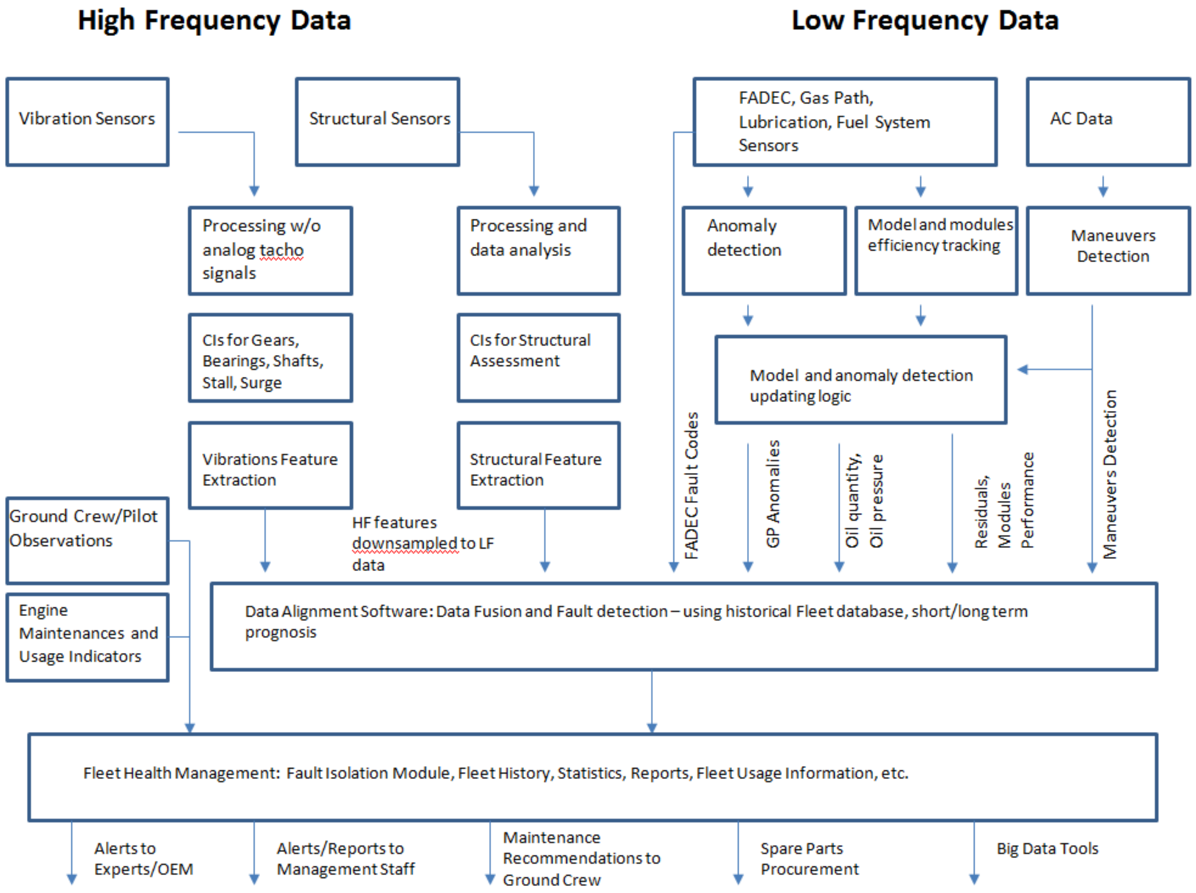
E4

Reliable, Comprehensive AI Powered Health Diagnostics and Prognostics of Turbo-Jet Engines and Gas Turbines through Fusion of Hybrid Methodologies

Michael Grebstein
RSL Electronics

Traditionally conventional and conservative diagnostics methods were employed for health monitoring of engines which provided an improved flight safety. However, it has resulted in limited effectiveness in terms of availability of aircrafts. Under the conventional framework, any alarm during diagnosis calls for withdrawal of the engines from service and carry out investigation. Such unscheduled engine withdrawal, investigation and actions generally result in cost and time issues. A false alarm would result in unnecessary effort for confirmation of fault and reduced availability of the aircraft.

