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Possibilities of FAM-C method in diagnosing ship power plants

SUMMARY

In the paper the FAM-C diagnostic method developed by the Air Force Institute of Technology, Warsaw, is described. The method based on measurements of electric alternator's frequency modulation, makes it possible to assess the level of usual wear-and-tear of subassemblies and to locate defects during operation of aircraft power transmission systems.

A few prototypes of a pocket-size tester based on this method were six years ago produced and practically implemented to indicate the most worn subassembly and its wear-and-tear level.

Actually, the computerized diagnostic system based on the testers' results is used. Attempts to experimental application of the FAM-C method for diagnosing some ship power plant devices, are presented and discussed.

INTRODUCTION

Shafts of driving systems often suffer premature wear-and-tear due to action of complex factors [1].The FAM-C method based on the measurement of modulation of alternator instantaneous voltage frequency, was proposed by this author [2,3] in order to be able to monitor and possibly to counteract excessive wear phenomena. For some years the method has been applied for diagnosing mechanical elements of aircraft equipment, a.o. failures of one-way couplings, converters and power transmissions. For diagnosing some equipment units of MiG-29 aircraft a pocket-size tester was elaborated. Measurements can be taken at some distance from dangerous structural components of an object under examination and the tester can be connected with the electric network at any its point. After one-minute test it can indicate diagnostic state of particular elements. In 2001 the SD-KSA diagnostic system operating on the basis of the data obtained from the testers, was designed, manufactured and implemented by the Air Force Institute of Technology, Warsaw.

The system makes it possible :

- to monitor wear of particular aircraft subassemblies, growing with time of operation (Fig.1a),
- to prepare a collective breakdown of wear state of particular subassemblies of an aircraft squadron under operation (Fig.1b).

A great advantage of the method is that no gauges are required to be fixed to an object – their role is fulfilled by the regular alternator installed onboard.

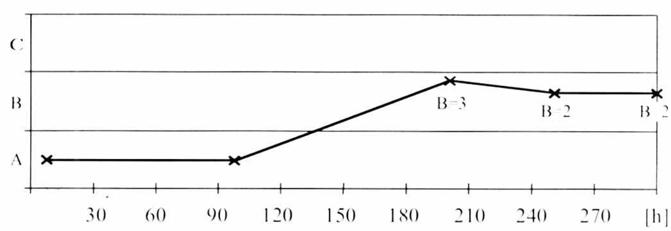

Fig.1a. *Example representation of wear of one-way clutch versus aircraft operational time, in a squadron database of SD-KSA diagnostic system*
Notation : *A,B,C – diagnostic levels, B=2, B=3 – number of characteristic set points appearing in a given diagnostic zone*

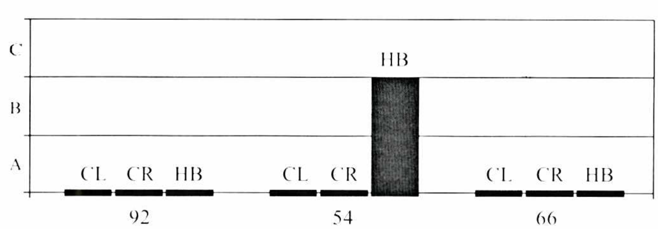

Fig.1b. *Example representation of technical state of one-way clutches and hydraulic units of particular aircrafts in BD-KSA database*
Notation : *CL – one-way clutch of left engine, CR – one-way clutch of right engine*
HB - hydraulic speed governor (also : hydraulic block)
92, 54, 66 – aircraft's tactical numbers

DESCRIPTION OF THE FAM-C DIAGNOSTIC METHOD

The method was thoroughly described in [2÷7]. However for better understanding the subject's context some its more important elements are highlighted below.

With every assembling or wear fault e.g. skew of transmission splined couplings, a modulation of the output rotational speed is associated. Period of the modulation is proved to be a characteristic parameter for the fault type and rated rotational speed of a given kinematic pair. Whereas the modulation amplitude is proportional to size of a given fault. The modulation effects are transferred through the transmission system to the rotor of the alternator (Fig.2).

