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# POSSIBILITIES OF USING THE FREE-END OF CRANKSHAFT IN DIAGNOSIS OF SLOW SPEED MARINE DIESEL ENGINES

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***Abstract***

*In this article there are discussed possibilities in diagnosis of large marine diesel engines by utilization the free-end of crankshaft in gaining information about engine load in particular cylinders on the basis of course of crankshaft's transient rotational speed overlapped by torsional vibration. There is defined and calculated crankshaft's transfer function for torsional vibration being crankshaft's response to exciting force caused by crank pin efforts. There is presented methodology of reconstruction of crank pin efforts' course on the basis of calculated transfer function and measured in any given condition course of crankshaft's speed. There are indicated that similarities between courses of torsional vibration in time and frequency domain for slow and medium speed marine diesel engines will allow to apply the presented methodology of reconstruction of crank pin efforts' course in large marine diesel engines.*

**Keywords:** *diagnostics, marine diesel engine, crankshaft, torsional vibration, transfer function*

## 1. Introduction

In searching new solutions and improvements in actually offered diagnostic equipment and systems for diagnosis of diesel engines more and more frequently elements of vibration diagnosis have been utilised. The reasons are given for that the measured at the free end of crankshaft: axial vibrations include information about crankshaft's alignment and crankpin bearings' condition [2], and torsional vibrations about main bearings' condition and the load in particular engine's cylinders [1, 2, 5]. Well known negative feature of vibration signals' measures is their random characteristic resulted from that their values are dependent not only on widely understandable condition which they are focused at but on load as well that is comprehensible as the load of engine and his particular piston – connecting rod sets. Such defined load is estimated by combustion force that value corresponds to transient values of combustion process in function of °ACR (angle of crankshaft rotation). Because to permanent and/ or effective purposes of diagnosis, usefulness of direct measurement of combustion pressures' courses is still not sufficient, and moreover limitation and problems, that characterise these methods, cause that they have not brought expected results yet, torsional vibrations as source of information about load have been adopted. The free end of crankshaft has began the place of interest for application angle encoders as °ACR indicators for combustion analysers – fig.1 [4] and cylinder liner lubricators – fig. 2 [3]. They are primary sources of information in relation to eddy current sensors (proximitors) applied close to engine's fly-wheel that use teeth or special marks as °ACR indicators. Adaptation of free-end of crankshaft with it extension outside of the engine housing was implemented on medium (4-stroke, medium speed) [2] and large (2-stroke, slow speed) diesel engines even with presence of axial damper [3, 4].

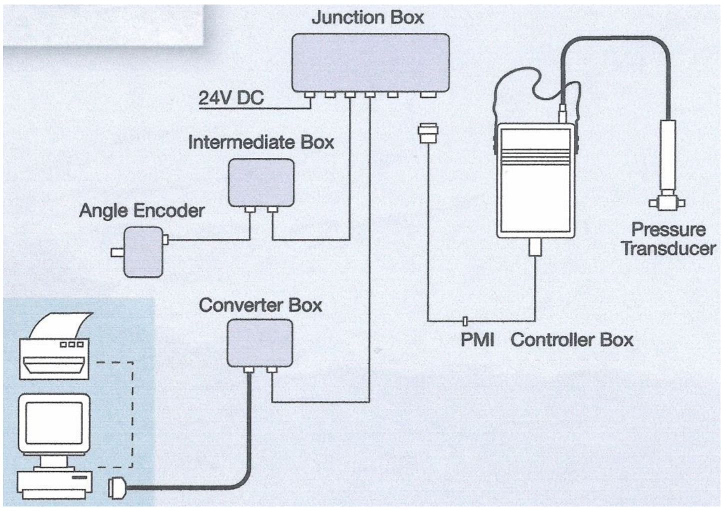


*Fig. 1. PMI System, cylinder pressure analyser with angle encoder assembled on free-end of crankshaft designated for slow speed diesel engines by MAN B&W Diesel A/S [4]*

