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Symptoms and a Sensor for Permanent Diagnosis of Machines with a Piston-Crank Mechanism

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Abstract – The piston-crank mechanism and influence of its technical condition on safety is presented. Diagnostic signals, which may be useful in diagnosing of mechanism elements are enumerated. The choice of taking the crankshaft free end as a point of diagnostic signals permanent measurement is justified. The classification of machine units and their loads are done. There is pointed out the possibility to increase the diagnosis accuracy made by measurements on the free end of crankshaft. Attention is drown to the necessity of considering dynamical characteristics of machine unit in process of inference about the technical condition of the piston-crank mechanism elements.

Keywords: piston-crank mechanism, torsional vibrations, axial vibrations.

1. INTRODUCTION

The majority of displacement machines, mainly piston machines, is equipped with a piston-crank mechanism. These machines are characterized by a very high maximum pressures of medium in the working chamber. The mechanism consist of cylinder liner, piston with piston rod, crosshead slide, crosshead with bearing, connecting rod with head and bottom end bearing, crankshaft and main bearing in the most extended version. Mentioned elements form tribological pairs – slide bearings. In all tribological pairs, with the exception of main bearings, reciprocating or oscillatory movement takes place. The large load of pairs elements, which is result of very large maximum working pressures, and relative velocities with temporary zero values, make that tribological conditions in such pairs are extreme difficult. Frequent starts and many inferences accelerate the wear process. It leads to defect of pairs, as excessive clearance and/or machine seizure and failure. Failures are a menace to life, health and environment. The diagnosis of such mechanism is desirable for the sake of safety and economic.

2. SIGNALS CONTAINING INFORMATION ABOUT THE MECHANISM TECHNICAL CONDITION

From own researches made by author and publications result that an information about technical conditions of the piston crank mechanism is included in courses as follow, as functions of crankshaft angle rotation:

- pressure of medium in working chamber,
- vibrations of machine body,
- torsional vibrations of crankshaft,
- axial vibrations of crankshaft,
- torque,
- angular velocity/acceleration of crankshaft.

Information concerning the condition of the piston-crank mechanism is also given in time changing temperature fluctuations of kinematics pairs elements and in changes of solid particles content in lubricating oil as well as in the content of oil mist in the crankcase. Such information is more connected with the intensity of wearing process than with effects of wear. From this reason there are more useful in monitoring of machine than in diagnosis and forecasting of machine condition.

Courses of pressures contain information about the condition – the tight of working chamber. The limited inference about the condition of valves and piston rings and cylinder liner is also possible. The closed indication courses are preferred [1]. Transducers for direct measurements of pressures and transducers for head vibrations and deformations of washers under head bolts are developed [10].

Absolute vibrations of machine body, which are measured near the crosshead guides, contain information about the condition (clearances) of slide bearings [9]. Such vibration may contain information about condition of screw connection of piston rod and crosshead [2]. The measurement is made by accelerometers e.g. piezoelectric which are offered in commerce.

The axial vibration of free end of crankshaft contains information about crank bearings. Good results are reached with using absolute vibration acceleration measurement. There is no measurements systems for commercial using [9]. The attempt to build contactless electrodynamics transducers for axial vibrations of rotating shaft was made. Components of body vibrations and axial vibrations are temporary periodical signals and they are generated by forces with changing sign [5].

In case of long crankshafts with many cranks, axial vibrations may also contain information about crankshaft alignment. The uneven wear of main bearings, deformation of machine body, changing of machine position in relation to cooperating machine has an influence on crankshaft alignment. Displacement of relative vibration is measured. Eddy current displacement transducers are useful for this purpose. Further research work on improving the model is continued to make it more useful for diagnosing of crankshaft alignment[6].