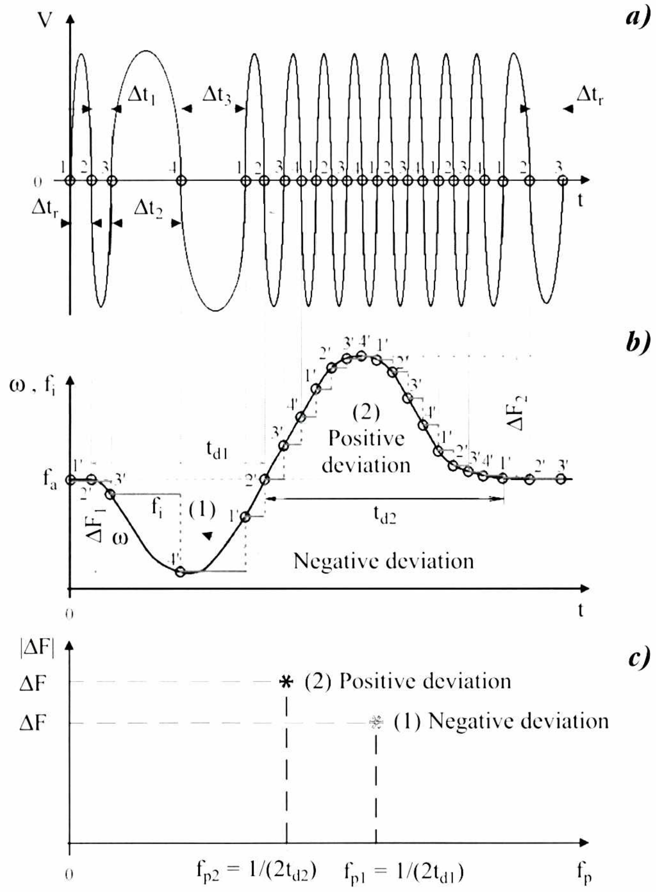

Fig.2. *Method of representation of characteristic points on (f_p , ΔF) plane :*
a) *Change of output voltage V versus time t*
b) *Change of input angular speed ω of generator's rotor and change of frequency f_i , representing it*
c) *Characteristic points represented on (f_p , ΔF) plane*

The aircraft alternator, being a synchronous machine, reflects changes of the instantaneous angular speed (Fig.2b) as a modulation of the output voltage frequency (Fig.2a). By measuring the time increments between successive zero-level crossing points (Fig.2b) and applying the inverses of their doubled values on the plane of the rectangular coordinates (t , f_i) a set can be obtained (stepped line in Fig.2b) which reflects, in a discrete way, a course of speed changes of the alternator's rotor (Fig.2a). Two parameters can be assigned to every i-th deviation, as follows:

- the deviation time t_{di}
- the deviation amplitude ΔF_i.

The deviattion time t_{di} can be replaced
with the process frequency f_p according to the formula :

$$f_{pi} = 1/(2t_{di})$$

Every such deviation can be represented on the plane (f_p , ΔF) (Fig.2c). During many investigations it was observed that the set of such points tends to gather into clusters. They were called the characteristic sets as they characterized wear state of particular subassemblies. It was observed that they had different shapes, heights and locations relative to the abscissa axis.

It was also stated that the greater the fault magnitude the greater height of a given cluster, $\{\Delta F_{max} + |\Delta F_{min}|\}$, and the bound accommodated by the cluster relative to the abscissa axis 0-f_p was characteristic for a given subassembly type.

During many applications of the method it was stated that the representations realized in the form of the characteristic sets have been applicable for a thoroughly recognized object, i.e. that of known relations between change of magnitude of a mechanical fault and that of depth of modulation amplitude. Use of such representations has many advantages :

⇨ easiness of diagnostic process automation
⇨ easiness of observation, on one plane, of arbitrarily long time courses, which is especially important in the case of occurence of stochastic signals
⇨ easiness of pulse component separation out of highly modulated signals, free from drawbacks of partial Fourier's analysis.

