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ANALYSIS OF OPERATION OF PISTON COMPRESSOR
DRIVEN BY OSCILLATING ELECTRICAL MOTOR

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ABSTRACT

This paper presents the method of an operation analysis of the piston compressor driven by an oscillating synchronous motor. The compatibility of parameters of oscillating electrical motor and piston compressor as load is the goal of this analysis. The properties of oscillating synchronous motor in the steady-state regime are evaluated by the characteristics as functions of the complex argument, that is, of load mechanical impedance. The properties of piston compressor are evaluated by equivalent mechanical impedance. The solution of motor and compressor equations gives the working points of the drive and enables to calculate the performance characteristics of device. The graphical interpretation of this solution makes the compatibility of parameters easier.

INTRODUCTION

The object of this paper is the piston compressor driven by an oscillating synchronous motor. It should be noted that the investigated device is called by different names (e.g., oscillating compressor, linear compressor, resonant free piston linear compressor, electromagnetic compressor etc.). Unfortunately, the current names don’t reflect the main point of these devices. Exceptional sign of these units is that an oscillating electrical motor drives a compressor. The oscillating electrical motors distinguish themselves by the specific temporal feature of motion, i.e. by the periodicity of movement. The oscillating motors with different trajectory of the mover (that is, with different spatial features of movement: rotary, linear, complex) are known. However in any of these cases, the theory of oscillating motors and the analysis of their operation can be general.

The compressors with the oscillating motors of different trajectory are known as well. For instance, the piston compressor driven by oscillating rotary electrical motor is shown in Figure 1 (Ref. 1). The compressor with oscillating linear motor is shown in Figure 2 (Ref. 2). In both cases the operation of a drive and its analysis can be the same. It’s important to emphasize in being named that it is the compressor driven by an oscillating electrical motor is the main thing, while the linearity (or another trajectory) of used motion should be only the secondary sign. Clearly, the linear motion is markedly more suitable for the compressor drive. So, the oscillating linear electrical motors are mostly utilized. For example, it is confirmed by the experience of Sunpower Inc. (Ref. 3).

The moving part of oscillating motor can be directly connected (or even coincided) with the compressor’s piston. In this way the intermediate transmission (or transformer) of mechanical part can be avoided and the mechanical losses can be reduced. This possibility to simplify the structure determines the expediency of such compressors. In this case the piston compressor and oscillating electrical motor becomes as the united device. It inevitably makes the examined drive as a multidisciplinary object.

The first attempt to create a piston compressor driven by oscillating motor was made by Paul Boucherot in France approximately one hundred years ago (Ref. 4). Regardless to the efforts of many inventors and researchers there are unsolved technical problems till now. The main reason of difficulties is the compatibility of motor and load parameters, because the compressor and oscillating motor are complicated non-linear systems.
The problems of compatibility of properties of oscillating electrical motor and of piston compressor as load ones form the aim of this paper. The recommended method enables to predict the work of a drive, to calculate the performance characteristics of examined compressor.

OSCILLATING ELECTRICAL MOTORS IN COMPRESSOR DRIVE

Oscillating motors types

The oscillating synchronous motors are used in compressor drive (Ref. 5). The strict relation between the frequencies of mover oscillations and supply voltage (or voltages) determines the synchronism of oscillating motors. Mostly these frequencies are the same or multiple.

The oscillating exciting and so-called pulsating current synchronous motors are used in compressor drive. The exciting motors have two sources of magnetomotive force: the winding of AC and the field winding of DC (or permanent magnet). The operation of this motor is grounded by variable mutual inductance between the windings. The sources of magnetomotive force can have the different position with respect to stator or mover. In principle, the performance characteristics of motor are independent of the location of windings. An example of oscillating synchronous exciting motor with permanent magnets in the rotor is shown in Figure 1.

