ענף הנעה
מחלקת מטוסים
להק ציוד
חיל האויר

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

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

יום העיון השישי
במנועי סילון וטורבינות גז

בחסות:

המעבדה למנועי סילון וטורבינות גז,
הפקולטה להנדסת אוירונוטיקה וחלל, הטכניון

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

ענף הנעה, מחלקת מטוסים, להק ציוד,
חיל האוויר

יום ה', כ"ה בחשון תשס"ז, 16/11/2006,
9:00 – 17:30, אולם האודיטוריום (אולם 235),
הפקולטה להנדסת אוירונוטיקה וחלל, הטכניון

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ענף הנעה
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יום העיון הישראלי השישי במנועי סילון וטורבינות גז
יום ה', כ"ה בחשון תשס"ז, 16/11/2006 (9:00 – 17:00), אולם האודיטוריום (חדר 235),
בניין הפקולטה להנדסת אווירונוטיקה וחלל, הטכניון, חיפה

6th Israeli Symposium on Jet Engines and Gas Turbines

To be held at the building of the Faculty of Aerospace Engineering, Technion, Haifa

08:30 - 09:30 הרשמה (Registration)

09:30 - 10:00:דברי פתיחה ▪ **פרופ' עמרי רנד\ דיקן הפקולטה להנדסת אוירונוטיקה וחלל,**

Opening:

- **Professor Omri Rand,** Dean Faculty of Aerospace Engineering, Technion**.**
- **Brig. Gen. D.Sc. Jacob Bortman,** Head, Material directorate, IAF
- **Ltc. Baruch Bar Netz,** Chief Propulsion Branch, IAF
- **Ltc. Roni Gordana**, Head, Propulsion Systems Branch, Aeronautical Division, MOD

10:00 - 13:10 מושב ראשון (First Session)
Session Chairman: Emanuel Liban, Edmatech

1. **New Laser Technology in Turbine Blade Measurements**, Danny Shacam, President, Nextec Technologies 2001 Ltd, Israel.
2. **Gas Turbine Engines Design Considerations For Unmanned Combat Air Vehicles**, Konstantino Kouris, F100 Engineering Manager, Pratt & Whitney, USA.
3. **Accelerating Technology to Address Emerging Global Issues,** Tom Maxwell, General Manager, Military Engine Systems Design and Integration, GE Infrastructure- Aviation, USA.

12:00-12:10 הפסקה וכיבוד קל (Break and refreshments)

4. **F16 Operation Profile Distribution Due To New Engine LCF Cycle Management Policy In The IAF,** IAF Propulsion Branch, Capt. Dimitry Perl, IAF
5. **Failure of DLN Combustion Chambers,** S. Arieli, I. Newman, Materials Laboratory, Israel Electric Co. LTd.
6. **Experimental- theoretical study of Spray combustion in Jet Engines and Gas Turbines at the Technion**, Yeshayahou Levy, Technion, Israel

13:10 - 15:10 ארוחת צהריים וסיור במעבדה (Lunch)

15:10 - 17:20 מושב שני (Second Session)
Session Chairman: Adam Weintraub, Engines research, IAI

7. **Analytical Investigation of the Rotor Response for Misalignment between Its Bearings**, Yuri Berlin, Bet Shemesh Engine Limited, Israel.
8. **A slip factor calculation in centrifugal impellers based on linear cascade data**, Shalman Evgeny, Becker Turbo System Engineering (2005), Israel
9. **T.S 550 Sub- Atmospheric Module (SAM),** A. David Lior, R-Jet LTd., Israel

16:10 - 16:20 הפסקה וכיבוד קל (Break and refreshments)

10. **UAV Engines in The next decade- Turbine Engines, Piston Engines and the newly Combat Proven Rotary Engine,** Hemi Oron, Silver Arrow LTd., Israel
11. **Normalized Control System For A Turbojet Engine,** Ori Yekutiel and Yinon Amir, Rafael, Israel**.**
12. **Stall and unbalance diagnostics by vibration methods**, Michael Grebshtein, RSL Electronics Ltd.

17:20 דיון ודברי סיכום (Closure)

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יום העיון השישי במנועי סילון וטורבינות גז

יום ה', כ"ה בחשון תשס"ז, 16/11/2006 (9:00 – 17:00), אולם האודיטוריום (חדר 235),

בניין הפקולטה להנדסת אווירונוטיקה וחלל, הטכניון, חיפה

הפעילות בתחומי ההנדסה השייכים לתחום ההנעה הסילונית מתרחבת בשנים האחרונות בצורה משמעותית. פרויקטים חדשים במימון משרד הביטחון, תגבור יצור החשמל בעזרת טורבינות גז ע"י חברת החשמל ובעיות הנוגעות לתחזוקה שותפת ותכנון עתידי של מנועי סילון בח"א מהווים כח מניע לפתוחים ופרויקטים רבים בנושא. כל זאת בנוסף לפעילות הרגילה של יצור סדרתי של מנועים, חלקי חילוף שונים, תחזוקה ועוד. מספר רב של גופים עוסקים בארץ באופן פעיל ושוטף בתחום זה ובהם מפא"ת, ח"א, חיל הים, אל-על, תע"א, מנועי בית שמש, רפא"ל, תע"ש, אורמת, חברת החשמל, RSL, בקר הנדסה, טכנולוגיות להבים, SIF, הטכניון ועוד.
שיפורים הנדסיים, חידושים טכנולוגיים ופרויקטים חדשים המתנהלים בארץ מצדיקים את המשך קיומם של מפגשים מקצועיים המיועדים להפריה הדדית, החלפת מידע ומהווים קרקע נוחה לעידוד שיתופי פעולה. בחמשת ימי העיון שהתקיימו עד עתה התכנסו ונפגשו כל פעם כמאה מהנדסים ומדענים מתחום ההנעה, הוצגו עבודות מהתעשיות השונות, ממשהב"ט ומהאקדמיה ולהערכת המשתתפים, ימי העיון הוגדרו כמוצלחים והסתיימו עם טעם של עוד...