However, in spite of the advantages of the representation method in question, its use is not recommended for the objects not recognized in the earlier given sense, and direct using the functional courses $f_i = f(t)$ is instead advised for diagnostic purposes. The experienced diagnostician is able to make use of it effectively for assessment of technical state of an object, however in a more time consuming way.

CONCLUSIONS FROM LABORATORY TESTS OF LUZES-III DRIVE SYSTEM AND OTHER INVESTIGATIONS

In order to better recognize possibilities of the method in question the laboratory tests were performed with the use of LUZES-III drive system [8,9]. It consisted of a driving motor, transmission with alternator, as well as a claw clutch connecting the motor shaft with the transmission input shaft. It was possible to precisely adjust :

- the skew angle of the claw clutch
- the excentricity of the connection of the clutch shafts.

Clearances, skews and excentricities of connections, generally called the kinematic pair faults, cause periodical change of instantaneous angular speed of a driven element. Each of such courses has its own characteristic occurence period dependent on design parameters of a kinematic pair [5].

Amplitude of the instantaneous angular speed
can be strictly determined
and it is proportional to a fault parameter, e.g. :

⅄ for clearances – to the clearance parameter
⅄ for excentricities – to the excentricity shift
⅄ for skews – to the skew angle.

On the basis of these and other tests as well as of results
of investigations carried out onboard aircrafts it was stated that :

✦ from the occurence period of a given phenomenon one can conclude about a type of a failed kinematic link
✦ from its amplitude – about magnitude of the parameter of a given kinematic pair.

For excentricities, skews and clearances of joints it was also possible to find suitable mathematical diagnostic relationships [2, 4, 5, 6, 7, 8].

RESOLUTION, SENSITIVITY AND ERRORS OF THE METHOD

Diagnostic investigations carried out on real objects as well as computer simulations made it clear that exactness of representation of changes of the angular speed $\omega_2(t)$, as well as of the course $f_i(t)$ obtained from the alternator's output voltage, depends, in direct proportion, on the product of the following factors :

- the ratio $k = T_{np} / T_{Vp}$, where :
  T_{np} – nominal period of observed angular speed modulation of an investigated kinematic pair
  T_{Vp} – output voltage period of the onboard alternator
- harmonic number h of the nominal angular speed of a given kinematic pair
- mechanical transmission ratio m between the alternator's shaft and a diagnosed kinematic link
- number of measurement voltage phases (1 or 3)
- a measurement system of time increments of alternator's output voltage (half-period – 2, full period – 1).

As far as the diesel engines are concerned their angular speed courses $\omega_2 = f(t)$ are characterized by many quasi-discontinuities, therefore a saw-like waveform was chosen for representing that phenomenon in the laboratory tests. The saw-like waveform was modulated by means of a signal generator of 400 Hz rated frequency and 115 V output voltage. Time increment changes of the so-modulated voltage signal were counted by using the instruments typical for the FAM-C method. The obtained courses $f_i = f(t)$ were compared with the reference saw-like waveform in order to determine phase-angle and amplitude errors. The total amplitude errors $\delta_A = f(k)$ are presented in Fig.3, and those of phase angle, $\delta_\varphi = f(k)$, in Fig.4.

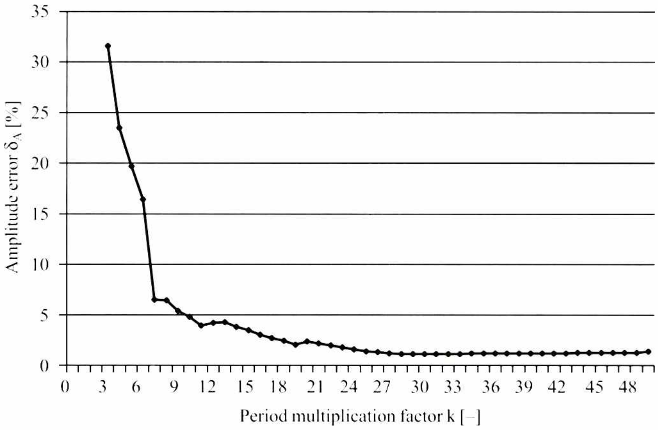

Fig.3. *Changes of relative values of amplitude error δ_A in function of period multiplication factor k*

