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Rotary Machine Sealing Oscillation Frequencies and Phase Shift Analysis

Liliia N. Butymova, Vladimir Ya Modorskii

***Abstract*—**To ensure the gas transmittal GCU's efficient operation, leakages through the labyrinth packings (LP) should be minimized. Leakages can be minimized by decreasing the LP gap, which in turn depends on thermal processes and possible rotor vibrations and is designed to ensure absence of mechanical contact. Vibration mitigation allows to minimize the LP gap. It is advantageous to research influence of processes in the dynamic gas-structure system on LP vibrations. This paper considers influence of rotor vibrations on LP gas dynamics and influence of the latter on the rotor structure within the FSI unidirectional dynamical coupled problem. Dependences of nonstationary parameters of gas-dynamic process in LP on rotor vibrations under various gas speeds and pressures, shaft rotation speeds and vibration amplitudes, and working medium features were studied. The programmed multi-processor ANSYS CFX was chosen as a numerical computation tool. The problem was solved using PNRPU high-capacity computer complex. Deformed shaft vibrations are replaced with an unyielding profile that moves in the fixed annulus "up-and-down" according to set harmonic rule. This solves a nonstationary gas-dynamic problem and determines time dependence of total gas-dynamic force value influencing the shaft. Pressure increase from 0.1 to 10 MPa causes growth of gas-dynamic force oscillation amplitude and frequency. The phase shift angle between gas-dynamic force oscillations and those of shaft displacement decreases from 3π/4 to π/2. Damping constant has maximum value under 1 MPa pressure in the gap. Increase of shaft oscillation frequency from 50 to 150 Hz under P=10 MPa causes growth of gas-dynamic force oscillation amplitude. Damping constant has maximum value at 50 Hz equaling 1.012. Increase of shaft vibration amplitude from 20 to 80 µm under P=10 MPa causes the rise of gas-dynamic force amplitude up to 20 times. Damping constant increases from 0.092 to 0.251. Calculations for various working substances (methane, perfect gas, air at 25 ˚C) prove the minimum gas-dynamic force persistent oscillating amplitude under P=0.1 MPa being observed in methane, and maximum in the air. Frequency remains almost unchanged and the phase shift in the air changes from 3π/4 to π/2. Calculations for various working substances (methane, perfect gas, air at 25 ˚C) prove the maximum gas-dynamic force oscillating amplitude under P=10 MPa being observed in methane, and minimum in the air. Air demonstrates surging. Increase of leakage speed from 0 to 20 m/s through LP under P=0.1 MPa causes the gas-dynamic force oscillating amplitude to decrease by 3 orders and oscillation frequency and the phase shift to increase 2 times and stabilize. Increase of leakage speed from 0 to 20 m/s in LP under P=1 MPa causes gas-dynamic force oscillating amplitude to decrease by almost 4 orders. The phase shift angle increases from π/72 to π/2. Oscillations become persistent. Flow rate proved to influence greatly on pressure oscillations amplitude and a phase shift angle. Work medium influence depends on operation conditions. At pressure growth, vibrations are mostly affected in methane (of working substances list considered), and at pressure decrease, in the air at 25 ˚C.

***Keywords*—**Aeroelasticity, labyrinth packings, oscillation phase shift, vibration.

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I. Introduction

LABYRINTH PACKINGS (LP) are used for noncontacting sealing arrangement between a rotary shaft and its fixed shell.

LP are in common use in different technology including aircraft engines and high-pressure pumps working under high temperatures and rotation velocity [1]. It should be noted that critical operation conditions cause a working substance to bring grate pressure upon the LP stricture [2]. The structure in turn affects the gas. This influence is an intricate problem [3]-[7] and requires us to clarify the approach to examine the factors affecting LP processes.

Classical formulation of a vibration problem allows us to take into account the influence of structural [8]-[11], physical, mechanical and technological parameters on vibrations, but does not allow to include the influence of gas-dynamic loads.