יום העיון השישי יכלול 2 הרצאות מבוא מוזמנות בנושאים נבחרים, ע"י מרצים אורחים מחו"ל, נציגים בכירים מהחברות General Electric ו- Pratt & Whitney, ארה"ב. בנוסף יום העיון יכלול הצגות קצרות על הפעילויות השונות במפעלים, במכונים ובאוניברסיטאות בארץ, דיון פתוח וע"פ דרישה גם סיורים במעבדות הפקולטה. כמו כן, זו תהיה הזדמנות טובה למפגשים מקצועיים, החלפת דעות והצגת דגמים ומוצרים ע"י חברות שונות. ביום העיון תינתן אפשרות לדון בכל תחומי הטכנולוגיה הרלוונטיים למנועי סילון וטורבינות גז, כולל אווירודינמיקה של טורבו-מכונות, שריפה, מבנה ודינמיקה, סימולציות ובקרה, חומרים, תהליכי ייצור ותחזוקה, מחזורי פעולה משולבים של טורבינות גז ועוד. עדיפות תינתן לנושאי פעילות ועניין בארץ.

בברכה,

פרופ"ח ישעיהו לוי
http://jet-engine-lab.technion.ac.il
e-mail: levyy@aerodyne.technion.ac.il

Propulsion Branch
DDR&D-MOD

Turbo and Jet Engine Laboratory
Faculty of Aerospace Engineering
Technion, Haifa
http://jet-engine-lab.technion.ac.il

Propulsion Branch
IAF

6th Symposium on Jet Engines and Gas Turbines
Thursday, November 16, 2006 (9:00-17:00), Seminar Hall (Room 235)
Faculty of Aerospace Engineering, Technion, Haifa

The last few years has seen a considerable expansion of activities in Israel in jet propulsion, in addition to the serial production of small engines, various spare parts and maintenance. In Israel many bodies are active in this area including: MAFAT, IAF, Israel Navy, EL-AL, IAI, Beit Shemesh Engines, RAFAEL, TAAS, ORMAT, Israel Electric Corporation, RSL, Becker Engineering, the Technion and more.

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

The symposium will include two invited introductory lectures on chosen subjects. In adition, there will be short presentations of different activities in Israeli by colleagues from firms, institutes and universities as well as an open discussion and tour at the Jet Engine Laboratory. The Symposium will also present a good opportunity for professional meetings, exchange of ideas and presentation of models and products from various companies.

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

Assoc. Prof. Yeshayahou Levy, Chairman

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

LIST OF ABSTRACTS

רשימת תקצירים

הרצאה מס. 1

A New Laser Technology in Turbine Blade Measurements

Danny Shacam, President, Nextec Technologies 2001 Ltd, Israel.

Mechanical touch probes on CMMs (Coordinate Measuring Machines) are the most common sensors used for blade inspection. Most Blade Measurements today are based on a mechanical probe.

The amount of useful data that can be collected using the mechanical touch probe is limited. Since blades are characterized by complicated free form 3D geometry shapes, the traditional solution of touch probes on a CMM is limited both in hardware as well as in measurement software.

The recent trend from the touch trigger probe to a mechanical (Analog) scanning probe is a step in the right direction, in terms of data collection rate, however it is still limited by some major fundamental characteristics of the mechanical sensor:

a. A mechanical probe needs to maintain continuous contact with the surface and thus scanning speed is limited
b. The working range of a mechanical probe is only a few hundred microns, which makes the scanning pattern, the alignment routine and the programming of the scan path more complicated.
c. Programming a mechanical probe for a cross-section scanning operation requires operator skill and experience.
d. The size of the features that can be scanned are limited by the diameter of the stylus, so features such as leading and trailing edges are not good candidates for any mechanical or analog probe measurements.

The need for an efficient, accurate and fast non-contact laser based metrology system for Turbine and Compressor blades has been a major challenge for the last few years.

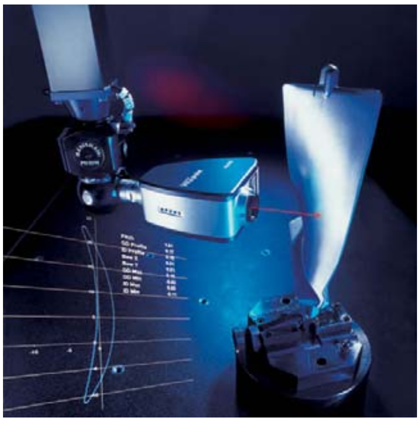
While various non-contact systems exist in the market for vision and digitizing, none has overcome the technology barriers and provided the required performance to bring efficient, fast and top accurate 3D sensor to the blade measurement world.

