SENSOR NETWORK APPLICATION FOR STUDYING MODAL PROPERTIES OF TURBOMACHINE

Aleksej Mironov[1], Pavel Doronkin[1], Vitalijs Kuzmickis[1], Aleksejs Safonovs[2]
[1]SIA "D un D centrs", Latvia; [2]Riga Technical University, Latvia
aleksei@ddcentrs.lv, pavel@ddcentrs.lv, vitalij@aviaresearch.eu, aleksejs.safonovs@edu.rtu.lv

Abstract. Vibration techniques become most useful for diagnostic and monitoring of operating turbomachine technical condition. One of the actual areas of diagnostics and monitoring to be developed is the detection of foreign objects entering the intake duct of running engines. When foreign objects impact the surfaces of the engine, this is reflected in its modal properties changing. Modeling the response to foreign objects entering into the inlet of a running engine, the modal properties of its casing parts have to be known. The paper presents FE modeling and the experimental study of the sensor network application to determine the modal properties of turbomachine casings. The study of modal properties was carried out using the technique of Operational Modal Analysis. A comparative analysis of simulated and experimentally determined modal parameters was performed. The conclusion was made about the possibility of using piezoelectric films as sensors for studying the modal properties of engine body parts in a wide frequency range. Analysis of the test results showed a high order of vibration modes due to the complex configuration of the housing parts.

Keywords: piezo electric films, structural modal properties, turbomachine.

Introduction

Application of vibration diagnostic techniques for turbomachines expands aiming to provide its operation safety and reduce maintenance costs [1; 2]. The effectiveness of these methods depends on the vibration models used to describe the complex interactions of rotating units [3] and dynamic properties of structural parts [4]. Such models consider the wide-frequency response of rigid casing units to the high-frequency impulse interactions of rotating blades, gears and bearings in a turbomachine. The paper studies the structural modal properties of the aviation engine required for detecting a foreign object damage (FOD) ingested from the environment or thrown up by the landing gear. Up to now vibroacoustic analysis was applied for foreign object debris detection aiming for motor design optimization [5] but not for diagnostics. For detecting FOD the authors proposed to use the short term increase of the vibration signal above background level. The greatest response to FOD the structural units may have at natural mode frequencies that composition depends on the engine unit configuration. Therefore, for FOD detection the frequency range of vibration measurement must be determined considering natural modes of the specific engine housing units.

The casing units of any machine may have plenty of natural modes in wide frequency range as, for instance, considered in [6]. For estimating the modal parameters of structures, the modal modelling and experimental study are used. To study vibration modes of structures, the Experimental and Operational modal analysis techniques are applied, like described in [7]. The latter one called OMA is used widely in recent decades as the most promising method in case of unknown excitation [8]. To study complex and rigid casing units of jet engine the high-order models have to be applied. A modal model must include many Degrees of Freedom (DOFs) to consider the unit's construction, and to validate the model each DOF must be measured by the proper sensor. Therefore, OMA method application requires an extensive sensor network distributed throughout the studied structural unit. Typically, accelerometers measure vibrations, however, its application for modal research is complicated due to fixation problem. Commonly used fixing by a stud violates the structural integrity, while an adhesive layer acts as a mechanical filter for high frequency vibration components. As the optimal solution, the piezoelectric film sensors may be applied for modal properties study of turbomachine casing parts. Flexible piezo films with negligible mass are easy glued on the surface and allow estimation of modal properties in wide frequency range. Earlier authors substantiated the use of uncalibrated piezo films as the sensors for modal properties study [9]. The signal of piezo film sensor is proportional to velocity of tensile stress variation in time so, as the vibration frequency higher, the signal amplitude less. This feature may limit piezo film application, as there are many natural modes of turbomachine casing units in high frequency range. Therefore, this experimental study aims to check whether piezo electric film sensors can provide determination of the modal properties of engine units in wide frequency band.