This paper considers the influence of gas-dynamic processes on vibrations within a unidirectional dynamical coupled problem formulation [12]-[15].

II. Physical Model

The following calculation model was developed to simulate LP gas-dynamic processes and takes into account accepted allowances:

- The structure is considered to be three-dimensional (x, y, z);
- The calculations are nonstationary, as it is required to study gas oscillations under forced structure oscillations, and oscillation periods of the shaft and gas have the same order;
- The walls of the structure nether absorb nor generate heat, as the temperature is expected to range within 30 °C and estimated time of the process is 0.03 s. The steel shaft (λ=47 W / m×K) does not have enough time to heat, friction force between the walls and the working substances is ignored, the perfect gas, air or methane can be used as the working substances:
- The vibrations of deformed shaft are replaced with an unyielding shaft section that moves in the fixed annulus "up-and-down" according to a set harmonic rule;
- Numerical analytic approach is used to simulate oscillations in the dynamic gas-structure system. Shaft

oscillations are described analytically with the set harmonic rule They cause gas oscillations, where processes are described numerically;
- Shaft oscillations do not depend on gas oscillations;
- The flow rate (leakage) through LP from the high-pressure area to the low-pressure area is taken into account. In addition, any gas flows in the LP gap under shaft vibrations are allowed;
- The shaft is in line with LP in their initial condition.

III. Design Diagram and Numerical Analytic Model of Gas-Dynamic Processes Considering Shaft Section Oscillations in LP

We propose the following approach to evaluate interaction of shaft vibrations and gas-dynamic volume in LP: To apply a numerical model for description of gas processes in the dynamic gas-structure system and an analytic model for description of structure behavior.

Shaft vibrations of the given frequency and amplitude were brought together in the gas-dynamic LP calculation via the "Movable Wall" boundary condition taking into account the desired movement law.

Mathematical model of gas-dynamic process for LP calculation:

- equation of total energy conservation

$$\frac{\partial\left(\rho h_{tot}\right)}{\partial t}-\frac{\partial P}{\partial t}+\nabla\cdot(\rho h_{tot}U)=\nabla\cdot(U\cdot\tau)+S_E \quad (1)$$

- momentum equation

$$\frac{\partial\left(\rho U\right)}{\partial t}+\nabla\cdot(\rho U\otimes U)=\nabla P+\nabla\cdot\tau \quad (2)$$

- continuity equation

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\left(\rho U\right)=0 \quad (3)$$

where t - time; ρ - density; $h_{tot}=h_{stat}+U^2/2$ - total enthalpy; P – pressure; τ - viscous stress tensor; S_E - source term; U - velocity vector; T - temperature.

- gas equation

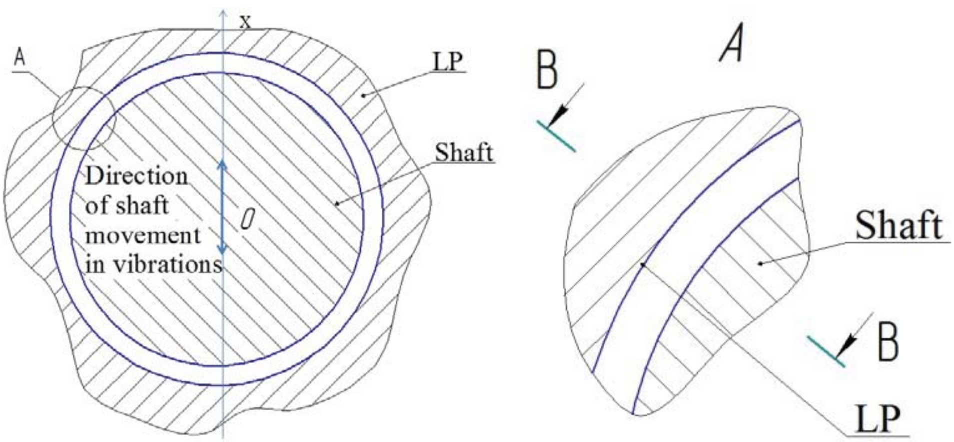
$$P=\rho RT \quad (4)$$

where R is gas constant.