The traditional design of laser-based probes is built around the fundamental triangulation principle. It involves the manipulation of a laser beam projected from the object through dedicated set of optics in a fixed position and angle and an optical detector. These sensors are very sensitive to the optical parameters of the measured object, including color, material, glare & reflection, surface finish and relative angle between the laser beam and the object. This sensitivity generates large deviations and unreliable output in the measurement results.

Non-contact vision systems are starting to penetrate various 3D applications leveraging on their 2D performance capabilities. When used for 3D applications, the vision systems provide fast scanning with very limited accuracy in the 3rd dimension.

A real breakthrough in this area is the Nextec WIZprobe, a 3D laser-based scanning sensor, combining advanced laser and vision technologies. It comprises an adaptable laser source; a sophisticated set of optics, two-dimensional CCD sensor and an advanced real time adaptive control.

In addition, this sensor utilizes an extensive set of image processing algorithms to analyze the acquired image



The WIZblade Measuring System

To address the new challenges, a 3D laser-based scanning sensor, combining advanced laser and vision technologies has been developed along with a state of the art motion controller and special application software for blade alignment, blade measurement and analysis.The sensor comprises of an adaptable laser source; a sophisticated set of optics; an advanced real time adaptive control and a two-dimensional CCD sensor. An extensive set of image processing algorithms analyzes and elaborates the high-quality data gathered This WIZprobe implementation provides a feature precision of 2 microns (100 points best fit, 2 sigma), meeting the high precision requirements for blade measurement. The small laser spot size enables to measure very fine geometry details, namely the leading edge and trailing edge profiles.

Based on the proprietary optics, the unique adaptive control feature and the sophisticated image processing software, the probe handles almost all material and surface finish types, automatically performing self-calibration via real time closed loop adaptive control.

The combination of a large dynamic range and high accuracy makes it very simple to set up the alignment loop and the airfoil cross-section path and collect hundreds of points fast and accurate, with no noise and no need to filter the data

The WIZblade advantages

- **High Speed** – Speed is critical for time saving, cost saving and efficiency. WIZblade is about 5 times faster then the mechanical probe on a CMM.
- **Short Set-Up** – Set-up time is a crucial cost and time consuming parameter in the production. WIZblade alignment is about 4 times faster then the mechanical probe on a CMM
- **Accuracy** – Accuracy is a must for blade inspection. WIZblade enables to accumulate many more points on-the-fly during the cross-section scan and as such, to significantly improve the measurement accuracy
- **Simple, User Friendly Software** – The WIZblade alignment and measurement software enables very easy mode of push button operation for obtaining the full quality control report in a nice graphical and numerical presentation
- **Shiny Materials and Different Surface Finish types –** The Turbine Blade Measuring System enables scanning of very shiny stainless steel alloys, Nickel, Titanium, Polished parts and a variety of Ceramic material, due to the unique real time adaptive control capability of the system
- **Small Spot Size** – Enables the measurement of very fine details and radius such as the leading and trailing edge geometry

Conclusion

The blade industry is looking for new measurement solutions with speed and accuracy, simple alignment, no programming and minimum setup time.

The modern technology of 3D laser scanning along with a rapid growth in the PC processing capabilities, motion control capabilities and friendly application software packages enables to offer new solutions to support the modern blade industry needs in the next decade.

הרצאה מס. 2

Gas Turbine Engines Design Considarations for Unmanned Combat Air Vehicles

Mr. Konstantino Kouris,
F100 Engineering Manager, Pratt & Whitney

It has been said that the Joint strike fighter will be the last manned aircraft to be developed. All engine and airframe manufactures are focused on the design and effectiveness of the next generation of unmanned air vehicles. There are many different types of UAV's operating today in all parts of the world, However, the next step in there evolution will be to equip them with speed, stealth, intelligence and the ability to perform the functions of today's manned fleet as well as retain there original functions such as battlefield reconnaissance, target acquisition and intelligence gathering. As we move from the propeller age to the jet age we only have to look back a few years to see how quickly the airframe and engines have changed to meet the needs. The one only difference is we do not have to worry about human equation. Jet powered UAV development is in the early stages of development but progressing quickly.

This presentation will present gas turbine engine design consideration and selection criteria for Unmanned Combat Air Vehicles. The discussion will focus on the practicalities and challenges of adapting existing gas turbine engines for use in UCAV/UAV. We will look at the three major focus areas, persistence, survivability and compactness; these three areas will initially define the appropriate engine configuration. We will review bypass ratio options and how to balance TSFC (fuel consumption) and specific thrust. We will review low observable design considerations and how they impact the engine performance. We will review the unique challenges of the UAV mission and how the lifing models are impacted. This paper will also discuss specific engine configuration challenges and solutions to achieve the UAV development and demonstration goals.