DOI: 10.22616/ERDev.2024.23.TF063

Methods and materials

The study included FE modeling and the laboratory tests of the turboshaft engine TV2-117 hull. For modeling the engine units, the Autodesk Inventor environment was used with built-in Autodesk Nastran-In-Cad for modal calculations. Typical metal alloys applied to turbojets were used as materials for housing part modeling. When calculating the dynamic properties, the solid elements of various sizes were used with bonded connections. FE models of engine units are illustrated in Fig.1.

a) b) c) d)

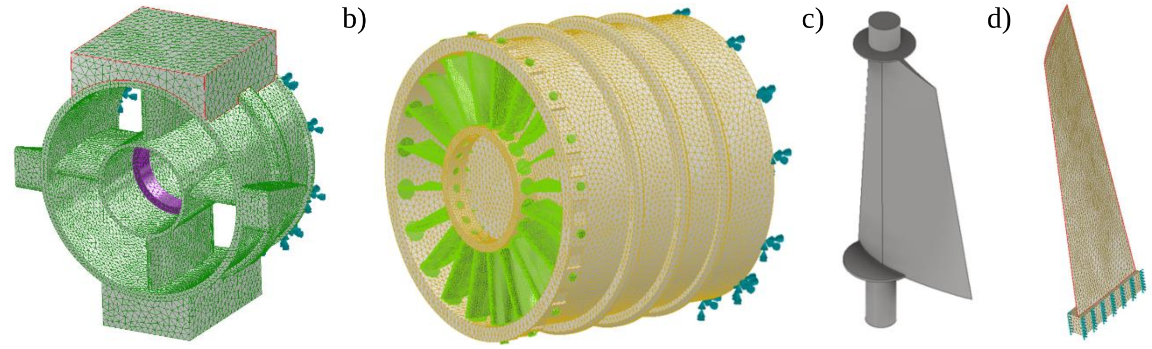

Fig. 1. **FE models of turboshaft engine structural units:** a – front bearing casing; b – compressor casing; c – blade; d – vane

At the first modelling stage the modes of each structural unit were computed to study the frequency bands and typical shapes. Data models, frequency range and mode quantity are presented in Table 1.

Table 1

Spread of the sensor sensitivity

Engine unit	Elements	Frequency band, Hz	Modes
Front bearing casing	101552	0-6000	50
Vane	10009	0-6000	10
Compressor casing with guide vanes	287686	0-2320	50
Assembled front part of engine	310777	0-10000	433
Blade	23287	0-12150	10

Next, the model combining the front bearing and compressor casings has been used to simulate modal properties of the front engine part. There were calculated 433 natural modes in frequency range up to 10000 Hz. Fig. 2 illustrates some types of mode shapes, like beam-shaped (1524 Hz) in lower frequency range, and high-order shell modes, like in the front part (3449 Hz) and in the rear part (5010 Hz). Analysis of high frequency modes showed high-order shapes due to complex model configuration.

a) b) c)

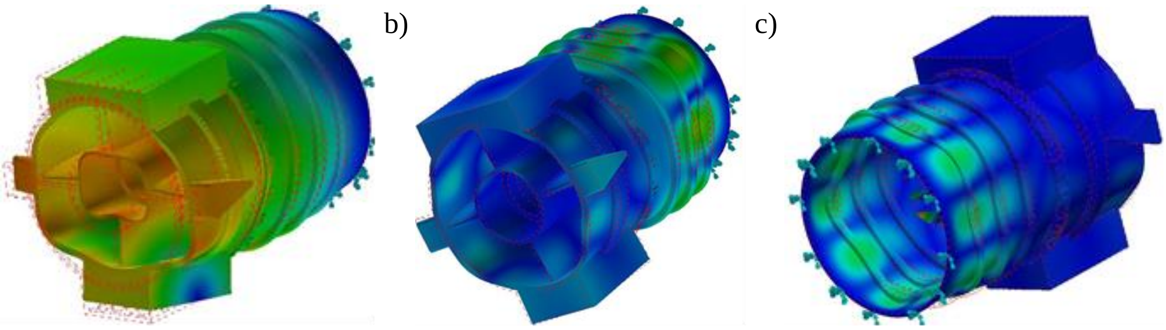

Fig. 2. **Modal shape samples: a – 1524 Hz; b – 3449 Hz; c – 5010 Hz**

Wide range of simulated modes requires a correspondingly wide frequency range from the measurement system.