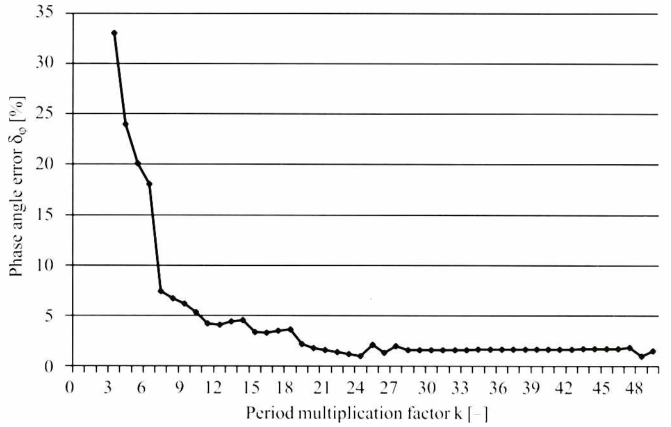

Fig.4. *Changes of relative values of phase angle error δ_φ in function of period multiplication factor k*

It was observed that both errors quickly decreased along with k factor increasing and then they slowly tended to a saturation level (from $\delta_A = 32\%$, and $\delta_\varphi = 33\%$ at k = 3, down to $\delta_A = 7\%$, and $\delta_\varphi = 8\%$ at k = 7).

As the error values less than 10% may be deemed initially acceptable therefore for $k \geq 7$ an obtained representation of rotational speed changes of a given kinematic pair becomes reliable.

EXPERIMENTAL DIAGNOSING THE MAIN PROPULSION SYSTEM OF THE FERRY „POLONIA" (one-phase voltage measurements)

During 4th Domestic Conference DIAG'98 the one-phase voltage experimental measurements were performed onboard the ferry POLONIA [4]. The kinematic scheme of the system in question is presented in Fig.5, and its parameters in Tab.1. In accordance with the sampling criterion it was assumed possible to measure values of the excentricity and skew of the main coupling, FC, as well as of the propeller shaft coupling PC (see Fig.5). The measurements were performed by means of the FAM-C method and their results were represented in the form of the characteristic sets (Fig.6). On the basis of the known data of the ferry's power plant (Tab.2) it was possible to deter-

Tab.1. *Selected design data of the ferryship POLONIA*

Name of unit	f_{EN} [Hz]	$1/f_{EN}$ [s]	m [–]
Alternator shaft	60	0.0167	1
Main engine shaft	60	0.0167	2
Propeller shaft	60	0.0167	0.46
Pulsations from 4 blades of propeller	60	0.0167	0.46
Pulsations from 6 cylinders of engine	60	0.0167	2

Tab.2. *Values of selected parameters of some units of the main propulsion system of the ferryship POLONIA*

Name of unit	Excentricity fault				Skew fault		
	n [rpm]	f_p [Hz]	$1/f_p$ [s]	k [–]	f_p [Hz]	$1/f_p$ [s]	k [–]
Alternator shaft	1200	20	0.05	3	40	0.025	1.5
Main engine shaft	600	10.0	0.1	12	20.0	0.05	6
Propeller shaft	140	2.3	0.4286	12	4.7	0.2143	6
Pulsations from 4 blades of propeller	560	9.3	0.1071	3	18.7	0.0536	1.5
Pulsations from 6 cylinders of engine	3600	60	0.0167	2	120	0.0083	1

Tab.3. *Values of parameters of faults of couplings of the ferryship POLONIA*

Name of unit	Value of excentricity *e* [mm]	Value of skew angle β [deg]
Left engine coupling	0.195	0.017
Propeller shaft coupling	0.602	0.011

mine the process frequency f_p and other parameters of some faults, shown in Tab.2. The calculated values of some fault parameters of the couplings under dynamic operation are presented in Tab.3.