The asymmetrical oscillating synchronous pulsating current motor may have the only source of magnetomotive force: the winding with unipolar current impulses formed by semiconductor element in AC circuit. The operation of this motor is grounded by variable self-inductance of the winding. An example of synchronous pulsating current motor is shown in Figure 2. Symmetrical (doubled) pulsating current motors are used also.

In general, the higher energetic performances are more easily realized in permanent magnet exciting motor, but the pulsating current motors are simpler and at a lower price.

The main regime and load of oscillating motors

The main regime of oscillating synchronous motor is steady oscillation regime with continuous unidirectional energy conversion. In the main regime all variables of motor are periodic time functions of fixed frequency. A very important feature of practical utilisation of the oscillating synchronous motors is the following: in many cases, oscillation of movable part is similar to sinusoidal (or at least the main harmonic of oscillation dominates very clearly). This is due to the inevitable inertia of movable part that damps the upper harmonics of oscillation.

Figure 1: Compressor driven by oscillating rotary electrical motor; 1 – motor’s stator, 2 – winding, 3 – motor’s mover, 4 – spring, 5 – cylinder, 6 – piston.

Figure 2: Compressor driven by oscillating linear electrical motor, its stator and electrical circuit (see the explanation in Fig. 1).
When the oscillation of a movable part is sinusoidal, the mechanical part of a motor can be analysed by using the symbolic method of alternating current to estimate electric circuits. In such case, the complex mechanical impedance expresses the motor load:

\[ Z = R + jX = R + j(X_m - X_s) = R + j\left(\frac{\omega m}{c} - \frac{1}{\omega}\right), \]  

(1)

where \( R \) is the mechanical resistance,
\( X_m \) is the inertial reactance,
\( X_s \) is the reactance of stiffness (spring-reactance),
\( m \) is the mass (or moment of inertia in case of rotary movement),
\( c \) is the spring constant,
\( \omega \) is the angular frequency of oscillation.

The mechanical impedance \( Z \) as oscillating motor’s load must evaluate inner and extern components of mechanical part.

**Oscillating motor characteristics**

In case of conventional electrical motor with continuous rotary motion, a system of characteristics presents the dependence of variables on load. The principle of oscillating motor’s characteristics is the same. Since the mechanical impedance \( Z \) (i.e., complex value) evaluates the load of oscillating motor, the characteristics of this motor are the functions of a complex argument. The characteristics can be represented graphically as 3D surfaces or as level lines of these surfaces on a complex plane (Ref. 5).

The dependence of oscillation amplitude \( H \) on the mechanical impedance \( Z \) is very important (especially in case of the compressor drive):

\[ H = f(Z). \]  

(2)

The oscillating motors, as a general rule, are non-linear systems; therefore their characteristics can be calculated by numerical methods. The graphical interpretation of characteristic (2) of exciting motor is shown in Figure 3 (Ref. 6). This motor can theoretically work in the whole region of mechanical impedance (i.e., until the conditional oscillation amplitude 1.7 in Figure 3), but practically the mover stroke can be limited (the shaded part of the characteristic in Figure 3). Figure 4 presents a characteristic of pulsating current motor (Ref. 7). For example, this characteristic may even widen to the top, contrary to characteristic of the exciting motor.

If the mechanical impedance \( Z \) is known, the amplitude of stroke \( H \) would be found according to characteristic \( H(Z) \) (see the points \( Z_1 \) and \( H_1 \) in Figure 4). The other characteristics of motor as function of a complex argument (e.g., input and output power, efficiency, power factor etc. as functions of load) may be formed by analogous way and corresponding indices of operation can be determined as well.
COMPRESSOR AS LOAD OF THE OSCILLATING MOTOR

Mechanical impedance of the compressor

As mentioned above, an oscillating motor work is determined by mechanical impedance, therefore it is desirable to determine the mechanical impedance of the piston compressor also.