The TV2-117 engine was used for experimental check of piezo film measurement abilities and validation of the modal simulation results. The turboshaft engine mounted on the test bench (Fig.3) comprises a ten-stage axial flow compressor, two-stage compressor turbine and a two-stage power turbine.

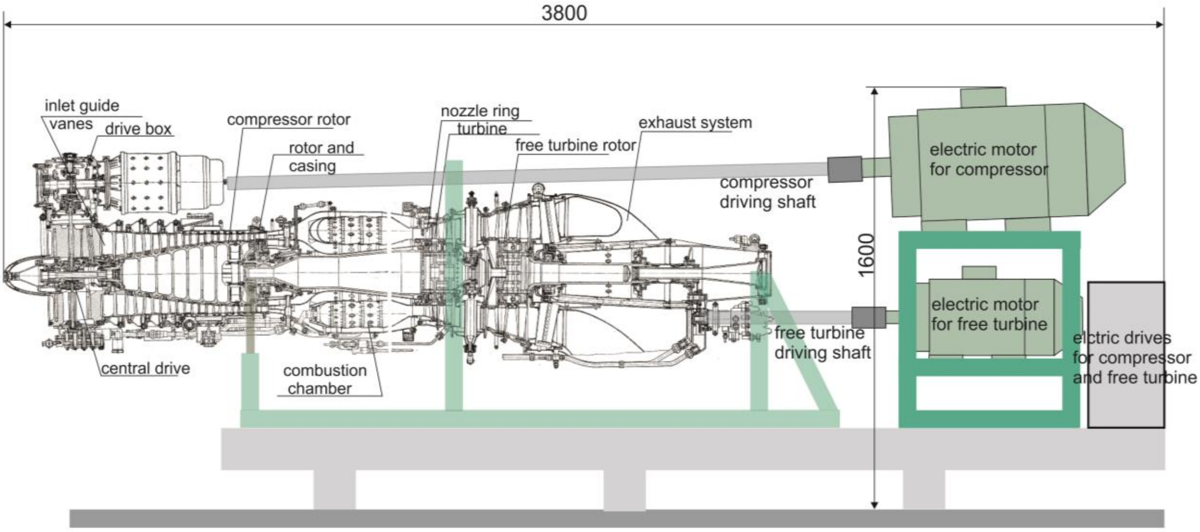

Fig. 3. **Test bench: technological complex layout scheme**

Rotation of the compressor and power turbine is provided by electric motors connected to the drive box and speed controller by means of shafts. The electric drives for the motor controlling are mounted on the same frame.

The piezoelectric film sensors are measuring vibrations at multiple points on the engine housing surfaces. The network of piezo film sensors allows OMA technique application to determine the modal properties of the engine constructions.