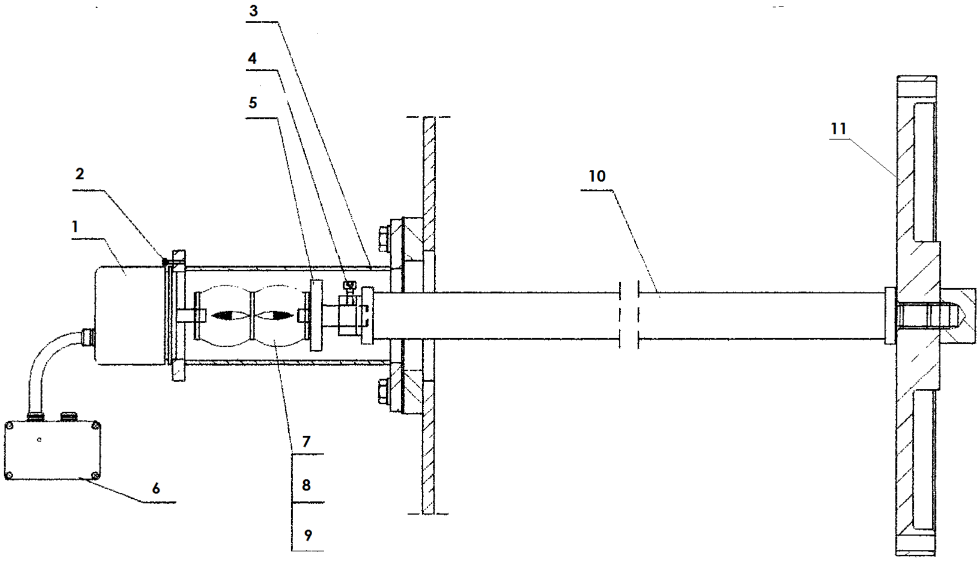


*Fig. 2. Alpha Lubricator System, angle encoder installation diagram [3]:*
*1 –angle encoder, 2 – assembling screw, 3 – housing, 4 – securing screw, 5 – connecting piece, 6 – intermediate box, 7 – coupling, 8 – damper plate, 9 – cable ties, 10 – shaft, 11 – free-end of crankshaft (axial vibration damper)*

For the purpose of measurement and analyse of axial and torsional vibration of crankshaft, non-uniformity of engine running and engine load in function of °ACR the following system to experimental researches on medium diesel engine (Sulzer 6AL24) [2] was implemented – fig. 3:

- Integrated Transducer of Axial and Torsional Vibrations (5-10) attached to free end of crankshaft (1) and body of engine (2) through blinding cover (3) and seal (5) together with measuring plate and shaft (4),
- Opto-electric Transducer rev/impulse with coupling type OLDHAM – Megatron (10),
- Eddy Current Sensor and Relative Vibration Measurement Instrument ZPW-2 by Sensor (8-9),

- System to Indicated Power Measurement (12) including: opto-electric key phasor by Sensor (13), 6 tensometric sensors of combustion pressure PT - 5101T and adaptation – antiknock heads by Unitest, 6 amplifiers AT – 5230 with autozero and stabilised BZ 5205 by Spais.
- Computer Diagnostic Analyser KSD – 400 by Sensor (11) including: notebook with software, 16 – channels PC CARD PCMCIA type DAS16S/330, input voltage cards and amplifiers.