<u>הרצאה מס. 3</u>

Accelerating Technology to Address Emerging Global Issues

Tom Maxwell, General Manager, Military Engine Systems Design and Integration, GE Infrastructure- Aviation, USA

The global environment is rapidly changing in the context of both military threats and ecological issues. The presentation addresses the need to accelerate development and focus propulsion system technology to formulate products that provide value to the customer in the changing environment

<u>**הרצאה מס. 4**</u>

F16 Operation Profile Distribution due to New Engine LCF Cycle Management Policy in the IAF

Capt. Dimitry Perl

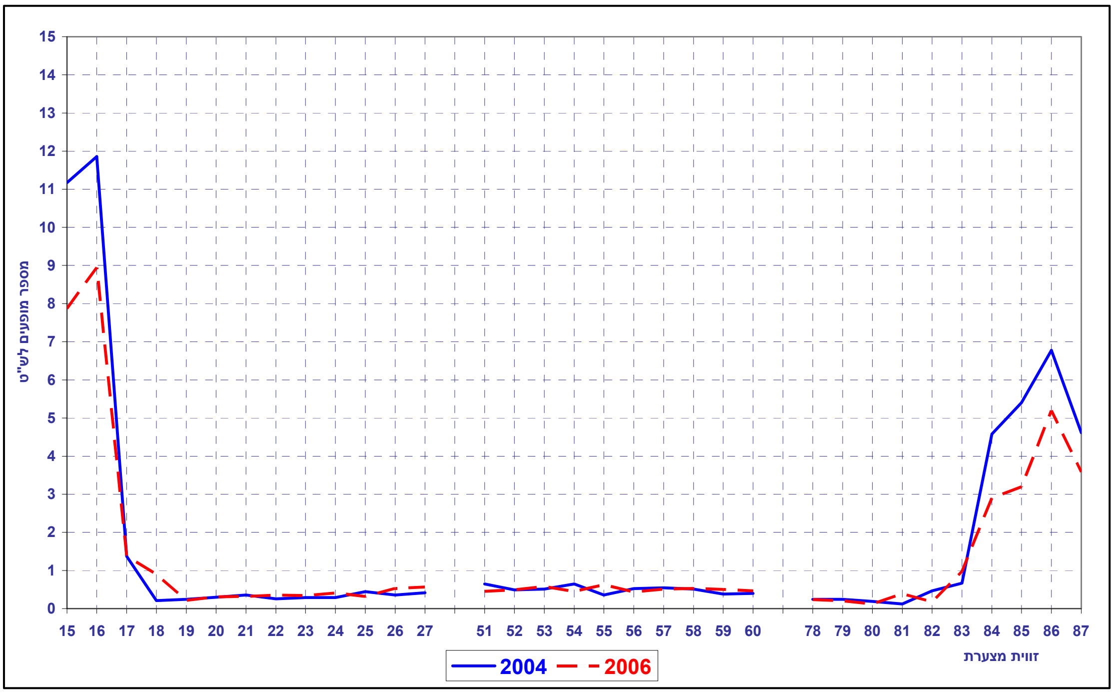
During the last year Symposium, the IAF Propulsion Branch presented a new concept for engine LCF cycles and fuel management aimed to obtain optimized cost savings for the F16 fleet.

Lately, a new risk was identified which is related to the possibility to reduce engine reliability and thus engine safety: Throttle operation very close to the control “rpm gates” <u>**without**</u> crossing them, could lead to critical engine parts damage while the engine cycle life tracking will not reflect it since the LCF cycles are not accumulated when no “rpm gates” are crossed.

The IAF propulsion branch performed a parametric research to analyze the F16 operator’s engine throttle movements in order to confirm or denounce the above

risk hypothesis. The research included a rather large data base, consisted of more than 100 F16 sorties which in turn compiled using a new developed algorithm.

The analysis results confirm a true reduction in engine LCF cycles due to the new cycle management policy. Furthermore, the risk hypothesis was removed based on the throttle distribution shown below:



הרצאה מס.5

Failure of DLN Combustion Chambers

S. Ariely, I. Newman

Materials Laboratory, Israel Electric Co., P.O.B 10, Haifa 31000, Israel, s-ariely@iec.co.il

Two Dry Low NOx (DLN) type combustion chambers failed in service. The chambers served at two different units that located at two different sites. One of the chambers was operating about 50 hours before failure, following an extensive overhaul (will be referred as Chamber 1). The second chamber failed after 5066 operation hours (will be referred as Chamber 2). Nevertheless, both failures had the same characters; inner liner had been torn out along the same circumferential weld. Both liners had been deformed during the event, since the gas blast push them into the transition piece.

The liners of both chambers sent to Materials Laboratory for failure analysis.

The inspection show that both liners failed along HAZ of dissimilar weld of cobalt-base Alloy 188 to nickel-base alloy HX. The melting temperature of fracture material is lower then of cobalt-base alloy. Relative small grains were found at fracture area.

Two mechanisms caused the both failures: stress rapture, and thermal fatigue. Both mechanisms were activated simultaneously.

Stress rupture is a mechanism that characterized with rapid creep due to high load at elevated temperature. The reason for creep to be activated at this part of the liner is the low melting temperature of the liner base material relative to other parts of the liner. Small grains that were found at that area, promoted the creep.

All the above mentioned findings show that service temperature of that part was higher then design.

Parallel cracks that were found along the bend of the liner are due to thermal fatigue, which is evidence to unstable combustion process. We assume that these cracks caused to partial exfoliation of the TBC. The TBC suppose to protect liners material against hot gases. Due to the exfoliation, liner material came to a direct contact of with hot gases. According to our results, liners material partially melted, and a blast of hot gases pushed outward some molted material. This material was found, in both cases, on the liner case.