Generally, the indicator diagram (dependence of pressure upon a volume of cylinder’s cavity; in another scale it would be interdependence of compressor resistance force versus position of piston) reflects properties of compressor as load. The theoretical indicator diagram of the single-side compressor is shown in Figure 5 (the solid bold line). As we see, the indicator diagram differs from ellipse. It signifies non-linearity of compressor properties. In this case, the equivalent impedance of compressor may be calculated according to equivalent ellipse. In Figure 5 the equivalent ellipse, formed according to the first harmonic and constant component of pressure (Ref. 8), is shown by the dotted bold line. The areas of indicator diagram and equivalent ellipse are equal and they determine the resistance of compressor $R_c$. An inclination of those figures determines the spring-reactance of compressor $X_c$ (see the fine lines in Figure 5). When the suction and discharge pressures (and other parameters of compressor) are fixed, the mechanical impedance of compressor depends on the amplitude of piston oscillation $H$:

$$Z_c = R_c - j X_c = f(H).$$

The attempts to calculate equivalent dissipative and stiffness components of compressor according to the indicator diagram were made by different researchers (e.g., Ref. 9, 10), therefore the proposed methods have been very inaccurate.

![Figure 5: The theoretical indicator diagram of single-side compressor and its equivalent ellipses](image1.png)

![Figure 6: The theoretical indicator diagram of double-side compressor and its equivalent ellipse](image2.png)

The theoretical indicator diagram of double-side compressor and its equivalent ellipse are shown in Figure 6. As we see, the equivalent ellipse of double-side compressor is more near to the indicator diagram. In this case, the even harmonics and constant component of pressure are balanced. The later circumstance permits to create a springless compressor driven by suitable oscillating electrical motor.

Characteristics of compressor impedance

The relationship (3) can be interpreted graphically as 3D curve, which is represented in Figure 7. As we see, the compressor impedance has only the component of spring-reactance, if the piston stroke is lower of certain limit. In excess of this limit the reactance appears and increases, but the spring-reactance decreases.
Figure 7: Function of compressor impedance as 3D curve and its projection on a complex plane of mechanical impedance.

If the discharge pressure changes, the spatial curves of compressor impedance (3) should form a 3D surface. This surface (with one curve of fixed discharge pressure $p_2 = \text{const}$ made clear) is shown in Figure 8. The dependence represented by this surface is very informative characteristic of compressor as oscillating motor load and it can be used to calculate the drive operation. In analogous way another characteristics of compressor can be formed as well (e.g., the gas flow, efficiency etc. versus mechanical impedance).

Figure 8: Compressor impedance characteristic as 3D surface with level lines of the piston’s stroke $H$ and the discharge pressure $p_2$.

OPERATION OF COMPRESSOR AND OSCILLATING MOTOR DRIVE

Principle of analysis

It was pointed out in the previous section, the compressor’s mechanical impedance is not constant, and therefore the working point of drive cannot be found in so simple mode, as was indicated in Figure 4. As in a case of conventional electrical motor drive, the system of motor equation and compressor one must be solved. Because these equations are non-linear, it is needed to solve them by numerical methods (Ref. 11). The equation (2) and (3) form, in fact, this system.
The graphical interpretation of the equations solution is shown in Figure 9. The result of this solution is the finding of the drive working point $A$, that is, the point of intersection of the motor’s characteristic (e.g., Figure 3) and the compressor’s one (e.g., the spatial curve of Figure 7). In such a situation, another load’s components must be taken into account (the inertial reactance of moving part, the reactance of spring, the resistance of friction etc.). According to position of the point $A$, the operation indices can be established. For instance, the position of the point $A$ directly shows the amplitude of oscillation (approximately 0.9). The others performances can be calculated according to working mechanical impedance $Z_A$.

![Figure 9: Graphical interpretation of the solution of oscillating motor and compressor equations (the discharge pressure is fixed).](image1)

If the discharge pressure changes, the compressor characteristic forms a 3D surface (see Figure 8). In this case, the graphical interpretation of equations solution is reflected by intersection of two surfaces shown in Figure 10. In that way, the working points of drive are established and afterward the performance characteristics can be calculated.