RSL's engine diagnostic and prognostic methodologies are based on information fusion, which allows inter weaving of different methods with different effectiveness, to produce a reliable coverage of diagnostics and prognostics which result with very low false alarms. It is a multidisciplinary domain wherein, data from the various domains are blended together to arrive at a more reliable monitoring. Decisions regarding the condition of a system are seldom based upon the output of a single measurement parameter. More often, these decisions are made on the analysis of multiple parameters either from the same type of sensor or from completely separate and different ones. A comprehensive framework for diagnosis of aircraft gas turbine engines is attached hereafter.



RSL's Approach to Turbo-Jet Engine Health Monitoring - EHUMS

F1

Combustion instability in swirl stabilized combustors

Nikhil Balasubramanian[1], **Dr. Dan Michaels**[2]

Technion- Israel Institute of Technology, Haifa, Israel, 3200002

A major motivation for research in combustion science and technology is to reduce emissions from power plants, large scale industrial furnaces, automobiles, aircrafts, etc. Using lean combustion to reduce emissions have become the norm in the gas turbine power generation sector and is currently introduced in to the latest jet engines. The allied negative of working in lean combustion is the onset of thermoacoustic instabilities, caused by a coupling between the acoustics of the combustor and the fluctuating flow field and an unsteady heat release. In lean premixed combustion prominent instability mechanisms are flow-flame interaction and fuel to air ratio oscillations. Combustion instabilities can lead to large pressure and heat release oscillations, which can permanently damage the combustor.

Flame stabilization in a premixed swirl combustor is realized by the formation of recirculation zones. An inner recirculation zone (IRZ) is formed along the central axis of the combustor and a toroidal outer recirculation (ORZ) is formed near the walls .Also, there exists two shear layers, which separate the high velocity annular jet from their associated recirculation zones, respectively called the Inner shear layer (ISL) and Outer shear layer (OSL). Although the influence of shear layers to define stable and unstable combustion is well established, there is a certain lack of qualitative understanding of its fluid dynamic properties when subjected to changes in Swirl number, Reynolds number and other operating parameters.

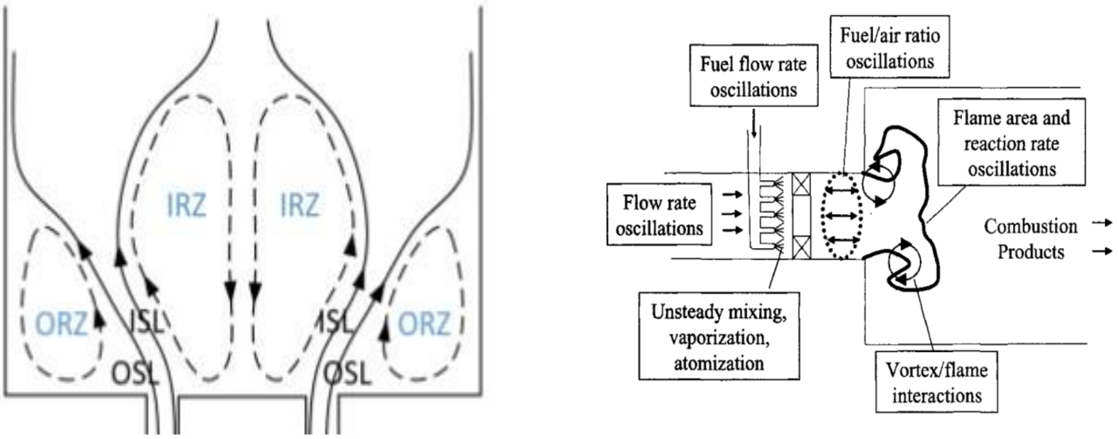


Figure 3: (a)Schematic of the flow field in a swirl-stabilized combustor followed by a sudden expansion, showing the Inner recirculation zone (IRZ), Outer recirculation zone (ORZ), and shear layers, taken from (b) Schematic representing the various sources of combustion instabilities in gas turbine systems

Vorticial structures emanating from the swirling flow at the dump plane can affect the instantaneous flame surface area, causing unsteady heat release. The vorticial structures are formed at the shear layer interface between the two recirculation zones are convected through the flame. Small vortices proceed without affecting flame surface area, but if the vortices are large enough, they will cause flame wrinkling or flame-roll up, depending on the size of the vortices. Flame roll-up or flame wrinkling results in unsteady heat release, and if its frequency of oscillation is in phase with the acoustics of the combustion system, combustion instability can occur. Flame thinning or widening is also a phenomenon observed in swirling flows, and its root cause is slight modulation in swirl number.