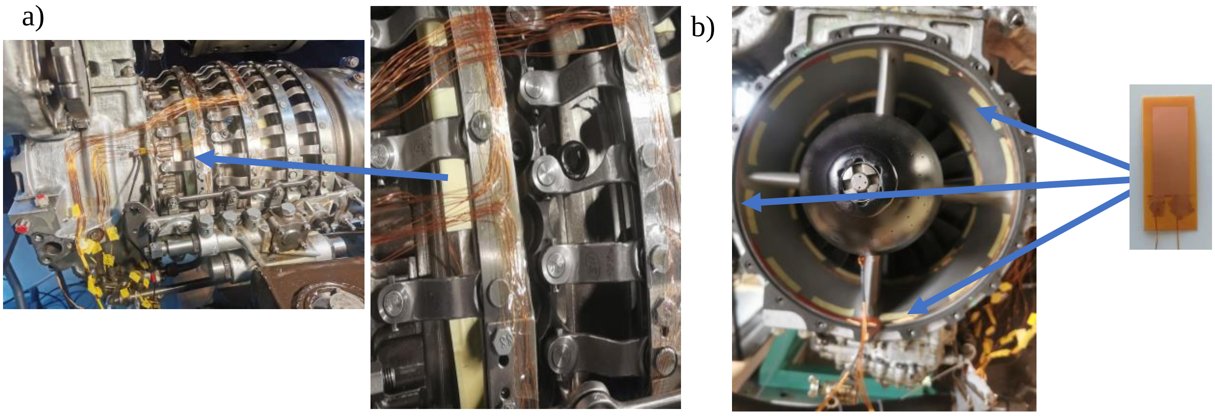

Fig. 4. **Engine casing with piezo film sensors:** a – piezofilms on the surface of the compressor casing: b – Piezofilms on the surface of the intake duct

The sensor network includes 48 piezoelectric films (Fig.4b), which number is limited by available measurement channels. Piezo films described more detailed in [10] and connection wires have been glued to the surfaces of the front bearing casing (inner) and compressor casing (outer). The measurement system is shown in Fig. 5.

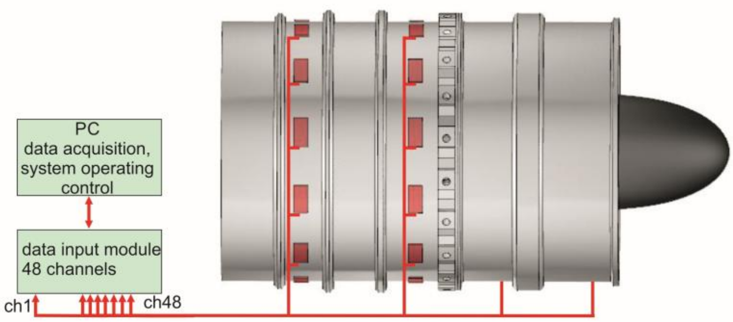

Fig. 5. **Measurement system**

Testing methods

The applied OMA testing method considers random impulse excitations and vibration measurements of the engine housing in multiple points. Vibrations are actuated manually using irregular impacts by a plastic hammer to engine massive front casing and casing side surfaces. Impacts are applied normally to the surface of the casing, with the point of impact gradually shifting in a circumferential direction until it is completely bypassed. Vibrations are measured and recorded using a sensor network and a multi-channel data input module B&K 3660 C. The sampling rate is 65536 Hz to provide the frequency range up to 25,6Hz. The duration of one test is 240 seconds, while approximately 65 impacts were applied to the casing. The series of 5 tests were conducted, using different impact hummers for excitation. The recorded signals of each test were the data set for modal estimation using the commercial software ARTeMIS.

Data processing methodology

The ARTeMIS software applies the most usable OMA techniques, including: Enhanced Frequency Domain Decomposition EFDD and Stochastic Subspace Identification [11]. The latter includes Canonical Variate Analysis (SSI-CVA), Principal Components (SSI-PC), Unweighted Principal Components (SSI-UPC), Extended Unweighted Principal Components (SSI-UPCX). To reflect normal vectors of tensile stress velocity signals measured by sensors the geometric model of DOFs configuration is used (Fig.6 left). Developing the data of a single test the ARTeMIS detects natural modes and calculates the parameters (frequency, damping and shapes). Processing of vibration signals was carried out in the frequency range up to 10 kHz to check the abilities of the measurement system to detect high-frequency vibration modes. The modal parameters estimated from the single test have high uncertainty, as the testing conditions do not fully comply with OMA requirements. The modal enhancement described in [9] may reduce uncertainty by averaging parameters between test series. The modal enhancement is based on eigenvector transformations, and includes modal shape normalizing, mode grouping and phase alignment. Enhancement allows detecting the sustainable modes, which shapes and frequencies may be used for assessing the similarity between experimental and simulated modes. For instance, Fig.6 (right) illustrates the mode 3385 Hz with 4 circumferential half-waves similar to simulated mode 3449 Hz in Fig.2.

