WIBROAKUSTYCZNA ANALIZA NIEWYWAŻENIA WIRNIKÓW W OKRĘTOWYCH TURBINOWYCH SILNIKACH SPALINOWYCH

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Streszczenie
Diagnozowanie okrętowych turbinowych silników spalinowych wymaga stałego profesjonalnego nadzoru diagnostycznego, który nie może być realizowany przez personel techniczny jednostek pływających. Z tego powodu zdecydowano o powstaniu zintegrowanego systemu nadzoru diagnostycznego okrętowych silników spalinowych eksploatowanych przez MW. Zrealizowany w AMW system został wdrożony na okręty wyposażone w siłownie typu COGAG. Prezentowane w artykule wyniki badań wibroakustycznych dotyczą kontroli wyważenia wirników w silnikach turbinowych oraz oceny dopuszczalnego czasu ich eksploatacji.

Słowa kluczowe: diagnostyka, wibroakustyka, turbinowe silniki spalinowe, wirniki, wyważanie.

VIBRATION ANALYSIS OF UNBALANCING OF GAS TURBINES ROTORS

Summary
In the paper results are presented of vibroacoustic research on balance control of gas turbine rotors and assessment of their permissible operation times. In the paper results of vibroacoustic research on balance control of gas turbine rotors and assessment of their permissible operation times are presented. The work is a part of implementation of an (the) integrated diagnostic control system of gas turbines installed on Polish Navy ships fitted with COGAG propulsion systems.

Key words: diagnostics, vibroacoustic, gas turbines, rotors, unbalancing.

ABSTRACT

The usage of naval gas turbines requires a professional technical supervision. Crews of small ships that are mainly provided in the Polish Navy can not fulfil such a requirement. Therefore, it was decided to support the crews of such vessels by the „Base Diagnostic System of Naval Gas Turbine Engines" (BDS) which was made in the Institute of Construction and Propulsion of the Vessels of the Polish Naval Academy.

In the paper results of vibroacoustic research on balance control of gas turbine rotors and assessment of their permissible operation times are presented. 1241 RE missile corvettes, which are fitted with COGAG gas turbine propulsion systems, are subject to a permanent basic diagnostic system. The investigations were based on the following assumption: If technical state degradation of gas turbine rotor sets is a function of their operation time (at a load spectrum assumed constant) then it is possible to select from the recorded vibration signal spectrum such parameters whose changes can be unambiguously assigned to the operation time. Application of the proposed approach makes managing the engine's operation time much more rational, especially at its end. The proposed approach is non-invasive and does not require taking the ships out of service. Realisation of investigations of the kind makes it possible to collect data for a database of the future monitoring system of ships, expected to improve their operational features. Applied diagnostic method is one of the element the „Base Diagnostic System of Naval Gas Turbine Engines" used by the Polish Navy. This diagnostic method of the gas turbine engines brings many advantages on the economical and reliability fields. It is one of the most important tasks of the exploitational policy in the Polish Navy.

BASE DIAGNOSING SYSTEM

Since 1984 the vessels equipped with gas turbine engines were operated in the Polish Navy. Exploitation of naval ship propulsion systems is a complex task due to specific features of marine environment as well as demand of maintaining high level of serviceability and reliability of the ships. From the side of users, doubts are often expressed concerning maintenance times or making decision on further exploitation of engines. It is very important task in the case when all elements of propulsion system are foreign.

Application of periodical or on-line diagnostic procedures makes it possible to operate ship propulsion systems in accordance with their current technical state. Especially in the case when ship's gas turbines hourly period of scheduled maintenance is presently the criteria for maintenance time determination. Though such exploitation strategy makes early scheduling of maintenance operations and their logistic assurance possible, but it simultaneously contributes to increase of costs because of its replacement system of elements (technically often still serviceable ones) as well as it makes impossible to early detect primary symptoms of failures occurring before the end of maintenance time.

For proper diagnosis of engine faults a single system is not sufficient. Several different systems are used to pin point engine faults and give confidence in the results of the diagnosis:

Performance monitoring:

- Measuring kit for on-board gathering of on-line performance data in real time. Typical parameters, like: pressure, time, temperature, rotation, fuel consumption and torque are gathered in parallel from four engines, using original device - DIAGNOZER, to the RAM and finally to PC. Specialised software is able to calculate all parameters and compare with producers characteristics or diagnosing data matrix.