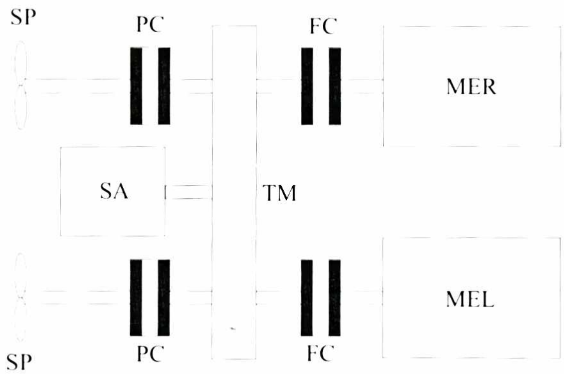

Fig.5. *Kinematic scheme of the main propulsion system of the ferryship POLONIA*

Notation :
MEL, MER – main diesel engines (left and right)
FC – flexible coupling, TM – transmission
SA – shaft alternator, PC – propeller coupling
SP – screw propeller

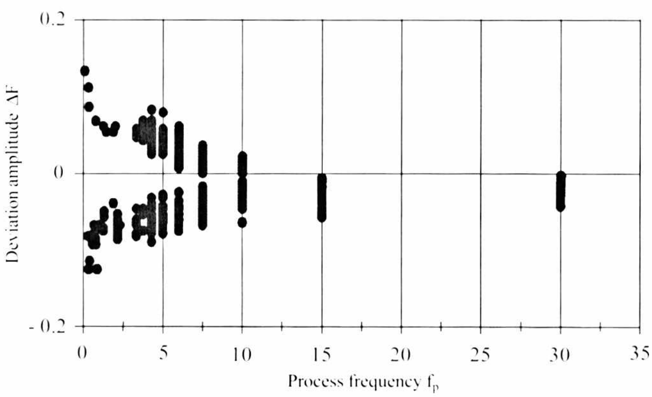

Fig.6. *Characteristic sets (clusters) for the main propulsion system of the ferryship POLONIA*

EXPERIMENTAL DIAGNOSING SOME POWER PLANT UNITS OF THE FERRY „POMERANIA" (three-phase voltage measurements)

Within the scope of 2nd International Scientific Technical Conference Explo-Diesel & Gas Turbine'01 the three-phase voltage experimental measurements of the power plant units, in different loading conditions, were performed onboard the ferry POMERANIA [10] during a regular voyage of the ship.

A general view of the investigated power plant units are shown in Fig.7.

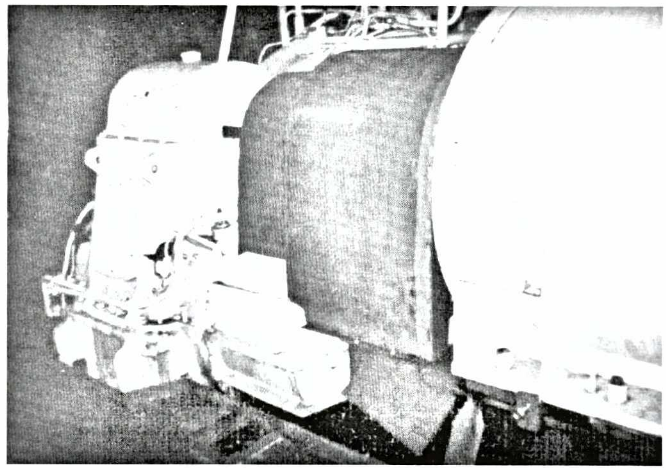

Fig.7. *A general view of some power plant units of the ferry POMERANIA (the shaft alternator and main transmission gear are seen)*

The measurements were performed by means of the FAM-C method.

On the basis of the known data of the ferry's power plant (Tab.4) it was possible to determine the process frequency f_p and other parameters of some faults, shown in Tab.5.