![Figure 10: Graphical interpretation of the solution of oscillating motor and compressor equations when the discharge pressure changes: intersection of the surfaces and projection of the line of intersection on a complex plane of mechanical impedance (two views).](image2)

If the discharge pressure changes, the compressor characteristic forms a 3D surface (see Figure 8). In this case, the graphical interpretation of equations solution is reflected by intersection of two surfaces shown in Figure 10. In that way, the working points of drive are established and afterward the performance characteristics can be calculated.

It may be noticed that the received working points of Figure 10 are located in a region with positive mechanical reactance, that is, the drive doesn’t operate in the mechanical resonance. Therefore the sometimes-used term *resonant compressor* is not correct.
Performance characteristics

If the working points of drive are known, some performance characteristics of device can be calculated. It would be the dependencies of diverse indices of operation from the discharge pressure \( p_2 \): input power \( P_1 \), output power of oscillating motor \( P_m \), output power of device (of compressor) \( P_2 \), efficiency of motor \( \eta_m \), efficiency of device \( \eta \), gas flow \( N \), stroke of piston \( H \) etc.

The Figure 11 represents a sample of power characteristics of compressor driven by oscillating electrical motor (according to the working points of Figure 10). Here the losses of motor \( \Delta P_m \) and mechanical ones \( \Delta P_{mech} \) can be observed. The others performance characteristics of compressor are shown in Figure 12 (the piston stroke \( H \) and compressor gas flow \( N \) are represented in relative units related by compressor cylinder dimensions).

According to performance characteristics of Figure 12, it may be stated that in this case, the accordance of parameters of oscillating motor and compressor is properly enough. As we see, the efficiency of drive is high in the range of discharge pressures from 5 to 11 \((10^5 \text{Pa})\).

Let us assume that the parameters of compressor rest the same, but the parameters of motor change. The Figure 13 represents the solution of motor – compressor equations as well, when the motor power is smaller and the inner inertial reactance is bigger. The performance characteristics show that the oscillation amplitude is decreased, especially in range of low discharge pressure. In result of this circumstance, the gas flow greatly diminishes also. In fact, this oscillating motor is not suitable for that compressor.

In analogous way, the compatibility of compressor parameters and oscillating electrical motor ones can be analyzed, the performance characteristics may be predicted. Also, the optimization of the drive can be realized.
DISCUSSION

It should be noted that the modern calculating tools (Mathcad, Matlab, finite elements methods etc.) give powerful possibilities to analyze the various processes of compressor and oscillating motor as complicated and non-linear dynamic systems by the direct solution of its differential equations. This solution can be realized in the desirable precision. Whereas the methods described above are approximate (the method of oscillating motor characteristics as functions of complex argument, of compressor equivalent mechanical impedance) and are allocated to analyze only steady-state periodical operation of the device. Maybe these methods are worthless?

The reply to a question should be following. In many cases, the direct solution of differential equations is supplies the surplus of information, which makes indistinct the principal results of the main regime (steady-state oscillation). On the contrary, the proposed method exposes the main features of the drive and enables to co-ordinate the compressor and oscillating motor parameters. Furthermore, this method must be and may be precise by estimation of different marginal effects (influence of valves, of gas leakage to compressor indicator diagram, the non-linear friction, the variation of oscillation center, the higher harmonics of variables etc.).

CONCLUSIONS

The expediency of the compressor driven by oscillating electrical motor is determined by direct connection of the moving part of motor and the compressor piston. The oscillating synchronous motors are used in the compressor drive and its characteristics can be expressed as functions of mechanical impedance.

The compressor as load mechanical impedance, depending of compressor parameters and piston stroke, can be calculated according to indicator diagram.

Analyzing operation of drive, one has to solve the equations of motor and load. In the graphical interpretation of analysis of drive the crossing of the two spatial surfaces should be found out. The crossing line reflects the operation indices, enables to form the performance characteristics and get information about the compatibility of parameters of motor and compressor. The experimental observations justify this method of analysis.

REFERENCES