We assume that exfoliation triggered the final failure by causing material melting and hot gases blast. The liner material, which was already weaken due to creep process, torn along Weld 1, causing the final failure.

We concluded that both liners failed due to combination of two mechanisms which were activated simultaneously: stress rapture, and thermal fatigue. The fact that two very similar failures were found at two different units that located at different sites exclude operation as a possible reason, and bring into question the validity of Dry Low NOx technology that was introduced into the combustion chambers that in question.

הרצאה מס.6

Experimental- Theoretical Study of Spray Combustion in Small Jet Engines

Yeshayahou Levy, valery Scherbaum, Vlademere Erenburg, Valery Nadvany, Ovcherenko Vitali

Turbo and Jet Engines Laboratory, Technion

The objective of the present work is to compare CFD simulation of the airblast atomizer performances with experimental results, obtained by Phase Doppler Particle Anemometry System. The work focus on the effect of the liquid properties, such as viscosity and surface tension, and of the velocity of the surrounding air on atomization. A self designed atomizer was tested and used for the simulation. The specific liquid and air properties were used to simulate initial conditions. The discharge coefficient of the liquid nozzle was taken from the test data. Three-dimensional grid was built using GRIDGEN. The computational model uses axisymmetric conditions. The STAR-CD code (Version 4) was used for CFD simulation. For the evaluation of the droplet breakup process, the Reitz-Diwakar model was applied. The following characteristics were taken into account: liquid and air properties (viscosity, density, surface tension for the liquid and the air temperature); liquid and air flow rates; liquid and air input pressure. The simulation results showed that in the near field region, close to the nozzle, an air vortex is formed. The interaction of this air vortex with spray deflects droplets and increases the spray cone. The droplets size distribution and the cone angle of the spray were compared with tested data. For simple swirl atomizer, the simulated droplets sizes were larger than the measured ones. However, comparison with other experimental results (published in the literature by A. Lefebvre (1989.) showed better agreement. For the airblast atomizer, the droplet size is strongly dependent on gas velocity at the exit from the air swirler and on the selected critical Weber number. The enhancement of the collapse-like phenomenon of the spray cone angle with increase in the gas flow rate that was observed during the experiments was not realized during the simulations. For larger values of liquid and air flow rates, there is better agreement between test data and simulation. The chosen parameters of the simulation were used in order to study the effect of viscosity and of surface tension on atomization. Comparison between simulated and test results, showed satisfactory agreement. This means that CFD simulations can be used for preliminary prediction of the effect of liquid and gas parameters on atomization characteristics. These results indicates too the possibility of using such atomization model as part of a more global jet engine spray combustion modeling that includes droplets generation, diffusion, evaporation and combustion.

הרצאה מס.7

בחינה אנליטית של תגובות מכלול סב למצב של אי –יישור בין המסבים שלו(MISALIGNMENT) והשוואה לתוצאות ניסיוניות.

מר יורי ברלין , מפעל מנועי בית שמש.

נבנה מודל תלת ממדי באלמנטים סופיים של רוטור מנוע כאשר פרטים שאינם אכסיסימטריים(להבים) מיוצגים בצורה מקורבת.

נבנה מודול של תומכי המסבים ושל מקדמי הקפיץ של המסבים הן בכיוונים של xyz והן מבחינת "סיבוב" ציר המסב.

בוצעה אנליזה מודלית של כל המכלול ע"מ ליצור בסיס נתונים לחישוב תגובות דינאמיות.

בוצע דימוי של עליית סל"ד המנוע ושל השתנות מלאכותית של האקסצנטריות שמעבר לו גדלות מאוד הריאקציות במסבים ,הסף הזה(0.06 מ"מ)תואם ממצאים ניסיוניים.

הרצאה מס.8

A Slip Factor Calculation in Centrifugal Impellers Based on Linear Cascade Data

Dr. Abraham Frenk, Becker Turbo System Engineering (2005).

Accurate modeling of the flow slip against the direction of rotation is essential for correct prediction of the centrifugal impeller performance. The process is usually characterized by a slip factor, which is the ratio of tangential velocities at exit of actual rotor and ideal rotor with the same geometrical characteristics and infinite number of blades.

Slip factor depends on various geometrical and hydro dynamical parameters. Most correlations available for calculation of the slip factor use parameters characterizing basic impeller geometry such as blade number (Z), blade discharge angle (β_{2k}), impeller radius ratio (r_2/r_1) and ratio of the meridional flow velocity to circumferential velocities of the discharge flow (c_{a2}/u_2). A general review of the available correlations was presented by Wiesner (1967) and recently by Backstrom (2006). Obtained relationships allow estimating of the slip factor with accuracy of ±5%. The 5% error in slip factor may leads to 5-10% error in estimated fluid work.