It was stated possible to observe angular speed pulsations resulting from work of particular cylinder-piston systems of the engine (the period multiplication factor $k = 9.6$). However as experience of

Tab.4. *Selected design data of the ferryship POMERANIA*

Name of unit	f_{EN} [Hz]	$1/f_{EN}$ [s]	m [–]
Alternator shaft	180	0.0056	1
Main engine shaft	180	0.0056	2.8302
Propeller shaft	180	0.0056	6.8182
Pulsations from 4 blades of propeller	180	0.0056	6.8182
Pulsations from 6 cylinders of engine	180	0.0056	2.8302
Natural frequency of propeller shaft torsional vibrations	180	0.0056	1

Tab.5. *Values of selected parameters of some units of the main propulsion system of the ferryship POMERANIA*

Name of unit	Excentricity fault				Skew fault		
	n [rpm]	f_p [Hz]	$1/f_p$ [s]	k [–]	f_p [Hz]	$1/f_p$ [s]	k [–]
Alternator shaft	1500	25	0.04	7.2	50	0.02	3.6
Main engine shaft	530	8.8	0.1132	57.6	17.7	0.0566	28.8
Propeller shaft	220	3.7	0.2727	334.7	7.3	0.1364	167.3
Pulsations from 4 blades of propeller	880	14.7	0.0682	83.7	29.3	0.0341	41.8
Pulsations from 6 cylinders of engine	3180	53	0.0189	9.6	106	0.0094	4.8
Natural frequency of propeller shaft torsional vibrations	–	25.1	0.0398	7.2	–	–	–

the measuring team in diagnosing diesel engines was insufficient for drawing diagnostic conclusions from the observed courses it was decided not to represent them in the form of the characteristic sets.

Nevertheless, the recorded courses $f_i = f(t)$, after confrontation with literature sources on operation of diesel engines, awoke many associations. As an example can serve the course obtained from one of the main engines mechanically loaded by a screw propeller, shown in Fig.8. The recorded pulsations were uniform, characteristic for correct work. However, a jump of a peak pulsation value was from time to time observed which might show an increased fuel charge to one of the cylinders.

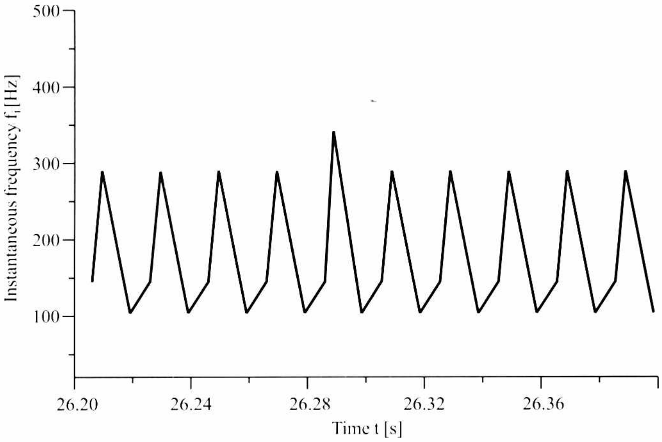

Fig.8. *Course of changes of instantaneous frequency values, $f_i = f(t)$, for one of the main propulsion engines of the ferryship POMERANIA (three-phase voltage measurements)*

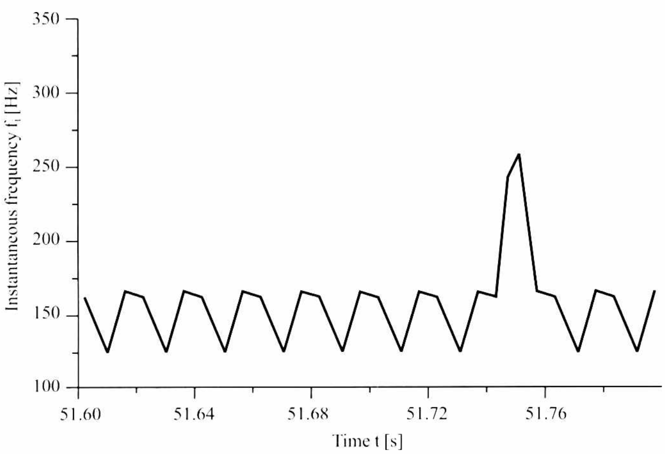

Fig.9. *Course of changes of instantaneous frequency values, $f_i = f(t)$, for an electric generating sets of the ferryship POMERANIA (three-phase voltage measurements)*

Another course (Fig.9) was recorded for alternator output voltage of an electric generating set. Its power was smaller than that of the main engine and, practically, it was not loaded mechanically – hence its pulsation amplitude was much smaller. The descending slope characterizing the compression stroke had two stages :

- ★ 1st stage – probably associated with removing clearances or deformations of the crankshaft
- ★ 2nd stage – compression after clearances being removed.