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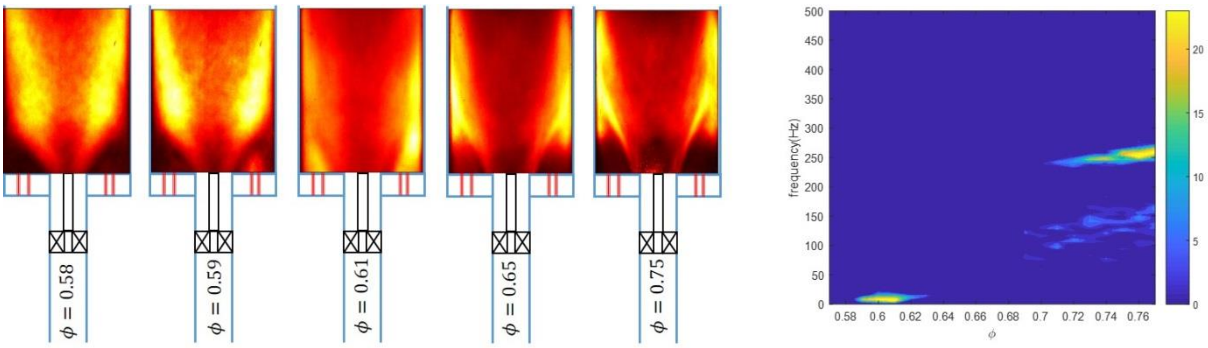
[1] M.Sc. Student, Faculty of Aerospace Engineering, nikhil.b@campus.technion.ac.il

[2] Assistant Professor, Faculty of Aerospace Engineering, danm@technion.ac.il

Vortices convected to the flame impact the instantaneous heat release significantly and thus flame-vortex dynamics is a major contribution to combustion instabilities.

Experiments are being performed in the swirl combustor test facility at the Fine rocket propulsion center to recognize the different instability modes. Flame shapes recorded in a high speed camera are processed to obtain the heat release intensity, which along with pressure measurements will show the modal frequencies.



(a) (b)

Figure 2: (a) Series of images depicting the standard deviation of the chemiluminescence intensity signal; (b) Power spectral density contour plot showing the excited frequencies

We observe two unstable regimes at $\phi = 0.59\ to\ 0.62$, with a signature from 8-12Hz and another unstable regime beyond $\phi = 0.74$. The instability at leaner conditions is purely dominated by fluid dynamic-heat release interaction, when the flame propagates into the ORZ thereby igniting the reactant mixture. The intermittent filling and emptying of the ORZ causes large amplitude oscillations with an 8-12Hz signature. The richer instability mode is thermos-acoustically triggered mode at a frequency of 250Hz. It was observed the instability was triggered by vortices impingement on the walls of the combustor. The vortex shedding triggered heat release oscillations which coupled with the fundamental mode of the combustion chamber (calculated using a simplified acoustic model). Recognizing the different instability regimes offers us a clear operating range for the experimental combustor setup. The mechanisms of instabilities compared well with other articles published, which suggests there could be a singularity parameter defining the transition from stable to unstable combustion.

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F2

Extended operation load range of gas turbines as a tool to control electricity grid equipped with renewable energy suppliers.