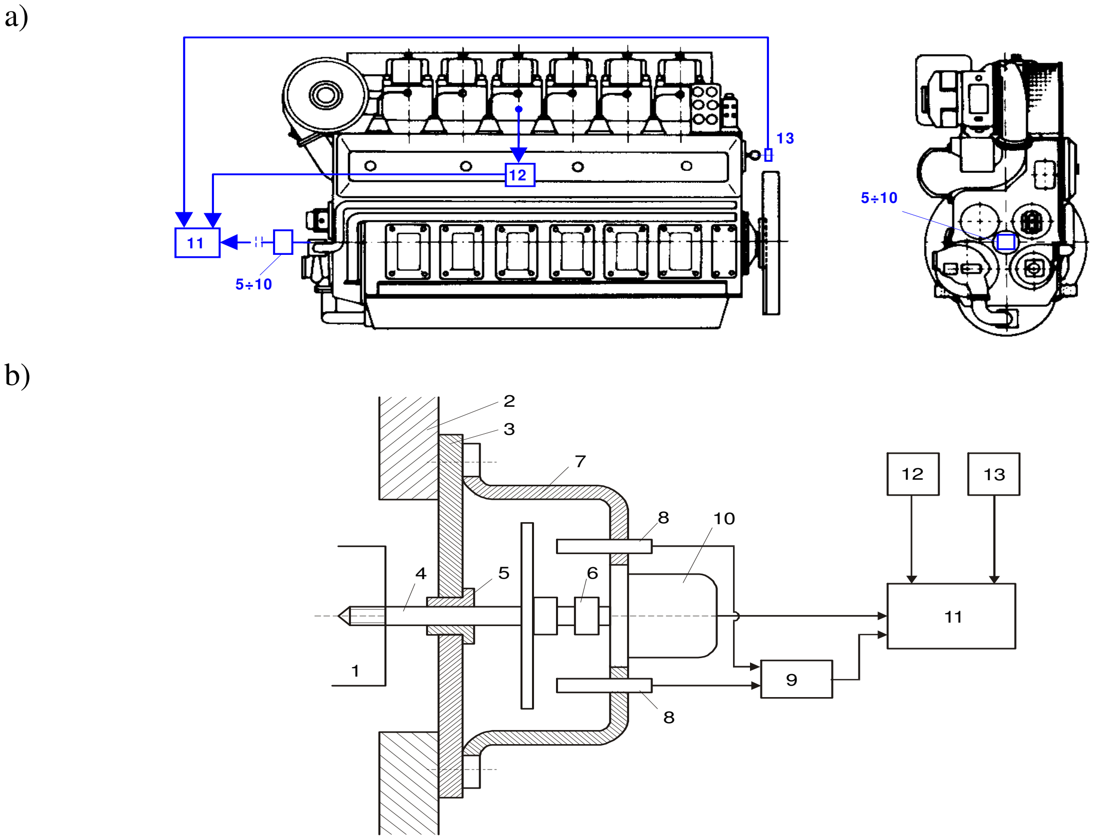
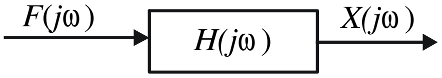


*Fig. 3. Means of measurement of vibration signal and engine load in function of °ACR*
*a – measuring points at the engine, b – scheme of integrated vibration transducer*
*1 – free end of crankshaft , 2 – body of engine, 3 – blinding cover, 4 – shaft and measuring plate, 5 – seal, 6 – coupling , 7 – housing, 8 – eddy current sensors , 9 – signal adder , 10 – opto-electric transducer , 11 – computer diagnostic analyser, 12 – indicated power measuring unit, 13 – key phasor*

For torsional vibration measurement on large diesel engines (Mitsubishi 7UEC72LII) angle encoder was used with same mounting as on fig. 2 (coupling and damping plates).

## 2. Crankshaft's transfer function for torsional vibrations

Crankshaft as a mechanical element of diesel engine possesses given mass, elasticity and damping. These magnitudes determine so called transfer function that means decide about crankshaft's response to exciting forces. Depending on place and direction of acting of exciting forces, crankshaft can execute torsional vibration being crankshaft's response to force caused by crank pin efforts and axial vibration being crankshaft's response to force caused by crankthrow efforts. Transfer function $H(j\omega)$ between these dependencies can be defined as a transmittance of researched object (crankshaft) – fig. 4.



Transfer function $H(j\omega)$ as a transmittance of researched object [1, 2]:

$$H(j\omega) = \frac{X(j\omega)}{F(j\omega)}$$

*Fig. 4. Definition of transfer function H(jω)*
*X(jω) – response as crankshaft's axial or torsional vibrations, caused by force being of resultant force F(jω), correspondingly to crankthrow and crank pin efforts*

In researches at utilisation of transfer function in diagnosis of diesel engines, crankshaft's transfer function for axial vibration has been utilised as a source of information about crank pin bearings' condition and for torsional vibrations as a source of information about the course of load in particular engine's cylinders. Taking into consideration dependencies between force in form of crank pin efforts and response in form of torsional vibration of crankshaft's free end, and treating crankshaft and dependencies existed in it and his bearings as so called "black box", crankshaft's transfer function for tosional vibration can be defined as inversion of the following transmittance:

$$H(TV(i)) = \sum_{i=0}^{n} \frac{T_{gas+m}(i)}{TV(i)} \tag{1}$$

where:

$T_{gas+m}(i)$ – harmonic components of crank pin efforts,
$TV(i)$ – harmonic components of torsional vibration,
$i$ – harmonic order,
$n$ – top harmonic order.