The approach presented below is based on reduction of radial cascade to equivalent linear cascade. The equivalent linear cascade has the same discharge angle (β_2). Inlet angle of equivalent linear cascade ($\beta_{1,eqv}$) is calculated using equation
$\cos(\beta_{1,eqv})=K_c \cos(\beta_1)$, where β_1 is inlet flow angle of the radial cascade. Coefficient K_c depends on parameters of the radial cascade. The reduction allows to calculate characteristics of radial blade row using well established experimental data obtained at various Mach numbers for linear cascades, diffusers and axial blade rows. Accuracy of the linear cascade data is proved by successful design of various axial compressors. Therefore the slip angle of the equivalent linear cascade $\delta\beta_{lc}$ is determined. Slip angle $\delta\beta$ is a difference of flow and blade discharge angles ($\delta\beta=\beta_2-\beta_{2k}$). The slip angle for radial impeller $\delta\beta_{rad}$ is calculated as $\delta\beta_{rad}= \delta\beta_{lc}* r_2/r_1$.

Rotors with splitters or with high loading must be divided into few radial blade rows. Dividing is based on number of blades or on the maximal allowed blade loading. In the case of multiple rotor blade rows the slip angle is calculated for each blade row. The slip angle of the rotor is a sum of the slip angles obtained for each row.

Suggested reduction of radial blade rows allows also calculating of other parameters essential for impeller design. For example, maximal flow deflection may be estimated for a blade passages with given blade discharge angle and solidity.

Calculated slip factor was compared with measured for eight centrifugal and mixed flow impellers. Geometrical and hydrodynamic parameters of the impellers are listed in Table 1. Table 2 includes calculated and measured values of the exit flow angle β_2 and slip factor σ. Slip factors obtained by other correlations are included for comparison. For all rotors difference between measured and calculated slip factors is less then 1%.

Equations for linear cascade take into account dependence of the slip angle on Mach and Reynolds numbers. Hence, suggested method allows for these parameters also. Existing correlations for calculation of the slip factor do not consider influence of Mach and Reynolds numbers. It may explain mentioned above 5% error in slip factor estimation by the correlations.

Suggested method allows also determine additional causes influencing slip factor. The slip factor depends not only on mentioned above parameters characterizing basic impeller geometry, but on difference of inlet flow angle from stall flow angle. In the rotors with the same basic geometry parameters slip factor depends on the length of the blade. Slip of the flow decreases and slip factor increases with blade length.

The method is realized as a part of a set of propriety MATLAB programs for calculation of characteristic map of centrifugal compressor.

Table 1. Parameters of tested impellers *).

Rotor No.	Z number of blades	π_k^* pressure ratio	G Kg/s	β_{2k} (outlet metal angle)	$\frac{r_2}{r_1}$	$t_{1,mean}$ (inlet relative pitch)	$t_{2,mean}$ (outlet relative pitch)	β_1 (inlet flow angle)	c_{a2} m/s	u_2 m/s (tip velocity)
1	6/12	4.35	0.41	16.99	1.83	1.0	0.695	57.8	180	472.3
2	12	3.95	3.0	33.58	2.30	0.50	-	32.7	170	483
3	11/22	5.23	0.48	12.0	1.89	1.27	0.397	57.48	189.3	500
4	7/14	3.87	1.0	48.28	2.1	1.50	0.641	56.33	182.9	550
5	27/27	4.54	2.7	9.0	2.12	0.25	0.346	46.65	185.3	455
6	15/30	3.86	2.0	8.48	2.0	0.74	0.316	50.47	160	425
7	18/36	6.79	2.75	6.25	2.18	0.56	0.175	46.25	161	520
8	12/24	6.36	2.89	19.9	1.78	1.0	0.612	60.05	165	510.6

*) All angles are measured in degrees.

Table 2. Calculated by various methods and experimental slip factors.

Rotor No.	β_2 measured	β_2 Frank	σ measured	σ Frank	σ Wiesner	σ Stodola	σ Stechkin	σ Eck
1	31.8	32.0	0.881	0.878	0.832	0.860	0.718	0.784
2	-	43.8	-	0.896	0.840	0.72	0.823	0.840
3	27.0	27.0	0.887	0.888	0.888	0.848	0.880	0.865
4	-	56.3	-	0.875	0.874	0.762	0.834	0.870
5	20.17	20.6	0.915	0.901	0.902	0.876	0.910	0.903
6	23.32	23.0	0.899	0.896	0.908	0.890	0.914	0.896
7	17.9	17.8	0.933	0.934	0.919	0.910	0.931	0.926
8	35.9	35.0	0.893	0.890	0.895	0.887	0.861	0.877

<u>הרצאה מס.9</u>

T.S 550 Sub-Atmospheric Module [SAM]

David Lior, R-Jet LTd., Israel

Abstract

The exhaust gases exiting gas turbines are hot [typically 450-600 C] at ambient pressure. This exhaust energy is usually extracted in Cogeneration systems either for heating or cooling. A Sub-atmospheric system has been designed which extracts mechanical energy and heat energy simultaniosly. This cycle is often used by employing special liquids which are vaporized by the exhaust gases through a heat exchanger ,expanded through a turbine and liquified again in a heat exchanger. The new system expands the exhaust gases directly through a turbine to a sub-atmospheric pressure , cools it with water and then compressed to ambient pressure. A power and thermal efficiency gain of 21.6% is calculated with a low cost turbo-compressor module. Controlling the module rotating speed and pressure ratio, different ratios between thermal and heat energy may be selected. Thus, a flexible cogeneration system is available.

<u>1.</u> Description-exhaust energy conversion.

The SAM converts the exhaust energy of the T.S 450 gas turbine into-

100 kw -electric energy by driving a generator.

