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OVERVIEW OF MODERN AND ADVANCED TECHNIQUES IN JET ENGINE TESTING

Presented work describes an overview of techniques, probes and sensors as well as methods used in modern and advanced jet engine testing. The main goal of the article is to present complexity of the subject and to obtain knowledge and survey about future undertaken research. Paper is based on broadly considered bibliography and describes various methods of measurement. Within the first chapter temperature measurement methods are shown. Usage of the most popular technique, which considers thermocouples, is described in contrary to noncontact temperature acquisition using pyrometer. Both traditional and alternatives noncontact pressure measurement techniques are mentioned in the next part. Author underlined following chapter showing few different ways of stress and vibration measurement. Conventional, using strain gauges; modern, using Fiber Optic Bragg Sensor, as an example of intrusive techniques are shown. Additionally noncontact stress and vibration measurement examples are described using eddy current, capacitive and optical probes.

Introduction

Modern aero-engine must fulfil many requirements which customer expects. Instrumentation equipment used for testing needs to withstand both the economical goals and many hostile environmental factors such as very high temperature (above 1800 K) and rotational speed (more than 18000 RPM) inside the engine. Thus there is a growing requirement for experimental techniques, test facilities, sensor and probes that can be used to evaluate the engine design, which was broadly described in [2, 4, 8, 9, 27, 28]. On the ground level, engines and its components are tested in so called test rig which operates in a mode with closed gas circuit in order to run the rig at Reynolds numbers typical for jet engines. The inlet and exit conditions can be separately settled to simulate variety altitude levels and to cover whole engine operation map.

The measurements in engine requires modification of the engine hardware. In the turbine itself there can be even more than 700 measuring points [8]. Thus measurement is limited due to physical space. Considering this, provision has to be made not only for tapping point, but also for the sealing of the instrumentation as it exist in the area of higher pressure and then leading the instrumentation out of the engine. Usually even dozen engines are used in thousands of testing hours. Sensors and probes are designed to withstand each development test period. In [3] 97,5% of used instrumentation was working until end of the testing period.

The instrumentation can be divided into three types according to the required rate of response for the measured variable: steady state, which gives the response in 10's of seconds; transient, which respond in seconds e.g. temperature and pressure (this depends also on the position of the probe installed in the engine); dynamic, which response in 10^{th} of seconds [14] which measures the frequency responses of specific transducers, such as strain gauges, rumble probes, AC pressure transducers and capacitive probes that are recording rapidly changing event [3].

Presented work shows the division of the instrumentation according to measured event. Goal of this article is to obtain knowledge and overview about the subject for the future research within modern and advanced techniques in jet engine testing.

1. Temperature measurement

To evaluate the performance of the engine or its components very precise measurement of total temperature is needed. High temperature inside the engine is challenging when it comes to sensors design. These includes thermocouples, resistance temperature detectors, thin films, optical probes and other acoustic techniques.

Thermocouple application

Low cost, robustness and simplicity of thermocouples make them the most used sensors in real engine environments. The sensor measures only its own temperature at the head junction, but this temperature can differ from the local temperature of the gas or material [16, 33].

In the engine testing the most in-use are N and K type thermocouples. Type K (chromel–alumel) is the most common general purpose thermocouple with a sensitivity of approximately 41 μV/°C, chromel positive relative to alumel and is available in its –200°C to +1350°C range. Type N (Nicrosil–Nisil; Nickel-Chromium-Silicon/Nickel-Silicon) thermocouples are suitable for use at high temperatures, exceeding 1200°C, due to their stability and ability to resist high temperature oxidation. Sensitivity is about 39 μV/°C at 900°C. Designed to be an improved type K, it is becoming more popular [33]. In some applications type N thermocouple is more suitable due to the removed hysteresis which can occur in type K thermocouple [3].

Material measurement of engine components is measured with wires which are usually connected to the measuring point of the engine component. Total air measurement needs to be evaluated in the stagnation tube which is used to compensate the energy of the flow and measure its total value. Usually the sensors consist of the thermocouple surrounded by the stagnation tube or so called Kiel head where the velocity is reduced to a level where no further compressibility effects occur. Combination of such elements along the shaft is called the total temperature rake [34]. Kiel heads can be also mounted on the leading edge of the airfoil creating in a such way a leading edge instrumentation.