Absolute torsional vibrations, measured at the free end of crankshaft, contain information about the condition of main bearings, which are placed close to nodes of torsional vibrations (torsional vibrations are main reason of accelerated wear of bearings) [11]. Knowledge about torsional vibrations modes, position of torsional vibrations nodes and resonance frequencies of vibrating system is necessary. Industrial transducers of torsional vibrations are very expensive and not easy to use. Measurements of absolute vibrations of the crankshaft free end are substituted with measurements of relative vibrations.

It seems to be possible to forecast wear defects of crankshaft and bearings based on axial and torsional vibrations permanent measured. This method is described in [7].

In multi cylinder machines absorbed or delivered torque has a value, which depends on the angle of rotation. Momentary values of torque depend not only on absorbed or delivered moment, but also on friction moments in tribological pairs of the piston-crank mechanism. Friction moments depend from load and condition of pairs; so course of machines torque contain information about condition of tribological pairs of piston crank mechanism [8]. Torsional stresses in connection shaft between machines are result of torque. There exist industrial systems for measurements of torsional stresses in connection shaft. These transducers are quite expensive and not easy to use.

The variable torque takes result in nonstationary of angular velocity. Momentary values of angular velocity are different than mean value. The mean value of shaft angular velocity is called rotational speed. There exist relations between torque and crankshaft angular accelerations [8]. Courses of relative accelerations of torsional vibrations are superimposed with courses of angular accelerations of shaft at crankshaft free end. Courses of angular acceleration may be determined by incremental transducers (optical, inductive, magnetic, eddy current) of angle rotation of shaft and its differential with respect to time. The main disadvantage of this measurement is loss of information contained in constant values of differentiated signal. Transducers which operate according to Ferraris principle (Galileo Ferraris 1847 – 1897) are now available in sale. They give electrical signals, proportional to relative accelerations in linear and rotational movement. But usability of them for measurements of angular accelerations of crankshaft free end has not been pointed up to now.

3. THE INTEGRATED SENSOR OF DIAGNOSTIC SIGNALS OF PISTON – CRANK MECHANISM

Because courses of torsional vibrations, axial vibrations, angular velocity and acceleration of crankshaft:

- contain information, which allow to generate, during the diagnostic inference process, a list of probable faults and damages of tribological pairs of piston – crank mechanism;
- may be measured contactless at free end of crankshaft;
- in the majority of machines free end is available for measurements, there is a threaded hole which allows to couple the transducer witch shaft;
- there is possibility to accurate measure of TDC of the chosen piston

it is purposeful to built sensor for above mentioned magnitudes of enumerated values of crankshaft free end and to adopt it for permanent diagnosis of piston-crank mechanism elements. Such sensor should allow to measuring angular rotation/position, angular acceleration, displacement and velocity of axial rotation and TDC of piston. The sensor for permanent diagnosis of machines should be very precise and reliable, should be easy to assemble, should not make difficult to use of machine, should be inexpensive, and it should be integrated with machine elements which operate with shaft.

The achievement of all features is made difficult because of:

- free end of crankshaft is also last, a little longer main bearing journal. Deformations of crankshaft due to forces and torques make that journal vibrates in axial and torsional directions and move in bearing radius, unparallel of journal and baring bushing periodical changes;
- other auxiliary machines may also be driven from the free end e.g. oil pumps. There are sometimes assembled torsional or axial vibration dumpers;
- axis of the threaded hole is non coaxial with the journal axis. This is the result of many technological operations during the production process and little requirements for threaded hole precision;
- there are no industrial transducers for contactless measurements of velocity and/or acceleration of axial vibrations.

The researches about building an integrated transducer for multi cylinder piston compressor with gear oil pump driven from shaft free end are made. In put into practice solution, additional shaft between shaft journal and pump, drive the pump and it is used for assembling movable parts of transducers. There are used Ferraris sensors to measure angular acceleration of shaft, eddy current sensors to measure axial displacement, special electrodynamic sensors to measure velocity of axial vibrations and optical incremental sensors of angle rotation.