## 3. Calculation of crankshaft's transfer function

Transfer function $H(TV(i))$, has been calculated according to formula (1), possessing data in form of amplitude and phase spectrums calculated from course of crankshaft's transient rotational speed $v$ (fig. 7 and 8), being response to force in form of course of crank pin efforts $t$ (fig. 5 and 6). Amplitude components of transfer function were obtained from quotient of average values of amplitude spectrums of crank pin efforts and crankshaft's speed:

$$\Phi\ (\mathrm{A}) = \frac{t_{\mathrm{aver}}(\mathrm{A})}{v_{\mathrm{aver}}(\mathrm{A})} \tag{2}$$

where:

$\Phi$ (A) – amplitude components of transfer function,
$t_{\mathrm{aver}}$(A) – average values of amplitude spectrums of crank pin efforts [MPa],
$v_{\mathrm{aver}}$(A) – average values of amplitude spectrums of crankshaft's speed [rev/min].

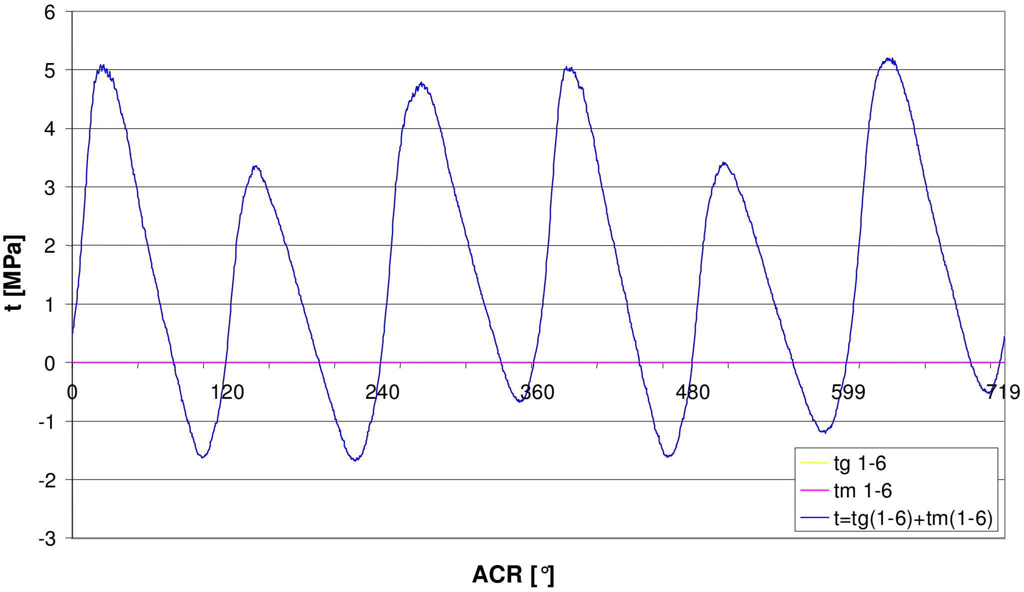


*Fig. 5. Course of the resultant from gas $t_g$ and mass $t_m$ components total crank pin efforts t in particular cylinders at 720 rev/min and load index 100% for medium marine diesel engine Sulzer 6AL24*