B. Chudnovsky, A. Lazenikov, I. Chatskiy

Israel Electric Corporation, Haifa

Over the past years there has been a dramatic increase in the global energy trends towards generation from renewable sources. Gas turbines are becoming the most common generation equipment for controlling electricity grid power fluctuations due to renewable energy nature of availability. The traditional methods of reducing emissions in gas turbines are firing system operating in a lean premix combustion mode and are equipped with DLN (Dry Low NOx) combustors. These combustors are very expensive and are limited at partial load operation due significant increasing of CO and particulates emissions. The DLN firing system design is optimized for NOx emissions below 20 ppm, while CO emissions are usually negligible at base load while they increase exponentially with load decrease.

The main driver for the CO increase is the decrease in flame temperature. Therefore, in order to minimize CO flame temperature should be as high as possible while providing low NOx emission. Constant load but higher flame temperature can only be achieved by reducing the air mass flow to the burners. Hence, every measure that reduces the air mass flow to the burners while keeping the load constant will increase flame temperature and, as a consequence, result in a reduction of CO. However, for DLN firing systems, the reduction of air flow is a very complicated task and strongly depends on the minimum compressor capacity and in order to allow operation at this minimal flow a significant reduction in compressor efficiency is expected. Therefore, gas turbines equipped with lean premixed combustion systems are limited in wide load range operation. In opposite, diffusion combustion of alternative fuel with low heat capacity (adiabatic temperature), fuel mixing with steam or water enables wide load range operation while achieving low NOx and CO emissions. Diffusion combustion takes place in a thin layer or “skin” of the flame where the concentration of oxidants is at stoichiometric conditions. This combustion mode is allowing the oxygen to penetrate deep into fuel zone and accelerate the combustion rate. Increasing the oxygen diffusion rate of the surrounding air into the diffusion flame reduces the burning and residence time of hot nitrogen and oxygen, thus diminishing NOx production. At the same time, the accelerated rate increases combustion efficiency such that CO and hydrocarbons are burned as completely as possible. Therefore, one of the attractive choices may be burning alternative fuels or fuel mixed with steam or water in diffusion mode.

For example, existing experience has shown that with minor system modifications in existing diffusion combustors, methanol is easily burned and is fully feasible as an alternative fuel. The experiments performed on gas turbines at wide range of loads following the conversion to methanol burning has clearly showed that with minor cost of fuel system retrofit, methanol firing leads to a significant NOx, SO2 and particulate emission reduction relative to LFO. NOx emissions were reduced by more than 75-80% and were equal to 90-100 mg/dNm3 at 15% O2. SO2 emissions were reduced to zero following the conversion to methanol firing. Particulate emissions vary from 1.3 to 1.6 mg/dNm3 at 15% O2 with methanol firing. Another example of alternative fuel (which contained CO2 and nitrogen) is blast furnace gas. Also, when blast furnace gas is burned in diffusion combustion systems, NOx, CO and particle emission is considerably lower than regulation requirements. Steam-fuel mix burning reduces NOx and CO emissions below 3 ppm without DLN or SCR. However, for combined cycle operation, steam injection taken as an extraction leads to steam turbine capacity reduction and GT capacity increase with increase in unit heat rate. The other possibility of providing wide load range of GT operation while maintaining low NOx and CO emissions is fuel mixing with flue gas being recirculated from the exhaust (FGR). The present paper discusses the effect of burning fuel mixed with FGR flow on GT performance and emissions in diffusion combustors. For the prediction of the combustion behavior of fuel mixed with FGR and its consequent impact on performance and pollutant emission from gas turbine calculations that are based on a methodology that combines experimental work and computational simulations was performed. Given the fact that due to the increase in renewable energy introduction into the grid, operation at partial and low loads of conventional power generation facilities becomes very significant. Hence, the problem of reducing of CO and unburned carbon emission at partial loads is challenging and should be resolved.