Vibration monitoring:

- Measuring kit for gathering on-line vibration data which is independent on performance monitoring devices. Application of vibration techniques to the gas turbine propulsion systems is justified not only regarding the same turbines but also for investigations of mutual geometrical position of elements of torque transmission system. For realisation of the investigations the measurement instruments: GC-89 analyser and FFT-2143 analyser of Bruel & Kjaer (Spectris), were used making it possible to collect and process measured data using program PULSE Version 5.1. Measuring transducers (accelerometers) were fixed to steel cantilevers located on the flange of the low-pressure compressor (for assessing the technical state of engines) [6] and over the main radial bearing of the input high speed flexible shaft (connected Power Turbine and Gear Box) on the gear boxes (for assessing coaxiality ot the shaft) [4, 7].

Lube oil testing:

- Lube oil sampling and testing equipment enables to find metal impurities and assessing the injection temperature, viscosity and content of a water. The off-line system implements the trend calculation, taking into account the consequential changes of the periodical oil supplements.

Visual inspections:

- Endoscopes and boroscopes for internal engine inspections enable to accomplish gas passage and combustion chamber examinations. The data camera allows to collect and analysis pictures of each blade on all stages of rotors and stators. Burner nozzles and swirl vanes inside combustion chambers can be examined as well.

The vibroacoustic monitoring systems of ship propulsion systems were first time applied in the middle of 1980s [3,7]. Application of periodical diagnostic procedures or on-line monitoring systems makes it possible to operate ship propulsion systems in accordance with their current technical state. In the case of ship gas turbines the hourly period of scheduled maintenance or repair surveys is presently the criteria for maintenance time determination. Though such exploitation strategy makes early scheduling of maintenance operations and their logistic assurance possible, but it simultaneously contributes to increase of costs because of its replacement system of elements (technically often still serviceable ones) as well as it makes impossible to early detect primary symptoms of failures occurring before the end of maintenance time [2,3,4].

Application of vibroacoustic techniques to the gas turbine propulsion systems, as an element of multi-symptom diagnostics, is justified not only regarding the same turbines but also for investigations of mutual geometrical position of elements of torque transmission system, as well as of control of electric energy generating sets.

OBJECT OF INVESTIGATIONS

The 1241 RE missile corvettes, among other Polish Navy ships, are also subject to a permanent basic diagnostic system. They are fitted with COGAG gas turbine propulsion systems. Their configuration scheme is presented in Fig. 1.

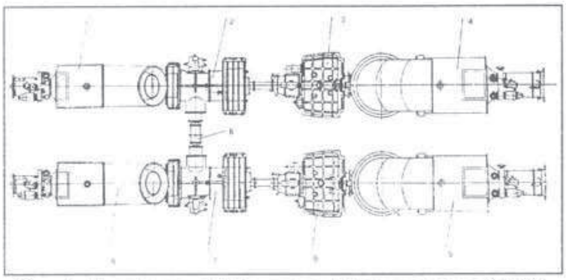

Fig. 1. A scheme of the propulsion system of 1241 RE missile corvette

1 – Starboard service turbine unit (TZSM PB) of abt. 3000 kW output

2 – Starboard service reduction gear (PM PB)

3 – Starboard peak-power reduction gear (PMS PB)

4 – Starboard peak-power turbine unit (TZSS PB) of abt. 9000 kW output

5 – Port side peak-power turbine unit (TZSS LB) of abt. 9000 kW output

6 – Port side peak-power reduction gear (PMS LB)

7 – Port side service reduction gear (PM LB)

8 – Intermediate shaft

9 – Port side service turbine unit (TZSM LB) of abt. 3000 kW output

To obtain reliable data on diagnostic parameters, investigations of the gas turbines installed in the presented propulsion system were carried out by means of the multi-symptom diagnostic model whose one of the main features is recording and analysing vibroacoustic signals. The investigations were aimed at determination of permissible in-service unbalance and appropriate assemblage of turbine rotors on the basis of selected vibroacoustic parameters, and - finally – determination of their permissible operation time resources.

The investigations were based on the following assumption:

If technical state degradation of gas turbine rotor sets is a function of their operation time (at a load spectrum assumed constant) then it is possible to select from the recorded vibration signal spectrum such parameters whose changes can be unambiguously assigned to the operation time.