650kw --hot water energy which may be used in variable prportions for heating or cooling through an absorption cooling system.

The combined energy output is –1267kw

550 kw electrical output resulting in 40% of thermal efficiency.

717 kw of heat energy.

The fuel energy input is 500/.333=1500 kw

The total cogeneration efficiency is thus --1267/1500= 84.5%

2. SAM technical concept—see -TS diagram figure 2.

<u>point1-point2</u> The exhaust gas [mass flow of 1.53 kg/sec and a temperature of 874K] expands through a turbine from ambient pressure to .344 kg/cm^2 cooled to a temperature of 680 k.

Turbine efficiency-89.5%

Expansion energy—329kw

<u>point 2-point 3—</u>the gas is cooled in a heat-exchanger with water at 290K to a temperature of 330K at a pressure of .331 kg/cm^2.

Heat exchanger efficiency-90%.

Heat energy -573 kw.

Point3-point 4—the gas is compressed to a pressure of 1.054 kg/cm^2 and a temperature of 469K.

Compressor efficiency-82%

Compression energy-239kw

Net mechanical energy-329-229=100kw

Net electric energy-100*.97=97 kw.

Points 4-5- the gas is cooled through a secondary heat exchanger by water at 290 K to 326 K .

Heat exchanger efficiency-80%.

Heat energy 144 kw.

Total heat energy-573+144=717 kw.

3. Technical description-figure 1

The SAM is a seperate unit mounted on top of the basic T.S.450 gas turbine and comprises the following details-

--an axial turbine made of stainless steel [Aisi 316]—500 mm max. diameter.

--a water/gas finned tube heat exchanger.

--a centrifugal compressor made of stainless steel [Aisi316]-with radial diffuser -560 mm max. diameter., driven by the turbine at 26000 r.p.m.

--a secondary water/gas finned tube heat exchanger.

Total weight—[water weight excluded]- 350 kg.

4. Performance—

550 kw electric energy.—at 40% thermal eficiency or 36.5% electric efficiency.

717 kw hot water energy which may be asigned at different proportions to heating and cooling according to specific client requirements. The absorption cooling size will be adapted accordingly. The client may control the proportion between cooling and heating day or night, winter or summer.