4. SOURCES OF ADDITIONAL INFORMATIONS AND THEIR USABILITY

Periodical or immediate measurements of additional measurements by additional sensors is necessary for make diagnosis based on axial and torsional vibrations more detailed.

The number and type of additional possible and useful sensors depend on type of the system where operate the machine with the piston – crank mechanism.

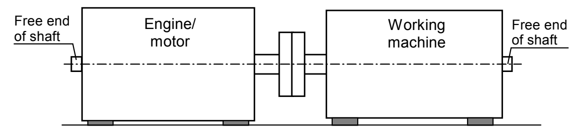
The machines with piston-crank mechanism are the part of MU cooperate with other machines and are connected by rigid or elastic couplings, also clutches. Types of MU with piston-crank mechanism are enumerated in table I.

Enumerated MU may operate in steady-state conditions or in unsteady-state conditions.

In unsteady-state conditions:

– without external load (acceleration/deceleration): without working machine or without load at working machine,
– with external load depended on operation carried out by the operating machine (with load depended on the load of working machine).

TABLE I. Types of machine sets/units (MS/MU)

		
1	Machine with piston-crank mechanism – internal combustion engine: • four-stroke without crosshead, • two-stroke with crosshead.	Impeller machine – gear +propeller, – propeller / propeller + shaft generator, – impeller pump, – impeller compressor, – generator.
2		–
3	Electric motor	Machine with piston-crank mechanism: – internal combustion engine four stroke / two stroke, – pump with crosshead, – compressor.

In steady-state conditions:
– with external load,
– without external load.

The most difficult to diagnose is the case where MU operates with variable load of working machine. Because of all enumerated signals of crankshafts free end are depended on load it is necessary to measure and take into consideration real load in diagnostic inference process or to make diagnostic measurements always in the same conditions of known machine load. In all cases of measurements of machine load may be made by measure of shaft torque. Information concerning load are also contained in indicated power of machine of piston crank mechanism and/or in electric power consumed by electric motor or developed by generator.

The indicated power is evaluated from courses of the medium pressures in machine cylinders. The pressure as a function of rotation angle may be also useful to evaluate losses of friction and courses of friction losses. The pressure in working chamber which acts for piston is part of force which acting for piston, and through it for other elements of mechanism, Fig 1. The tangential force which acts on the crank pin and generate torque is a force component from pressure. The real force which acts for crank pin is smaller than the calculated one because of sum of friction forces between piston and cylinder liner, in connecting rod head bearing and in crosshead bearing.

There is possible to calculate of tangential forces which act on crank pin from measured torsional vibrations of crankshaft free end and set earlier transition function [4].

It is allowed to take an assumption that difference between tangential force evaluated from pressure and from vibrations will be value of friction forces in mechanism pairs [10]. It seems that evaluated in that way courses of friction forces will allow to find system with the biggest friction force. Such way is a convenient to realization on ship propulsion systems with two and four stroke combustion engines equipped with indicating cocks.

The electric power of a machine is the product of voltage and current intensity with a phase shift between voltage and intensity for an alternating current. It is possible to find information in publications, about attempts to build practical equipment for electric power measurements. The researches, more often, are going to use courses of voltage and current intensity for a direct diagnosis of electric machine elements. It is possible to infer about course of friction forces of machine with piston-crank mechanism with base on course of electric power, but in operate conditions without external load [3].