During measurement of total temperature in Kiel heads several errors effects have an influence. Velocity terror can be reduced by minimizing the mach number of the internal flow by reducing the inlet to exit ratio. Conduction error after implementation the actual convective heat transfer coefficient into the computation that error can be minimized. Those errors together with radiation error can manipulate the results of the total temperature measurement significantly. In [34] the ratio of the Kiel head inner diameter to the thermocouple diameter, the position/ length of the thermocouple and the size of the bleed holes and the internal velocity was investigated to reach the most optimized solution. The results shows a significant reduction of the measuring errors, which is only the 0,4% of the total temperature above the 1300 K. Among the others the example is the probe which consists of a chocked nozzle located in the flow and a system downstream including a cooler, a flow measuring device and a valve. It can operate in two modes: in the first mode the valve is open, the probe is aspirated and the nozzle is choked. The mass flow through the probe is measured using instrumentation place downstream of the cooler, so that it does not have contact with hot flow. In the second mode the valve is closed and the stagnation pressure is measured using the same instrumentation downstream the cooler. The total temperature is computed as a derived variable from the measurements of stagnation pressure and mass flow rate. Studies show that uncertainty of such system is still decreasing and for now is on the level of ±6 K at 1800 K (0,3%) [16].

Pyrometer measurement

In modern engines gas in the high pressure turbine (HPT) is so hot that its temperature can be measured by pyrometers which is a noncontact method of measurement. They are usually mounted to the casing. The pyrometer measures the heat radiation of the turbine blade surface. Using the Planck law the surface temperature can be deduced. Reaction to temperature change is nearly without delay, they are applicable at the higher temperatures and non-reactivity, i.e. as the pyrometer and the blade surface have no contact, heat exchange is not taking place, thus the measured temperature is undistorted. Basically pyrometers contains of four parts: the optical system with lens included, diaphragm and filter for capturing and imaging the radiation, the detector for transformation of the radiation into electrical signals, the evaluation unit for amplifying and linearising of the signals as we as the output unit [1]. There are several factors which have a strong influence on the measurement using pyrometer. Radiation of the surrounding components, contamination of lens, pollutants and soot particles may handicap the correct measurement of the radiation. Nevertheless the research related to using this method of temperature measurement is being performed and the results shows that there is still a potential in it. In some development the error margin had been change from 5% to 3% [1].

2. Pressure and flow characteristic measurement

Within this chapter the measuring types of pressure (static an dynamic), flow direction, basically behavior of the flow in the turbo-machinery are considered.

Traditional techniques

Pressure is measured in many different ways. Semiconductor pressure sensors are most widely used because of their small size and their ability to measure both steady and unsteady components of pressure, with a high bandwidth (150 kHz÷1 MHz) over a wide pressure range (0,35÷70 bar). Nevertheless, stability of the sensor in high temperature applications requires a cooling configuration [7]. Usage of two piezoelectric sensors located on the stem and on the inclined surface at the tip of the probe respectively can measure dimensionless yaw, pitch, total and static pressure can be obtained with 0,3% of accuracy [23].

The flow behavior using the intrusive method is mainly taken by the fast response pressure probes integrated into the engine. Those probes can be designed as a head probes with holes or as a rakes with pressure tubes installed instead of thermocouples. For simpler measurement, it is important to use total-pressure tubes which are insensitive to flow direction [7]. Multi-hole pressure probes are widely used as accurate and robust and versatile flow measuring instruments. They are often used in strong gradient fields, e.g. traversing wakes or shocks. The probes with 12 or even 16-hole are taken under consideration but they have usually large heads. They measure the flow velocity from 50÷70 degree to even 160 degree (18-hole probe) [22, 25].

Sensors detecting wall shear stress are either direct-measurement based devices using floating elements or make use of indirect measurement principles relying on heat transfer phenomena, correlation methods, or momentum balance. Within the study [5] micro-machined wall hot-wire sensors composed of a highly sensitive, nickel, thin-film resistor spanning an air-filled cavity in a mechanically flexible substrate are presented. Also the application of the different types and design of anemometers and high-frequency oscillating-hot-wire sensor for turbulence measuring can be found in the studies [31].