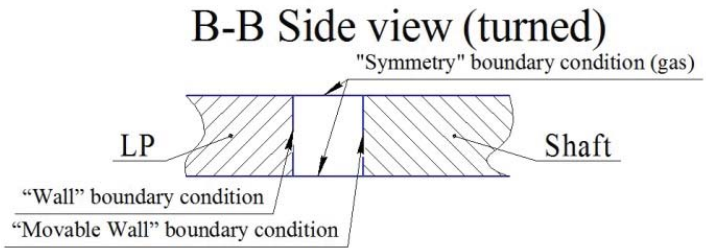
The mathematical model is closed by initial and boundary conditions.

The flow rate through LP from the high-pressure area to the low-pressure area was taken equal to V=0 m/s (basic), V=10 m/s or V=20 m/s. The shaft moves according to the set harmonic rule $U=U_0\times\sin(2\pi/T\times t)$, where U_0 – shaft movement amplitude, T – oscillation period, t – estimated time. Initial values of temperature, pressure, flow rate and shaft oscillation frequency were as follows: T_{int}=50˚C, P_{int}=0.1 MPa, f={50, 100, 150} Hz.

Fig. 1 shows the design diagram and LP processes research boundary conditions: internal LP surface received the "Wall" boundary condition – Fig. 1 (c); the plane perpendicular to the shaft axis at the circular surface of the gas-dynamic gap received the "Symmetry" boundary condition – Fig. 1 (c); the external shaft surface (moving medium) received the "Movable Wall" boundary condition – Fig. 1 (c). Parameter "Definite movement, axis OX" in the tab "Mesh movement" of the ANSYS preprocessor was changed for the last boundary condition.



(a) (b)



(c)

Fig. 1 Design diagram and boundary conditions: (a), (b) design diagram; (c) boundary conditions

IV. Development and Evaluation of Solid and Mesh Models of Gas-Dynamic Calculation in LP

Fig. 2 shows a fragment of the LP solid model. The solid model for the problem was developed using the ANSYS engineering complex, the Design Modeler module, which makes easier data transfer to subsequent ANSYS modules. A geometrical model in the form of the gas-dynamic region was developed on the basis of the design diagram to perform the simulation experiment.