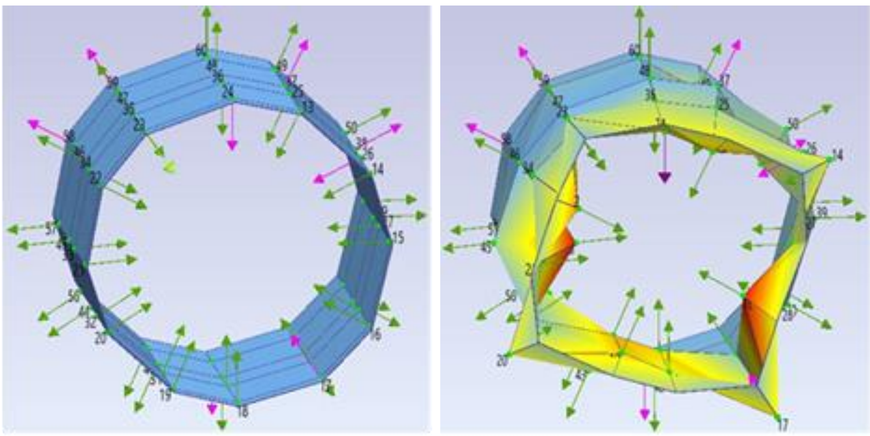

Fig. 6. **Geometric model (left), mode 3385 Hz**

Results and discussions

Modal simulation of the engine casing showed the specific clusters of multiple modes generated by guide vanes and concentrated in narrow frequency bands, demonstrated by the diagram in Fig. 7. In the model such clusters are caused by Autodesk techniques allowing a spread of the modelled vane properties. Few differences between properties of the simulated neighboring modes lead to closely located modal frequencies on the frequency axis. Actually, this is similar to mechanical property spread of actual guide vanes in a compressor, where permissible technological deviations may cause local grouping of natural modes in the frequency domain.

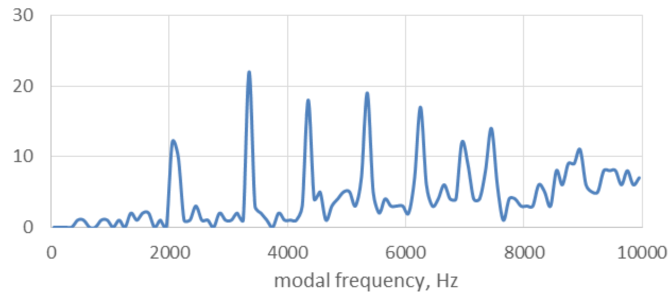

Fig. 7. **Mode density variation depending on frequency range**

Simulation has demonstrated vibration modes of the engine body in a wide frequency range (up to 10 kHz). For proper definition of modal shapes, the number of measured DOFs (sensors number) must exceed the modal order. Since the used measurement system had a limited number of channels, the capabilities for modal identification in this study were also limited.

Data processing techniques (OMA and modal enhancement) applied to experimental data provided 11 sustainable modes of the engine front casing. Although identification of the calculated modes was not the research objective, visual comparison made it possible to find the correspondence of the most pronounced modes to the modeling results. For example, the shape of the 3385 Hz mode (Fig. 6 right) was consistent with the presented simulated 3449 Hz mode when the latter is represented in terms of voltages.