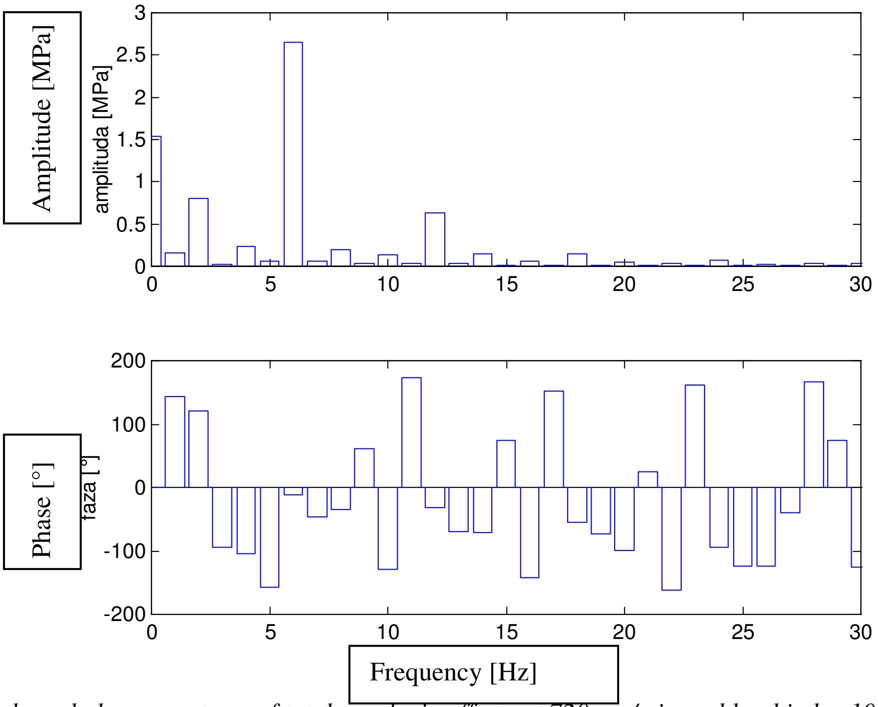


*Fig. 6. Amplitude and phase spectrum of total crank pin efforts at 720 rev/min and load index 100% medium marine diesel engine Sulzer 6AL24*

Phase components of transfer function were obtained from difference of average values of phase spectrums of crank pin efforts and crankshaft's speed:

$$\Phi(F) = t_{aver}(F) - v_{aver}(F) \tag{3}$$

where:

$\Phi$ (F) – phase components of transfer function,
$t_{aver}$(F) – average values of phase spectrums of crank pin efforts [MPa],
$v_{aver}$(F) – average values of phase spectrums of crankshaft's speed [rev/min].

On the basis of quotient of harmonic components of amplitude spectrums (2) and difference of harmonic components of phase spectrums of crank pin efforts and crankshaft's speed (3) there was determined set of amplitudes and phases values of transfer function:

$$H(TV(i)) = \{\Phi(A),\Phi(F)\} \tag{4}$$

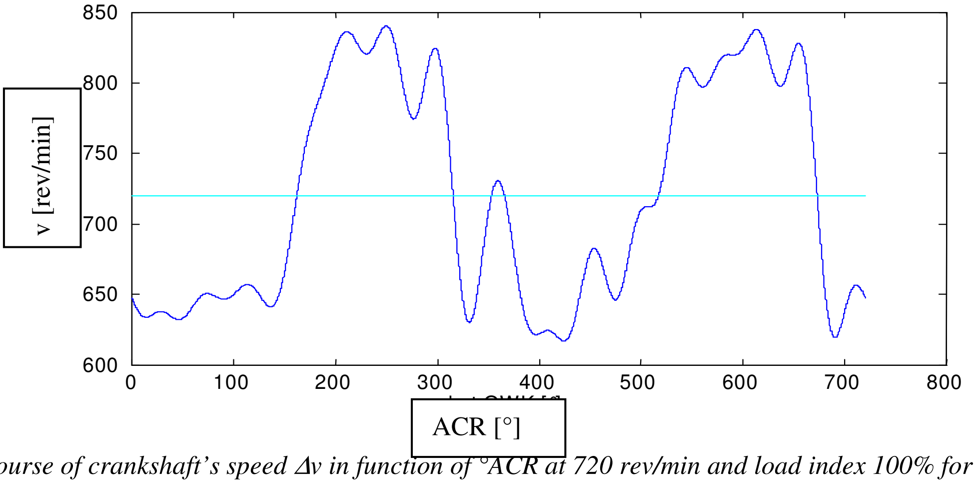


*Fig. 7. Course of crankshaft's speed $\Delta v$ in function of °ACR at 720 rev/min and load index 100% for medium marine diesel engine Sulzer 6AL24*