F3
Lagrangian Injection Simulation of a Slinger Combustor

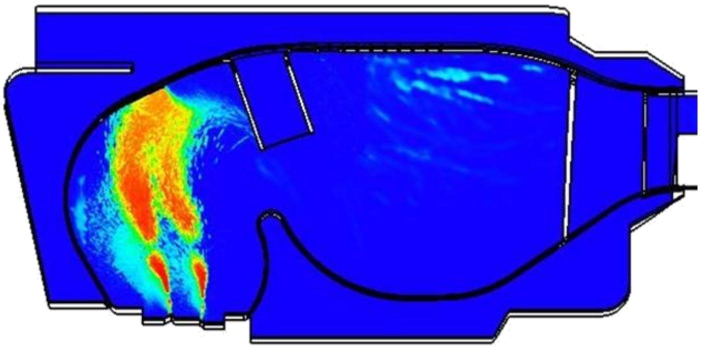
Ariel Cohen

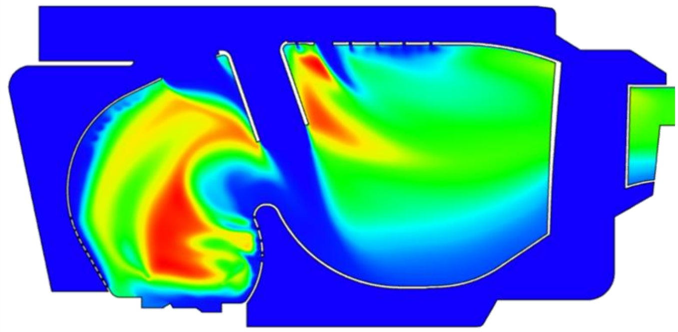
Bet Shemesh Engines Ltd

Historically, gas turbine combustor CFD simulations have been challenged to correctly predict the flame location. In particular, the use of gas-phase fuel injection, whilst greatly simplifying the calculation procedure, results in an unwanted smoothing of the fuel-air ratio in the critical regions.

Thus, in order to accurately predict the flame location in a non-premixed combustor, the Lagrangian method must be utilised to model, statistically, the transport of the fluid-phase fuel through the combustor primary zone. Primary and secondary breakup should be modeled along with fuel droplet evaporation.

In the present work, this approach is applied to a slinger combustor. Results are compared with previous simulations which assumed a gas-phase fuel injection, with the latter demonstrating significantly worse correlation with experimentally measured results.





היסטורית, סימולציות CFD של תאי-שריפה של מנועי סילון התקשו בלחזות בדיוק סביר, את מיקום הלהבה. אף עם פי שהשימוש בהזרקת דלק בפאזה גזית מפשט מאוד את תהליך החישוב, הוא גורם להחלקת היחס דלק-אוויר באזורים הקריטיים.

לכן, כדי לחזות בצורה מדויקת את מיקום הלהבה בתאי-שריפה ללא ערבוב-קדם, שימוש בשיטה הלגרנג'יאנית – למידול סטטיסטי של מעבר הדלק הנוזלי דרך האזור הראשוני – הינה הכרחית. בנוסף, יש למדל את הפירוק הראשוני והמשני של הסילון הנוזלי ואת איוד הדלק.

בעבודה הנוכחית, השיטות הנ"ל יושמו במקרה של תא שריפה מסוג סלינגר. התוצאות הושוו לסימולציות קודמות שהניחו הזרקה של דלק בפאזה גזית אשר מייצגות התאמה פחות טובה לתוצאות שנמדדו בניסויים.

F4

A New Tunnel for Ignition Research

Iker Laso, Natali Rozin, Joël van der Lee, Joseph Lefkowitz
Faculty of Aerospace Engineering, Technion – Israel Institute of Technology

I. INTRODUCTION. Ignition is a fundamental stage in every combustion process, regardless of the nature of the engine. It becomes a particular challenge in the field of aerospace for cases like –but not limited to– ramjet and scramjet engines, where some attributes (e.g. ignition probability, kernel growth rate, etc.) are determined by both the ignition device and the scenario in which the ignition is intended to happen. Specifically, in these engines, this process takes place at high subsonic or supersonic velocities in the combustor, resulting in short flow residence times and highly turbulent flow fields in the flame-holder. Thus, ignition needs to be established on the order of milliseconds, and quenching of the kernel in the turbulent environment must be avoided. However, laws that govern and explain ignition behavior in this scenario are not yet well understood.

In the last years, nanosecond-pulsed high-frequency discharge (NPHFD) plasmas have been pointed out as an optimal ignition method in flowing mixtures [1,2]. The re-application of nanosecond pulses in a repetitive fashion offers further advantages as compared to a long duration DC discharge [3,4,5,6].