Conclusions

1. The study confirmed the capability of piezoelectric sensors for measuring vibrations being glued to the surface of engine body parts. The system included that these sensors provide signal measurement in the frequency range up to 10 kHz.
2. The OMA technique processing the piezo film signals makes it possible to determine the modal parameters of the engine housings. Therefore, piezoelectric film sensors allow measuring vibrations of engine body parts, including a high-frequency band, and provide determining the modal parameters using state-of-the-art analysis methods.
3. Analysis of the test results showed a high order of vibration modes due to the complex configuration of the housing parts. To detect high-order modes, the number of sensors in the sensor network must exceed the order of modes required for detection.

Author contributions

Methodology, A.M. and A.S.; validation, P.D.; investigation, P.D., V.K., A.S.; data curation, P.D., and A.M.; writing – original draft preparation, A.M; writing – review and editing, P.D. and A.S.; visualization, V.K., A.S. All authors have read and agreed to the published version of the manuscript.

Acknowledgements

This research was funded by the European Regional Development Fund Project No. 5.1.1.2.i.0/1/22/A/CFLA/001 " Investigation of the application of predictive diagnostics technology for aircraft power plant".

References

[1] Report EASA_REP_RESEA_2012_6. Research Project: (VHM). Vibration Health or Alternative Monitoring Technologies for Helicopters. (2014). [online] [11.02.2024] Available at: https://aerossurance.com/helicopters/easa-hums-activity/

[2] Wronkowicz-Katunin A. A Brief Review on NDT&E Methods For Structural Aircraft Components Fatigue of Aircraft Structures, vol.2018, no.10, 2018, pp.73-81. DOI 10.2478/fas-2018-0007

[3] Mironov A., Doronkin P. Verification of Vibration Diagnostic Technique for Flow Path of Turbomachines. In: Kabashkin, I., Yatskiv, I., Prentkovskis, O. (eds) Reliability and Statistics in Transportation and Communication. RelStat 2023. Lecture Notes in Networks and Systems, vol 913. Springer, Cham, 2024. DOI: 10.1007/978-3-031-53598-7_20.

[4] Yan W. B., Pan H. X., Jiang S. Z. Dynamic Properties of Engine Main Components. In Advanced Materials Research, Trans Tech Publications, Ltd. vols. 455-456, 2012, pp. 1454-1458. DOI: 10.4028/www.scientific.net/amr.455-456.1454
[5] Ahmad A., et al. "Foreign Object Debris Detection and Automatic Elimination for Autonomous Electric Vehicles Wireless Charging Application." SAE International Journal of Electrified Vehicles, vol. 9, no. 2, JSTOR, 2020, pp. 93-110.
[6] Król E., Maciążek M., Wolnik T. Review of Vibroacoustic Analysis Methods of Electric Vehicles Motors. Energies 2023, 16, 2041.
[7] Di Lorenzo E., Manzato S., Peeters B., Ruffini V., Berring P., Haselbach P.U., Branner K. Modal Analysis of Wind Turbine Blades with Different Test Setup Configurations. In Topics in Modal Analysis & Testing, Volume 8, Mains, M.L., Dilworth, B.J., Eds, Conference Proceedings of the Society for Experimental Mechanics Series, Springer: Cham, Germany, 2020.
[8] Abdelghani M., Goursat M., Biolchini T. On-Line Modal Monitoring of Aircraft Structures under Unknown Excitation. Mech. Syst. Signal Process. 1999, 13, pp. 839-853.
[9] Mironov A., Chate A., Safonovs A., Kuzmickis V., Doronkin P. SHM System Prototype for Serial Structures Operating Under Different Conditions. In: Limongelli, M.P., Giordano, P.F., Quqa, S., Gentile, C., Cigada, A. (eds) Experimental Vibration Analysis for Civil Engineering Structures. EVACES 2023. Lecture Notes in Civil Engineering, vol 433. Springer, Cham, 2023.
[10] Product Features: Piezo Solutions. [online] [11.02.2024] Available at: https://www.te.com/usa-en/products/sensors/piezo-film-sensors.html?tab = pgp-story
[11] ARTeMIS Structural Vibration Solutions. [online] [11.02.2024] Available at: https://www.svibs.com/operational-modal-analysis/