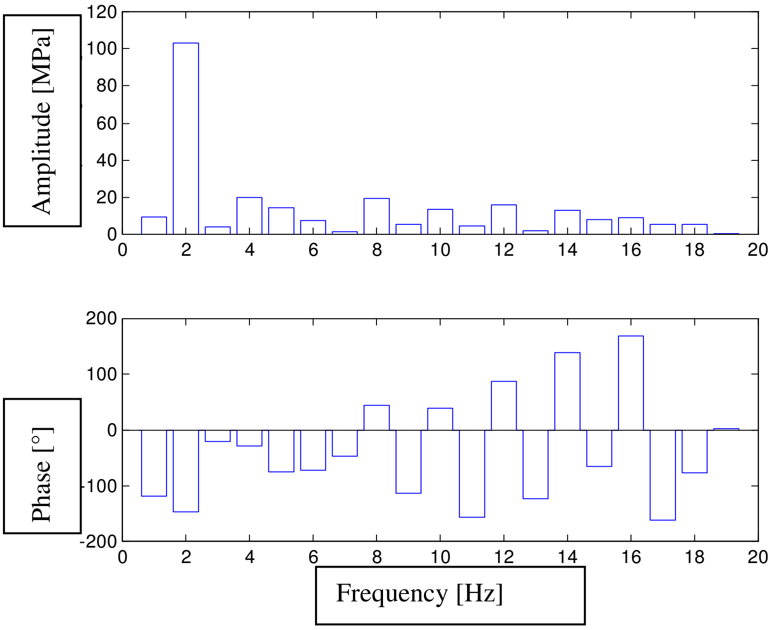


*Fig. 8. Amplitude and phase spectrum of crankshaft's speed $\Delta v$ at 720 rev/min and load index 100% for medium marine diesel engine Sulzer 6AL24*

As it can be observed from fig. 9 and 10 the presented courses of torque fluctuation and its harmonics for large marine diesel engine have same character as for medium marine diesel engine depending on number of cylinders, fire order, crank-web's angles between particular cylinders and taking into consideration the number of cycles coinciding with engine's revolutions. Due to lack of technical possibilities (6 sensors) of simultaneous measurement of combustion pressure changes in particular cylinders and calculation of the resultant from gas $t_g$ and mass $t_m$ components total crank pin efforts t in particular cylinders, the contained in chapter 4 application of transfer function to reconstruction of course of crank pin efforts was made therefore only for measuring results obtained for medium marine diesel engine, however same methodology can be utilized for large marine engines.

*Fig. 9. Course of torque fluctuation t in particular cylinders at 72 rev/min and load index 80% for large marine diesel engine Mitsubishi UEC 7L85II*

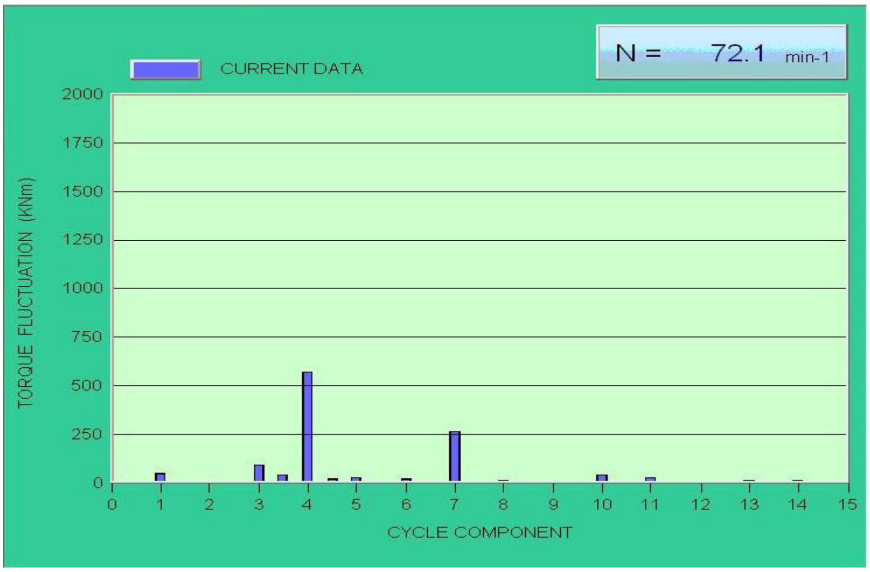


*Fig. 10. FFT of torque fluctuation t in particular cylinders at 72 rev/min and load index 80% for large marine diesel engine Mitsubishi UEC 7L85II*

## 4. Application of transfer function to reconstruction of course of crank pin efforts

On the basis of calculated transfer function $H(TV(i))$ there was made an attempt to reconstruct course of total crank pin efforts from measured at crankshaft's free end, in any given condition course of crankshaft's transient rotational speed.

In this purpose calculated amplitude spectrums of measured course of crankshaft's speed have been multiplied by amplitude components of transfer function Φ(A):

$$t_{tv}(A) = \Phi(A) \cdot v_{meas}(A) \tag{5}$$

where:

$v_{meas}(A)$ – harmonics values of amplitude spectrums of measured course of crankshaft's speed [rev/min],
$t_{tv}(A)$ – harmonics values of amplitude spectrums of reconstructed course of crank pin efforts [MPa].

and to phase spectrums have been added phase components of transfer function Φ(F):

$$t_{tv}(F) = \Phi(F) + v_{meas}(F) \tag{6}$$

where:

$v_{meas}(F)$ – harmonics values of phase spectrums of measured course of crankshaft's speed [°],
$t_{tv}(F)$ – harmonics values of phase spectrums of reconstructed course of crank pin efforts [°].