In recent experiments by Lefkowitz and Ombrello [1,2], inter-pulse coupling –defined as the ability for multiple pulses in a burst of nanosecond discharges to amplify the plasma volume– was explored in a well-controlled wind tunnel where parameters that foster ignition were studied for flowing mixtures of methane and air. Trying with different values for the relevant variables (pulse repetition frequency, total deposited energy, equivalence ratio, flow velocity and gap distance), three different groups were found: fully-coupled, partially-coupled and decoupled ignition regimes. Each of them –mainly defined by the pulse repetition frequency (PRF), but also dependent on the remaining parameters– provides a different ignition probability and kernel growth rate.

II. NEW DESIGN. Despite the significant progress of NPHFD ignition in flowing mixtures, experiments carried out so far have been constrained to certain scenarios in which the temperature and the velocity were limited to 300 K and 10 m/s, respectively [1,2]. In addition, methane is the only fuel implemented until now.

Having enhanced previous designs, the innovative ignition tunnel –located in the Combustion & Diagnostics Laboratory at the Technion– goes one step further approaching real scenarios in high subsonic or supersonic jet engines. Being able to handle more extreme conditions, such as temperatures above 1,000 K, velocities up to 100 m/s and Reynolds numbers (Re) up to 240,000, it allows to explore the effects of the following on ignition phenomena:

a) Increasing the temperature,
b) Increasing the velocity, and
c) The different turbulence regimes.

In order to permit these, the system is composed of:

- » A mass flow control system combined with heaters which provide, together, air flow rates up to 790 m^3/min at 1,000 K,
- » An expanded test section (5 cm x 5 cm) which allows to reach Reynolds numbers (Re) up to 240,000,

- A plasma pulse generator which provides 10 ns FWHM pulses with peaks up to 20 kV at a maximum PRF of 200 kHz,
- A high-speed schlieren imaging system which is able to take up to 50,000 frames per second at high image resolution, and
- A high-speed infrared camera capable of taking images up to 5,000 frames per second in the spectral range of 1-5.5 µm.

In addition, this ignition tunnel is designed to be run with other gaseous fuels (e.g. hydrogen, ethylene and propane), as well as heavy hydrocarbon fuels. To accommodate liquid fuels, a high-temperature vaporizing system will be integrated prior to the fuel injection location. The liquid fuel system can raise the temperature of the fuel independent of the air temperature. Higher temperature fuel can reduce the ignition energy according to Arrhenius reaction rate equation. Eventually, high temperature cracking of hydrocarbon fuels will be explored. In addition, a spray injection nozzle will also be incorporated to explore fuel injection in the liquid phase.

Figure 1. Schematic model of the new ignition tunnel.

III. RESULTS. Results of previous research by Lefkowitz and Ombrello [1,2] show on Figure 2 that, for each set of conditions, ignition probability is always close to 1 in the fully-coupled regime (short inter-pulse time) and significantly poorer at longer inter-pulse times. However, the transition from the decoupled (long inter-pulse time) to fully-coupled regime is a non-linear function of flow velocity, with a general trend of increasing power with increasing velocity in order to achieve high ignition probability. This indicates that a significant increase in energy deposition will be required at the 100 m/s flow velocity the present tunnel is designed to achieve.

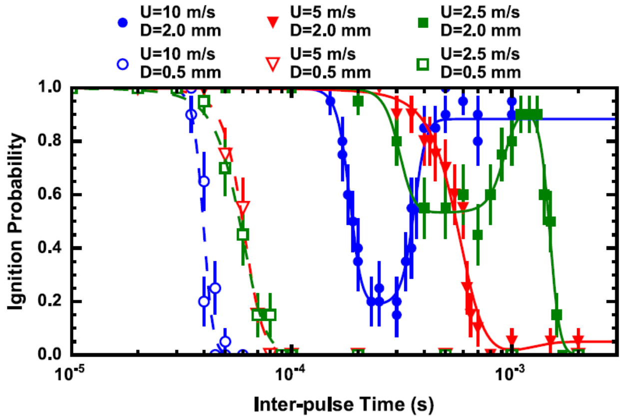


Figure 2. Probability of ignition as a function of inter-pulse time.
Reproduced with permission from Lefkowitz et al [1].