In one case, at the beginning of the second stage, a premature self-ignition occurred which produced an additional instantaneous torque. In a time instant it was summed up with the torque of another cylinder system with correctly realized ignition, hence the angular speed peak value of the diesel engine crankshaft increased by 70% relative to that occurring in the regular ignition conditions.

Also, the phenomenon of shifting an „observation window" along with k - factor changing, observed from comparison of the measurement courses performed onboard the ferries POLONIA and POMERANIA, is worth mentioning (Fig.10a, and 10b).

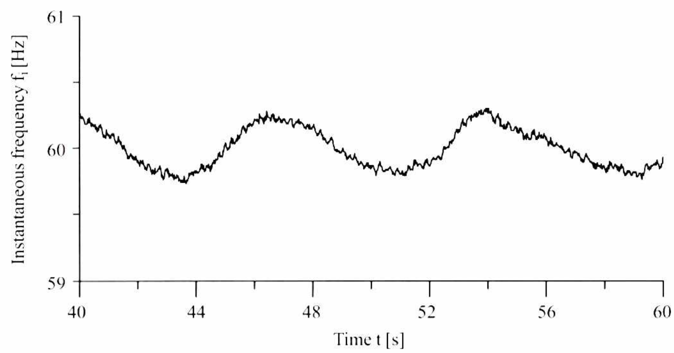

Fig.10a. *Changes of instantaneous frequency values, $f_i = f(t)$, obtained from shaft alternator of the ferryship POLONIA (one-phase voltage measurements)*

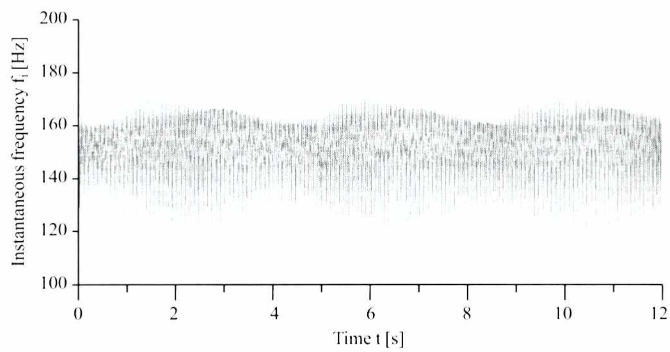

Fig.10b. *Changes of instantaneous frequency values, $f_i = f(t)$, obtained from shaft alternator of the ferryship POMERANIA (three-phase voltage measurements)*

The k-factor value, three times greater in the second case than that of the first case, led to occurence of visibility of high-frequency courses recorded on the second ship and to lack of visibility of low-frequency ones, though both ship power plants had similar parameters and natural vibration frequencies of mechanical units.

RECAPITULATION

- ❍ In the paper the theory and example applications of the diagnostic method based on analysis of parameters of alternator output voltage frequency modulation of ship's electric generating sets driven by diesel engines, were presented.
- ❍ By applying the FAM-C method it is possible to detect in advance a subassembly defect before it becomes hazardous for the entire object. The method has been proved fast, exact, inexpensive, safe and nondisturbing operation of an diagnosed object.
- ❍ *If a diagnosed object is well recognized* it is possible to represent faults in the form of the characteristic sets having bounds associated with particular faults of kinematic links, as well as to determine diagnostic levels for each of them. This makes it possible to apply a special pocket-size tester that is able, after several minutes, to locate defected subassemblies and to assess their wear levels.
- ❍ *For less recognized objects* it is necessary to make use of the time representation of instantaneous frequency changes. On this basis the experienced diagnostician is able to draw many important conclusions on probable faults of an investigated object.
- ❍ In the author's opinion the FAM-C method has many, yet not recognized, diagnostic possibilities, perhaps especially in the area of diesel engines; for instance, shaft torsional angle monitoring. Another possibility is presenting images of faults in the polar coordinate system for particular rotating elements [11,12].