If critical values of the vibroacoustic parameters are known then it is possible to estimate a permissible operation time period on the basis of changes with time of the investigated parameters. During realisation of the investigations in question the use was made of producer's guidelines for permissible values of vibration parameters, as a initial comparative and verifying element. Because DR 76, DM 76 and DR 77 turbines are similar to each other an uniform measurement method was applied to all the considered engines (at observing individual values of symptoms).

REALISATION OF THE INVESTIGATIONS

For realisation of the investigations the measurement instruments: GC-89 analyser and FFT-2148 analyser, of Bruel & Kjaer, were used making it possible to collect and process measured data. Measuring transducers (accelerometers) were fixed to steel cantilevers located on the flange of the low-pressure (LP) compressor only. It was decided to carry out the investigations with the use of the transducer fixed to the LP compressor flange for lack of transducers and equipment suitable for measuring signals at the temperature as high as 200°÷ 300° C occurring on the HP compressor flange.

The fixing cantilevers characterised of a vibration resonance frequency value different enough from harmonic frequencies due to rotation speed of the turbine rotors. The measurements were taken perpendicularly to the rotation axis of the rotors. Such choice was made on the basis of theoretical consideration of excitations due to unbalanced shaft rotation, and results of preliminary investigations of the object [6].

As signals usable for the „defect-symptom" relation the following magnitudes were selected by the turbines' producer:

– Ysnc - 1st harmonic value of vibration velocity amplitude connected with the LP compressor ,
– Yswc - the same but connected with HP compressor
– Yrms - root-mean-square value of vibration velocity amplitude within the range of 35 Hz ÷ 400 Hz.

The changes of the vibroacoustic symptoms were analysed in function of service time within the ranges:

for DR 76 and DM 76 engines : from 0 to 2000 hours

for DR 77 engines : from 0 to 1000 hours.

The choice was justified by the time-between-repair values scheduled by the turbines' procedure. For purpose of these investigations a simplification was made consisted in assuming values of the after-repair turbine vibroacoustic symptoms as those of the new turbine. To make such assumption was necessary due to rather low number of the investigated objects (only eight turbines of each type). The following limit values of rms vibration velocity amplitude were specified by the turbines' producer:

for DR 76 and DM 76 engines :

- permissible value of Yrms equal to 24 [mm/s] ,
- permissible value of harmonics Y equal to 17 [mm/s],

for DR 77 engines :

- permissible value of Yrms equal to 30 [mm/s],
- permissible value of harmonics Y equal to 20 [mm/s].

For further diagnostic inference the criterial 1st harmonic values of HP compressor was rejected for the reason of an important influence of damping decrement on recorded values of Yswc signals. Determination of the maintenance time on the basis of a Yswc signal value is possible only indirectly - by analysing Yrms and Ysnc signals.

Results shown in Fig. 3 and 4 of the investigations of changes of the considered values of symptoms during ship operation indicate that the maintenance time is a function of not only turbine design features, but also of a selected exploitation policy. At the considered service load spectrum the expected maintenance time for both types of turbines was two times longer than that specified by the turbines' procedure.

As it was necessary to adjust operation procedures to warranty terms it was decided to establish two-way control of cleanness of the gas flow part of the turbines: 1st - by means of the endoscopic method and 2nd - assessment of changes of the vibroacoustic parameters. The control is carried out at least two times a year for all gas turbine engines in service. Its scope also contains recording the values of the operational parameters whose changes could be an initial symptom of failures of the coupled devices as well as elements of the fuel supply system. All information is recorded and stored in the database of the system in operation.

Results of the maintenance time assessment on the basis of Ysnc parameters for DR 77, DR 76 and DM 76 engines are presented in Fig. 2 and 3.

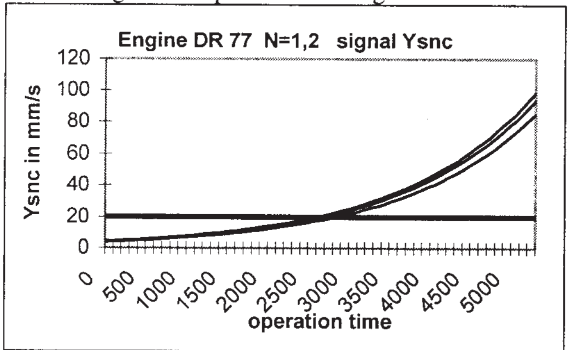

Fig. 2. Maintenance time assessed by means of Ysnc parameter

In order to obtain uniform diagnostic procedures regarding unbalance assessment of the turbine rotors the dimensionless parameters characterising that states were applied. On the basis of theoretical considerations as well as results of other diagnostic investigations carried out for some years the following parameters were selected as those most sensitive:

S1 – ratio of the mean vibration velocity amplitude of a given rotor (1st harmonic) and the velocity component relevant to 2nd harmonic excitation frequency of the rotor in question

S2 - ratio of the mean vibration velocity amplitude of a given rotor (1st harmonic) and the velocity component relevant to 3rd harmonic excitation frequency of the rotor in question.