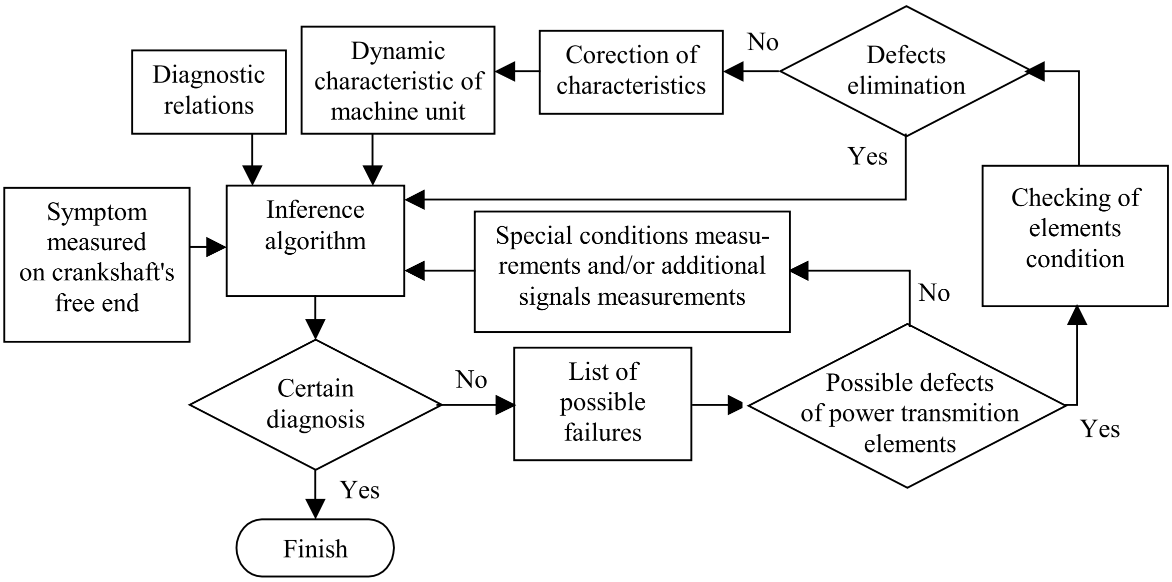


Fig. 1. The algorithm of diagnosis of machine set with piston-crank mechanism machine

The diagnostic researches in described, special conditions of operation may reduce the demanded number of sensors. In case of combustion engines, when exist possibility of disconnecting of working machine or operating machine without load, it is possible diagnosing of machine at idle running or with no external load. A lot of information is contained in courses of angular acceleration in engine accelerating and decelerating conditions without external load. The Ferrari transducer, which is part of integrated sensor for free end, seems to be useful for acceleration measurements in acceleration and deceleration of machine. An angular velocity may be calculated from measured angle of rotation by differentiation with respect to time.

Information about the load distribution for each cylinder may be taken from course of angular acceleration of the shaft as function of rotation angle. The mechanical efficiency of engine may be calculated from course of angular acceleration as function of angular velocity during acceleration and deceleration.

It seems to be justified to determine courses of angular acceleration as function of rotation angle and revolution speed of working machines with piston-crank mechanism, which are driven by electric motors, at no load conditions and during accelerating and decelerating of machine set. From the acquired courses may be taken an inference about distribution of friction forces and about mechanical efficiency of machine set.

5. THE INFLUENCE OF DYNAMICAL VALUES OF MACHINE SET ON DIAGNOSTIC RELATIONS

Relations between failure and diagnostic symptom measured on free end of crankshaft are depended not only on load, but also on dynamical values (distribution of masses/inertia moments, stiffness and dumping) of machine set. Dynamic characteristics of the machine set will change if some part of the machine set will be changed. If with the same machine with piston-crank mechanism be changed other machine or coupling or part of shaft, dynamic characteristic will change. The wear of couplings, specially flexible couplings, takes result in course of torsional vibrations. Also deformations of foundation of machine set loosen of bolts or regulation washer wearing change course of axial vibration. Wear of vibration dampers takes effect in raising amplitudes of vibrations.

The diagnosis of the machine with piston- crank mechanism needs to fit algorithms of diagnosis to dynamical characteristics of machine set. The influence of power transmission elements wear on courses of measured diagnostic signals should be taken into consideration in inference algorithms. The list of possible failures, generated during inference, should also contain possible failures of power transmission elements. It is desired to have methods and resources for condition assessment of power transmission elements to confirm or exclude failure. The simplified algorithm of diagnosis of machine set with piston crank mechanism is presented on Fig. 2.