Appraised by Jerzy Girtler, Prof.,D.Sc.

NOMENCLATURE

BD-KSA	–	computer database
e	–	connection excentricity of clutch shafts
f_a	–	average value of ¦ f_i ¦ set
f_{EN}	–	rated frequency of ship electric power network
f_i	–	instantaneous frequency (inverse of doubled Δt_i value)
f_p	–	process frequency (= $1/(2t_d)$)
FAM-C	–	a diagnostic method based on the measurement of modulation of alternator instantaneous voltage frequency
ΔF	–	deviation amplitude
ΔF_{max}	–	maximum value of ΔF in a given set ¦ f_{pi} , ΔF_i ¦
ΔF_{min}	–	minimum value of ΔF in a given set ¦ f_{pi} , ΔF_i ¦
$H\Delta F$	–	height of a given set ¦ f_{pi} , ΔF_i ¦
h	–	harmonic number of rated angular speed of a given kinematic pair
k	–	ratio of T_{np} / T_{Vp}
LUZES-III		a ground–based drive system for supplying aircrafts with voltage of stabilized frequency
m	–	mechanical transmission ratio between the alternator's shaft and a diagnosed kinematic link
n	–	number of revolutions
SD-KSA		a system for diagnosing one-way clutches and blocks of hydraulic controllers of MiG-29 aircrafts
t	–	time
t_d	–	deviation time of f_i (t) „course" from the average frequency f_a
t_{di}	–	i-th element of ¦ t_d ¦ set
Δt_i	–	time increment between successive zero–level crossing points
Δt_r	–	rated time increment between successive zero-crossings, equal to 1/2 rated frequency of alternator
T_{np}	–	nominal period of observed angular speed modulation of an investigated kinematic pair
T_{Vp}	–	output voltage period of the onboard alternator
V	–	voltage
β	–	skew angle of claw clutch
δ_A	–	relative amplitude error
δ_φ	–	relative phase angle error
φ	–	rotation angle of a driven element
ω	–	angular speed
ω_1	–	angular speed of driving shaft
ω_2	–	angular speed of driven shaft

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Conferences

New laboratory stand

On 27 May an official activity inauguration of a new laboratory stand in Szczecin Maritime University was the occasion to arrange the first in this year, scientific meeting of the West--Pomeranian Regional Group, Section on Exploitation Foundations, Machine Building Committee, Polish Academy of Sciences. The stand is provided for carrying out research on water deoiling, and this facility has been the only topic of the lectures given during the meeting in question :

- *Design concept of the water deoiling research stand and outline of planned investigations* – by Antoni Wiewióra
- *Computer system for supervising the research stand in operation and recording, processing and storing measurement data* – by Piotr Treichel.

Next, the official activity inauguration of the research stand and presentation of its functioning had place.

In the meeting, apart from the Group's members, took part also the University authorities and the guests from the institutions which financially supported the new research facility important for protection of the marine environment.

Regional group meeting

On 6 June this year the Regional Group of the Section on Exploitation Foundations, Machine Building Committee, Polish Academy of Sciences, held its sucessive scientific meeting. This time it was hosted by the Faculty of Technical Sciences, University of Varmia and Masuria at Olsztyn.

In accordance with the Conference program its participants heard four papers :

- *Viscoelastic constitutive relationships in technical fabrics* by Wiesław Komar, M.Sc., M.E.
- *Modelling a diagnostic method for complex heavy machines, by using a hybrid expert system* – by Arkadiusz Rychlik, M.Sc., M.E.
- *A model of cooperation of an elastic wheel and ground, with application of reology* – by Krzysztof Ligier, M.Sc., M.E.
- *A diagnostic model of equilibrium of machine unit* by Piotr Szczyglak, M.Sc., M.E.

The authors are young scientific workers of the University. During the debate they had an opportunity to be acquainted with friendly comments and advices from the side of experienced and recognized scientists, that surely would help them in their further educational and research efforts.