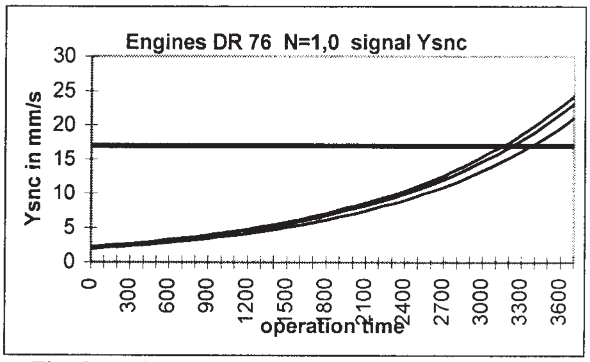

Fig. 3. Maintenance time assessed by means of Ysnc parameter

From an analysis of the results the following minimum values of S1 and S2 parameters were determined:

- *for DR 76 and DM 76 engines* :

S1SNC = min 1.5
S2SNC = min 2.5
S1SWC = min 1.5
S2SWC = min 2.5

- *for DR 77 engine* :

S1SNC = min 1.5
S2SNC = min 1.8
S1SWC = min 1.7
S1SWC = min 2.9

where :

SNC stands for LP compressor, SWC – for HP compressor.

By analysing the kinematics system, the front internal bearing of the HP compressor rotor was selected as the most dynamically and thermally loaded one. By means of harmonic analysis of the vibration excitations connected with the bearing's work regarding the internal shaft unbalance it was possible to determine permissible values of the velocity amplitude V_R of the vibrations characteristic for frequency difference of the rotor velocities of HP and LP compressors. They are as follows:

1st harm $V_R = 8$ mm/s
2nd harm $V_R = 1.6$ mm/s

The presented method was verified by investigating also other parameters characterising technical state of the engine in function of operation time, such as skid, endoscopic control, starting parameters, lubricating oil contamination etc. Moreover, the permissible diagnostic parameter values specified by the producer were taken as those verifying the assumed vibration symptoms. The accelerometers were fixed in the same way as that assumed in the turbine producer's model of vibration energy propagation. Changes of values of S1 and S2 parameters are presented in Fig. 4 and 5.

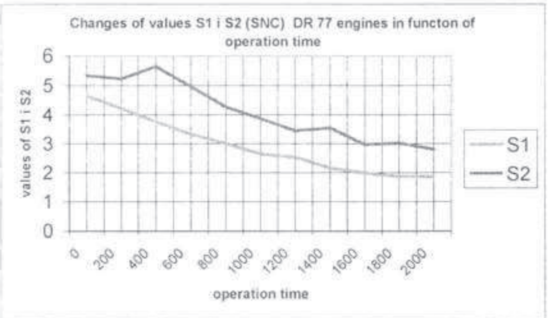

Fig. 4. Changes of values of S1 and S2 parameters in function of operation time for DR 77 engine

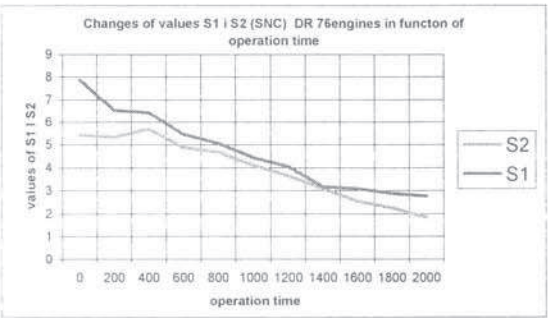

Fig. 5. Changes of values of S1 and S2 parameters in function of operation time for DR 76 engine

COMMENTS TO RESULTS OF THE INVESTIGATIONS

Two-way realisation of the investigations made reliable verification of the investigation results possible.