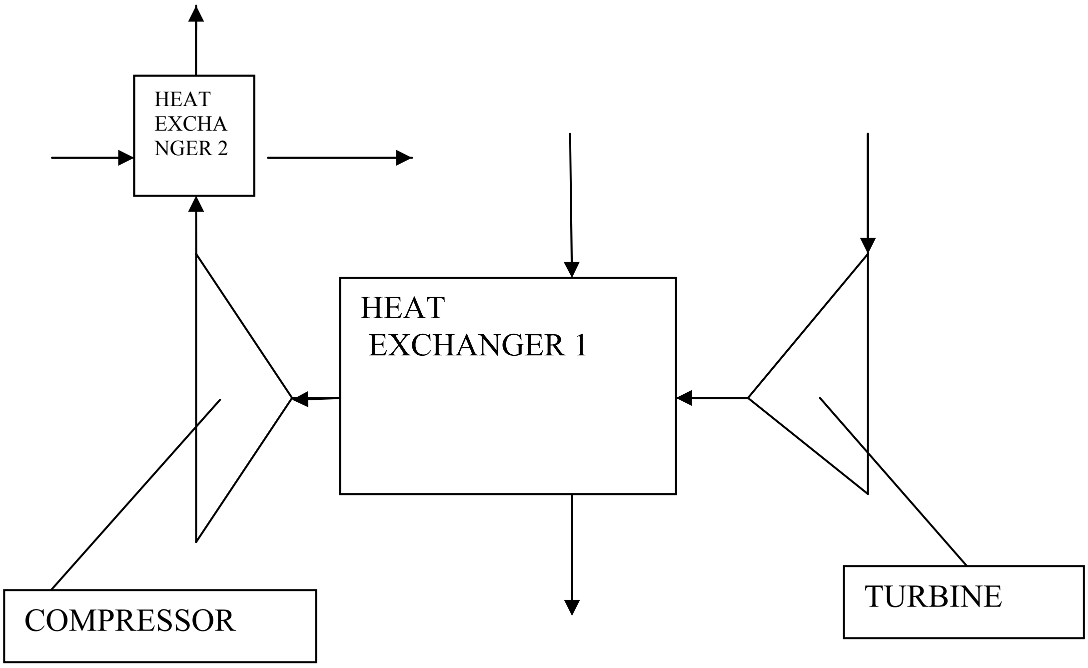


FIG.1---SAM CONFIGURATION

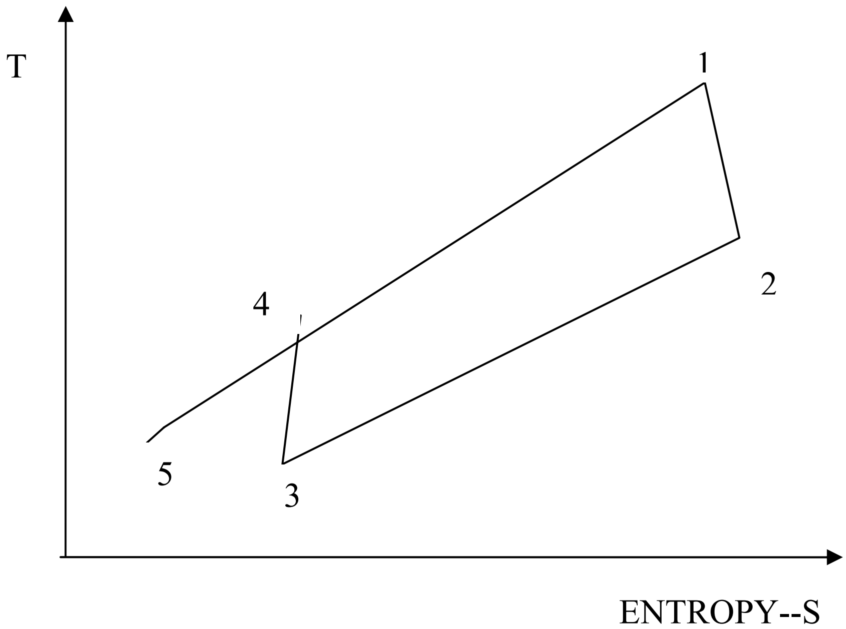


FIG.1: T-S diagram

<u>הרצאה מס.10</u>

UAV Engines in the Next Decade - Turbine Engines, Piston Engines and the Newly Combat Proven Rotary Engine

Hemi Oron, B.Sc., MBA, Director, UAV Engines Plant, Elbit Systems Ltd.

For years UAVs industry was far behind the Fighter Aircrafts and Commercial Aviation markets, in all aspects: Technology, budgets, R&D, priorities. UAV Engines were regarded in an inferior level, and the Engine Industry Leaders (GE, P&W, RR, SNECMA…) did not show any interest in this niche, and left the market to small non-aerospace manufacturers.

Recent years brought a dramatic change in attitude towards the UAVs around the world, with big prospects for the future, and growing budgets being directed towards this market. Combat experience in various arenas (Kosovo, Iraq, Afghanistan, Lebanon) has proven the expectations from these Vehicles are not exaggerated.

The requirements of future UAV powerplants are discussed (unfortunately most of the UAV market is based on the military). Battlefield experience is being translated to UAV Engine needs, emphasizing their special requirements that differ them from Helicopter and Fighter engines.

Current and future UAV engines are presented, and their characteristics are compared to the future needs. Technical concerns (e.g. sfc, endurance, noise) are discussed.

Special attention is given to the newly combat proven Rotary (Wankel) Engine, which played a major role in recent battle experiences (Iraq, Lebanon). A new Model of a rotary engine currently under development will be presented, including dynamometer test results and analysis.

A map of the UAV engines for the next decade will be outlined, with the specific application of the engine families (turboprop, jet, piston and rotary) in the future battlefield.

<u>הרצאה מס. 11</u>

Normalized Control System for a Turbojet Engine

By Ori Yekutiel and Yinon Amir, September 2006
RAFAEL- P.O.B 2250 (39)
Haifa 31021, Israel

The design and performance of a Control System for a Turbojet Engine are presented. The approach employs normalization and linearization of fuel flow, RPM, and atmospheric temperature.

Measurements are normalized, and a single controller is designed for all flight conditions. The output of the controller (normalized fuel flow) is thereafter "denormalized" and applied to the engine.

The design process leans on physical aspects over the operational envelope, and enables a simple design of Fuel Limiting, based on normalized conditions only.

Though only a simple PI-controller example is included herein, engine normalization also simplifies the design process and the controller obtained with other control design approaches. Simulation results are included, and display good performance.

הרצאה מס. 12

Stall and Unbalance Diagnostics by Vibration Methods

Dr. Michael Grebshtein

RSL Electronics Ltd., Ramat Gabriel Industrial Zone, P.O.B. 21, Migdal Ha'Emek,

www.rsl-electronics.com

The vibration signatures of a turbine engine contain information related to the structural properties, dynamic properties (rotation related) and other properties assumed to be aerodynamic related. For a failure related to the dynamic class, the change in the signature is directly related to the rotating motion (e.g. shafts, bearings, gears etc), the structural and geometric information on the engine and specific components is sufficient for estimation (prediction) of the expected changes in the signature.

Vibration methods for diagnostic of stall and unbalance of shafts of turbine engine are presented. The methods include few major stages:

- Validity checks of the vibration signals and engine rotation speed validation and analysis.
- Separation between stationary (steady-state) and non-stationary recordings, in order to adapt the type of analysis required
- Validation of the vibration signatures-pointers correspondence.
- Graphical comparison between signatures of the engines at similar test conditions.
- Baseline calculation based on signatures of the production engines at different conditions.
- Calculation of diagnostic indexes that compare the signatures of the suspect and production engines at similar conditions versus the calculated baseline.

Unbalance is manifested in intensified vibration levels at the first harmony of the subject shaft rotating speed. When the unbalance is severe it may be manifested at higher harmonies of the shaft rotating speed. The most reliable results are expected to be obtained in the order domain of the phase average, but can be observed in the frequency or order domains.

The stall was identified by observing of rotating speed data of the both low and high pressure shafts and shock pulse in vibration sensors raw data that manifested in the second and fourth statistical moments of the vibrations signals (RMS and kurtosis).

Results of application of the proposed methods on real data of normal and degraded engines are presented and discussed.