6. CONCLUSIONS

1. Vibrations of the crankshaft free end may be used in a permanent diagnosis of piston-crank mechanism.
2. It is necessary to build an industrial integrated sensor of crankshaft free end.
3. Information acquired from a shaft free end sensor may be extended by additional measurements in specific operation conditions of a machine set.

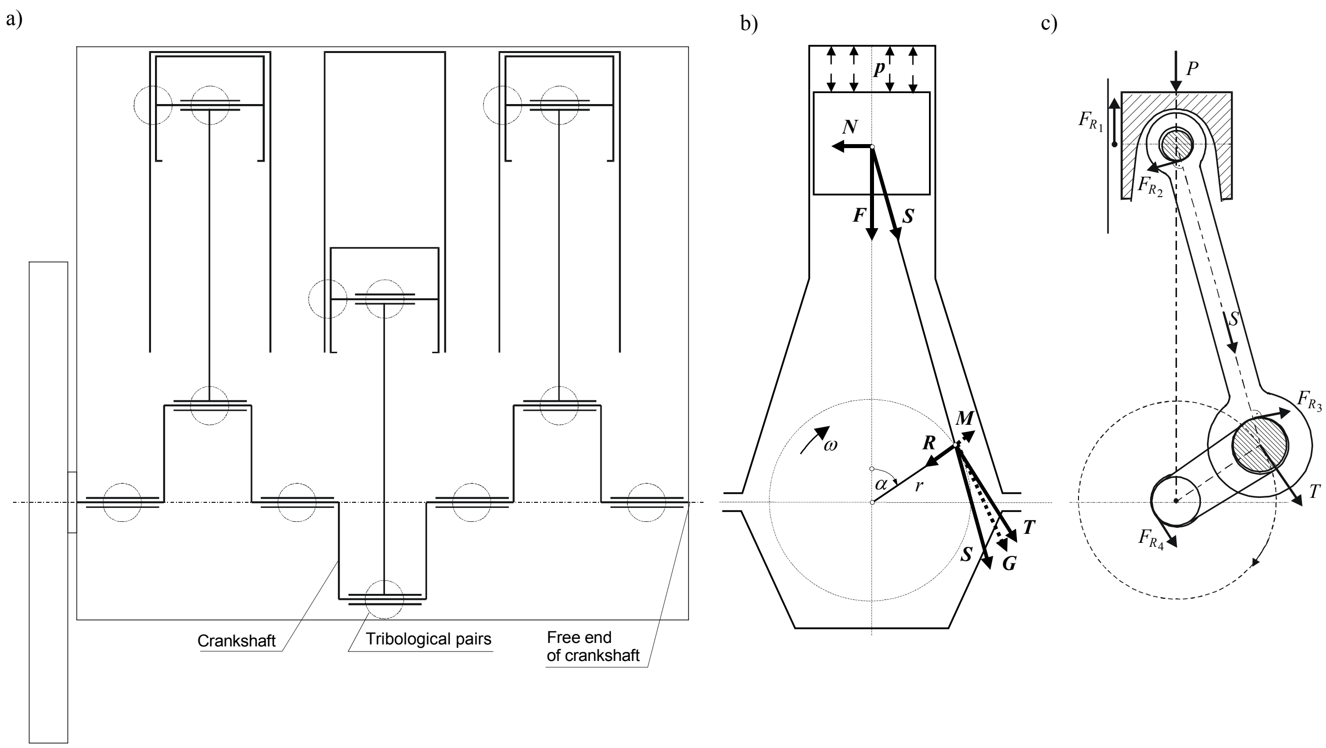


Fig. 2. Machine with piston-crank mechanism: a) tribological pairs, b) forces from medium pressure and masses, c) friction forces

4. The algorithm of inference has to be fitted to dynamical characteristic of the machine set. It also has to take into consideration the wear of power transmission elements of the machine set.

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