Additionally there is a technique to measure pressure and temperature of the flow using special sensitive paint. It has been widely described in [10, 26, 30].

Nonintrusive methods

Nonintrusive techniques for whole field of measurements are being investigated to infer the structural details of complex supersonic jets [32]. Various optical techniques are available for temperature, molecular number density, and velocity measurements [15]. Optical flow-measurement techniques can be divided into two basic categories: molecular-based techniques can involve elastic (non-energy exchanging) or inelastic (energy-exchanging) scattering processes from atoms or molecules or absorption of light by molecules sometimes followed by spontaneous emission; particle-scattering techniques involve elastic scattering from particles (Mie scattering) entrained in the flow. Among others starting from particle image velocimetry [20], fiber-optic MEMS pressure sensors [24], laser Doppler velocimetry [17], through miniature rainbow Schlieren deflectometry system [12], molecular Rayleigh scattering technique [19] a tremendous variety of nonintrusive measuring techniques are constantly being developed [21].

3. Stress, vibration and tip clearance measurement

To prevent damage to the test rig of the developed engine and to predict the numbers of life cycles of the rotor blade stress and vibration data need to be taken. Thus testing those figures requires a precise evaluation using unquestioned techniques and sensors. Mostly used method of rotor blades strain and vibration data acquisition is the method based on strain gauges and modulated grid. Usage of gauges requires centrifugal force resistance instrumentation on the rotor and radio telemetry system for signal transmission. With the frequency modulated grid, a specially formed wire in the compressor casing interact with a magnet mounted on the tip of a blade. During operation, the magnet generates altering current in the wire that is modulated by the blade vibrations. There have been several studies already performed to develop any new and better methods of stress (including crack detection) and vibration measurement e.g. using eddy current probes or noncontact techniques [29].

Fiber Optic Bragg Sensors (FOBS)

Strain measurement with FOBS can not compete with strain gauges according to precision but they have advantages. They are small and lightweight and because they are built with the glass or coal fiber they can be integrated into the structure of the testing component. They can measure very high strain

(>10,000 μm/m) and they are immune to electromagnetic interference. The FOBS are intrinsically passive and no-distance dependent (up to 50 km connection is possible). Long term stability is high and great corrosion resistance is observed. As it is mentioned above they are not as precise as metal foil strain gauges yet. The FOBS shows high temperature dependences (1°C→10 μm/m) and they need additional temperature measuring system to operate efficient enough (they can not self compensate). The radius of the fiber needs to be >10 mm so rosettes tend to be quite big. And as each experimental and innovative technique is much more expensive than that in-use. The FOBS consist of the two fiber: inner core (from 4 μm to 9 μm) and the outer, cladding (around 125 μm diameter). The core has a higher refraction index causes by high Germanium doping. Light propagate only inside the small core because of differences of refraction indexes. The Bragg grating is written into the fiber core. To measure the strain the sensor as it is in case of strain gauges need to be glued on the specimen. Stretching the Fiber Optic Bragg sensor causes a change in grating period resulting in a change in wavelength of the reflected ultraviolet light. Due to techniques the wavelengths of the reflection peaks are shifted. To measure the strain precise measurement of these shifts is required. For laboratory task the special interferometers are used but and special design filters are usually designed [13].