On the basis of formulas 5 and 6 there have been calculated values of amplitude and phase spectrums of crank pin efforts $t_{tv}$, moreover utilising synthesis – sum from definition of trigonometric series of particular harmonics of both spectrums (formula 7) there have been obtained course of total crank pin efforts $t_{tv}$ in function of °ACR (fig. 11).

$$t = t_o + t_k \cdot \sin[(k-1)\omega t + \varphi_k] \tag{7}$$

where:

$t_o$ – zero harmonic of amplitude spectrum of total crank pin efforts [MPa],
$t_k$ – next harmonics of amplitude spectrum of total crank pin efforts [MPa],
$\varphi_k$ – next harmonics of phase spectrum of total crank pin efforts [°].

Attempt of utilisation of transfer function confirmed correctness of reconstruction of course of total crank pin efforts from courses of crankshaft's speed in range of load 50-100%. In lower range of load irregularity and stochastic character of combustion process and connected with it non-uniformity of engine's speed caused oscillation of revolution. These oscillations have not important influence at harmonics of amplitude spectrums but caused significant differences for harmonics of phase spectrums. Next these differences caused important inaccuracy in calculation and reconstruction courses of crank pin efforts.

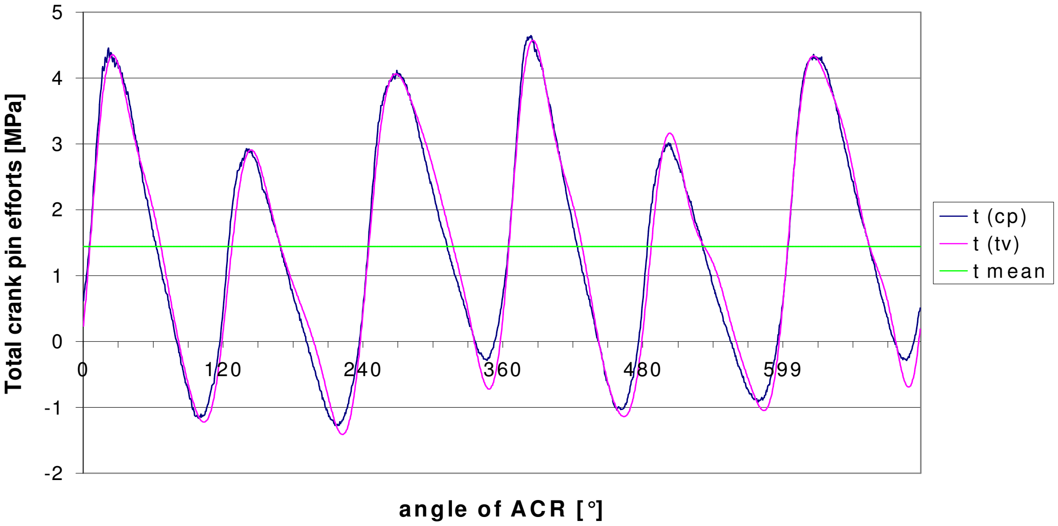


*Fig. 11. Comparison of course of total crank pin efforts calculated on the basis of combustion pressures $t_{cp}$ with course of total crank pin efforts obtained by multiplication of measured crankshaft's speed by transfer function $t_{tv}$*

## Conclusions

As it results from the above there is possibility to use the free end of crankshaft in diagnosis of marine diesel engines including large two stroke slow speed engines and to define crankshaft's transfer function in form of quotient of crankshaft's speed and total crank pin efforts spectrums.

Besides, there is possibility to reconstruct from course of crankshaft's speed and determined transfer function at defined load (but above 50 % of nominal engine load) the course of total crank pin efforts and to determine the load in particular engine cylinders. Moreover, there is possibility to apply the presented methodology of application of transfer function for large marine diesel engine to gain information about load in particular cylinders but it will demand to create separate characteristic between exciting data in form of courses of crank pin efforts and response in form of courses of torsional vibration/ crankshaft's transient rotational speed in purpose of calculation of transfer function for particular engine.

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