Figures 3 and 4 present how the velocity influences the kernel development dynamics showing that, for high PRF in the fully-coupled regime, the kernel is larger due to the bigger volume of gas exposed to the discharge. Figure 4 proves that the kernel growth rate increases with the flow velocity and suggests that there is a lot of value in going above 10 m/s.

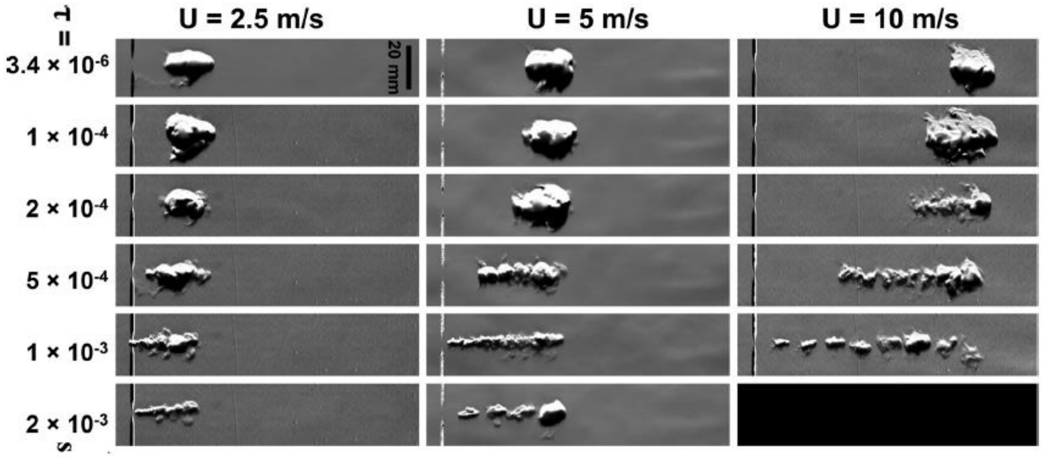


Figure 3. Schlieren images of ignition at different flow velocities and inter-pulse times. Reproduced with permission from Lefkowitz et al [1].

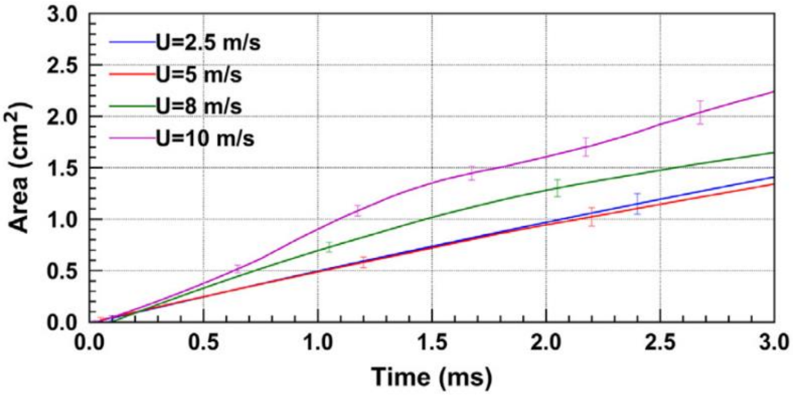


Figure 4. Kernel area as a function of time at different flow velocities. Reproduced with permission from Lefkowitz et al [2].

During the presentation, preliminary results of experiments run in this new ignition tunnel will be shown. In them, three timescales will be taken into account: flow residence time of the gas in the electrodes, plasma timescale, and timescale of the outwardly propagating flame front. However, at velocities higher than 10 m/s the latter is expected to be negligible and the kernel growth rate is likely to be determined by the flow velocity and plasma duration (among other forenamed parameters) [2]. Results obtained from experiments in this new ignition tunnel are intended to provide a better understanding of ignition phenomena and contribute to its optimization in the previously mentioned engines.

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