The following detail conclusions were drawn for further diagnostic inference:

- *For DR 76 engines*: Ysnc vibroacoustic parameters are diagnostically susceptible at the engine load N = 1.0, and *for DR 77 engines* : Yrms and Ysnc parameters at the engine load N = 1.2.
- Changes of 1st harmonic values connected with HP compressor rotors (Yswc) and LP ones (Ysnc) at the work of DR 76 and DR 77 engines at BJ load are hardly noticeable in function of operation time therefore their operational susceptibility is too low.
- Changes of Yrms parameter with operation time are not unambiguous hence it is of a low diagnostic merit.

On this basis „symptom value – operation time" relationships were determined, and the time to next maintenance finally assessed. The engine load was assumed the criterion for estimation of the compulsory maintenance time for DR 76 and DM 76 engines, evolving from exceedance of permissible symptom values during normal operation of the engine. For the calculation of Y(t) values the factor k = 1.1 (covering 10% measurement error) and the user confidence factor m = 1.05 was applied as follows :

$$Y(t) = k \cdot m \cdot Yr(t)$$

where :
Yr(t) –vibration parameter function of operation time

For DR 77 engine Ysnc parameter is diagnostically susceptible because it leads to a shorter maintenance time at the considered maximum load. By taking into account the between-repair-time period for DR 77 engines amounting to 1000 hours the expected maintenance time of 2600 hours was assessed in accordance with its technical state on the basis of Ysnc parameter values (Fig. 2).

DR 76 turbine engines are installed in the considered M - 15 E service propulsion system. The load N = 1.0 of them was assumed the criterion for determining their maintenance time basing on exceedance of permissible values of the considered symptoms at normal engine operation.

For estimation of the engine's maintenance time according to its technical state such parameter was selected whose normal service changes determine the maintenance time shorter at a higher load.

This was based on two following assumptions:

- Forces connected with various unbalance forms, manifested in recorded vibration signal changes, increase along with rotational speed increase (hence also with engine's load)
- Results of the investigations at the load N = 0.6 of DR 76 service engines and N = 0.8 of DR 77 peak-output engines have been rejected as the least credible ones. At these loads the engines operate within resonance speed ranges therefore the results could not be the basis for technical state assessment of the engines.

Hence for estimation of their maintenance time, Ysnc parameter was selected and its value of 3150 hours was determined from exceedance of the permissible value (Fig. 3).

FINAL REMARKS AND CONCLUSIONS

- Application of the proposed approach makes managing the engine's operation time much more rational, especially at its end.
- The proposed approach is non-invasive and does not require taking the ships out of service.
- Realisation of investigations of the kind makes it possible to collect data for a database of the future monitoring system of ships, expected to improve their operational features.
- Experience gained during the investigations would be utilised for other power plants equipped with gas turbines.
- The proposed diagnostic method is a coherent element of Basic Diagnostic System used by Polish Navy for many years.

- The proposed exploitation method leads to important economical profits and especially to reliability improvement, a first-rate problem.

From analysis of the presented results the following detail conclusions dealing with vibroacoustic investigations can be offered:

- For further research the following target operation times of rotor systems (at the assumed load spectrum), required for their maintenance should be assumed :
- 3150 hours - for DR 76 and DN 76 turbines
- 2600 hours - for DR 77 turbines.
- Assessment of the engine technical state by means of S1 and S2 vibration parameters makes it possible to flexibly utilise engine operation time in the case of not performing repair operations.
- Periodical control of Ysnc parameter trend development enables to credibly represent changes of a given parameter in function of operation time.
- The Ysnc parameter was selected the same for both considered engines due to its unambiguous dependence on operation time and similar character of its changes.
- Control of S1 and S2 parameters during exploitation makes it possible to assess state of contamination of the gas flow part of the considered turbine engines, and exceedance of its permissible value could be taken as a signal for necessary washing of their compressor units.
- The proposed maintenance time resources concern only the rotor sets. Assessment (in the proposed time instant) of serviceability of the coupled devices, fuel supply and lubricating systems was not included into the scope of the present investigations.

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Andrzej Grządziela was born in Gdansk, Poland, in 1965. He joined to Polish Naval Academy in 1994 as a research-lecture assistant and in 1998 he became an assistant professor in the Institut of Construction and Propulsion of Vessels in the Polish Naval Academy. His current research interests are vibration condition monitoring of gas turbine engines, the torque transmission elements alignment and construction of ship propulsion plant. He is the author of several papers on condion monitoring and selection of propulsion systems for naval vessels.