Non intrusive tip clearance measurement

The blade vibration is under influence of many different effects. Significant is the varying blade tip clearance between tip of the blade and casing components. It might be caused by non-concentric casings or orbiting around the main shaft. Distortion of the inlet flow (caused by irregular intake geometries) and stationary vane or struts upstream or downstream of the rotor blade. In addition to this the tip clearance varies for each operating point. As the speed increases extension of the rotor, as a result of increasing centrifugal force, reduces the clearance. On the other hand, heating the casing by compressed and thereby warmed-up working medium increases the clearance. The first phenomena is dangerous because it can cause disturbance in the blade working condition, which can lead to variety of vibration modes, the second one decrease the efficiency of the turbo-machinery. Vibration of the blades can eventually cause the cracks or damage, which in many cases leads to the engine failure. Within this paragraph the tip clearance techniques are described. Despite the different names the methods are called, from Non-contact Strain Measurement System (NSMS), Blade Tip-Timing (BTT) [6], Optical Blade Vibration (OBM) [36], *from germ*. Berührungslose Schaufelschwingungsmessung (BSSM) [35], the concept is common. Systems use sensors, optical, eddy current, microwave probes or capacitive, mounted in the casing around to measure and analyze the time of arrival of the blade tips [11]. Its passing time at the sensor vary in the presence of vibration and depends on the amplitude and frequency of this oscillations. The signals are correlated with the blades using 1/rev input. Because of the typical operating condition within the turbine which results in blade tip speeds of approximately 400 m/s and circumferential blade tip vibrations amplitudes of order 0.3 mm, the time period over which the vibration is measured is 1 μs.

Eddy current sensors are most commonly used for contact proximity and displacement measurements. Their application is well established and measurement accuracy is high. The sensors are rugged and often used in contaminated environments such as turbine of the jet engine. They are available in various shapes and sizes for positioning measurement. Two types of probes are in use. The passive probe deploys permanent magnet to generate the magnetic flux and coil to measure the voltage generated by the eddy currents in the targets. Active probes can have one or multiple coils, in the simplest form a single coil is used to generate the magnetic flux and measure the voltage generated by the eddy currents induced in the target. Range of the probe is generally half of the diameter of the coil. With this approach the measurement can be made through casing material, in some cases even up to 2 mm thickness [6].

The capacitive probes is made from metallic sensing surface-electrode of the probe, which is surrounded by two mutual insulated concentric screens. In conjunction of the blade surface it forms a capacitor. A constant voltage is applied between electrode and blades. The passing blades cause the change of the capacitance at the blade which corresponds with size of the tip gap. This causes the shift in charge converted into a voltage signal by a charge amplifier [36].

The principle on which the **optical system** operates involves focusing of a narrow laser light or light beam, led through cylindrical lenses onto the passing blade tip. As the blade tip enters the path of this beam, the light is reflected back to photo sensor. The reflected beam can be coupled, through the front glass plate into receiving fibers and is routed forward to the silicon avalanche photodiode based signal conditioning system. The intensity of the reflected light rises very rapidly during blade passing. In the absence of any structural vibration, the time fro the tip of a particular blade to reach the optical probe, called blade arrival time, would depend on the rational speed alone. However, when the blade vibrates arrival time will depend on both the amplitude and frequency of the blade vibrations. A particular mode of the vibration is captured by a given optical probe depends on the location of the probe with reference to the vibration [6, 36].

Except mentioned methods there is still a development within tip clearance measurement performed. Active Clearance Control is a subject of research [18] and tip clearance using plasma actuators is described in [21].

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PRZEGLĄD NOWOCZESNYCH I ZAAWANSOWANYCH TECHNIK W TESTOWANIU SILNIKÓW ODRZUTOWYCH

S t r e s z c z e n i e

Prezentowana praca przedstawia przegląd technik oraz czujników pomiarowych użytych w nowoczesnych metodach do testowania silników odrzutowych. Głównym celem pracy jest przedstawienie złożoności zagadnienia oraz zdobycie wiedzy na prezentowany temat. Praca oparta jest na rozbudowanej konferencyjnej bibliografii oraz dziennikach branżowych z ostatnich lat.

W pierwszej części artykułu zostały opisane metody pomiaru temperatury. Przedstawiono charakterystykę najpopularniejszej z metod – wykorzystującą użycie termopary i porównano ją z wybraną techniką bezkontaktową – wykorzystującą pyrometr. Omówiono tradycyjne i alternatywne oraz bezkontaktowe sposoby pomiaru ciśnienia i zachowania się przepływu wewnątrz silnika. Przedstawiono również kilka metod pomiaru naprężeń i drgań w silniku lotniczym. Metody inwazyjne, konwencjonalne, wykorzystujące do pomiaru zarówno tensometry, jak i nowoczesne czujniki Bragga, zostały porównane z metodami nieinwazyjnymi. Dodatkowo opisano przykłady technik wykorzystujących czujniki prądów błądzących, pojemnościowe i optyczne.

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