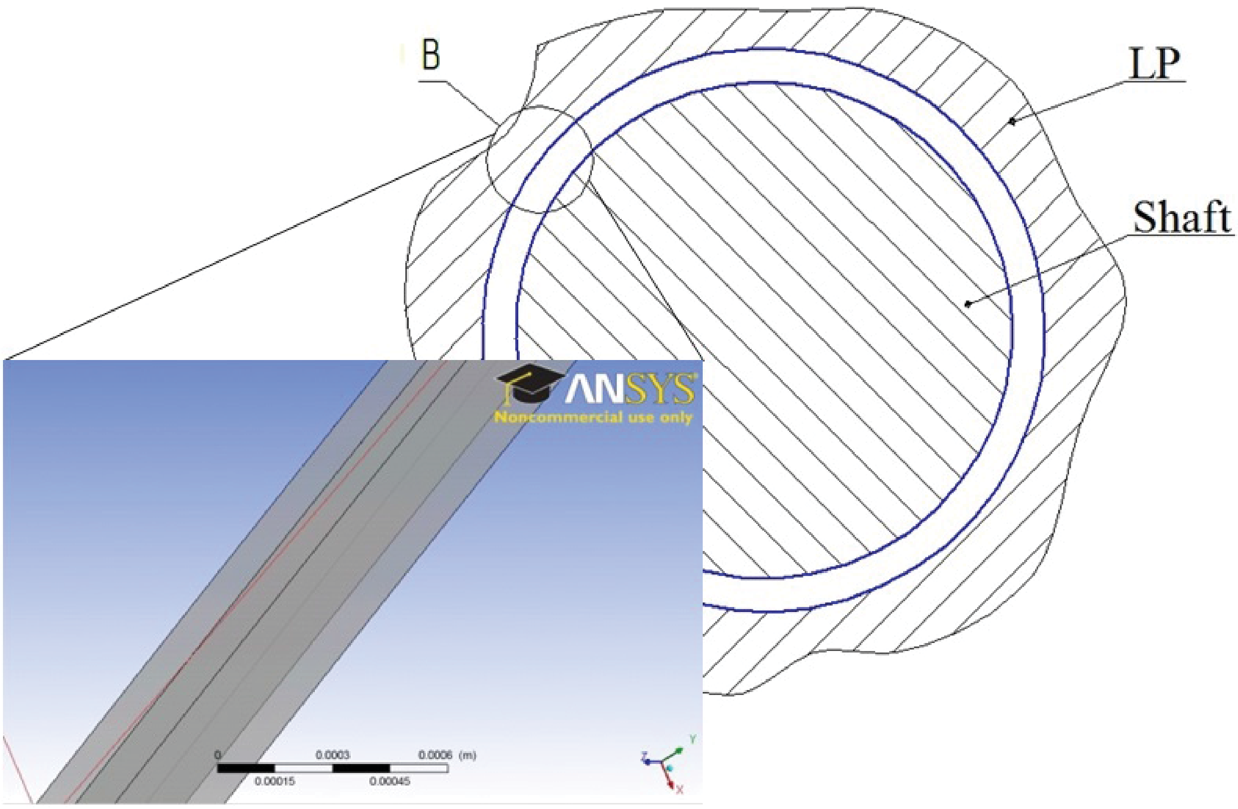


Fig. 2 Fragment of the gas-dynamic region

External diameter of the shaft in the LP area equals to 262.25 mm. The LP gap width δ equals to 0.18 mm. It is assumed that the shaft moves "up-and-down" according to the set harmonic rule. It was decided that the period of time corresponding five shaft oscillations is considered.

The gas-dynamic region was divided into calculation elements. To increase convergence and decrease uncertainty of obtained results a mesh with cells resembling tetrahedron by their form should be applied. Among other matters, it is recommended to avoid critical differences in geometrical dimensions of adjoining cells, and their linear dimensions should not differ more than two times.

Fig. 3 shows mesh model properties describing quantity and quality of the elements and units used for calculation. Fig. 3 shows the side view, where the model is divided through-the-thickness in such a way that one of the cells is frozen to avoid collision of the movable boarder and side wall conditions. The calculation mesh has a uniform structure. Quantity of calculation mesh elements is 110.040 cells.

Statistics	
Nodes	192570
Elements	110040
Mesh Metric	Element Quality
Min	0.99563793449494
Max	0.996144854180538
Average	0.996114368255542
Standard Dev...	2.16021477281825E-05

Fig. 3 Mesh model properties

V. Calculation Experiments (CE) Plan

To perform CE for calculation of gas-dynamic processes in LP of GTU three-stage compressor, we designed a plan including the description of calculation cases (Table I). All calculations were performed for only one design solution of the model GTU three-stage compressor.

TABLE I
CE Plan for Evaluation of Gas-Dynamic Processes in LP of GTU Three-Stage Compressor

Case No.	1 (BC[1])	2 (BC[2])	3	4	5	6	7	8	9	10	1 (BC[1])
P, MPa	*0.1*	*1.0*	*1*	*10*	0.1	0.1	0.1	0.1	0.1	0.1	*0.1*
f, Hz	*150*	150	150	150	*50*	*100*	150	150	150	150	*150*
U_a, μm	*50*	50	50	50	50	50	*20*	*80*	50	50	*50*
Working substance	*Perfect gas*	Perfect gas	Perfect gas	Perfect gas	Perfect gas	Perfect gas	Perfect gas	Perfect gas	*Methane*	*Air*	*Perfect gas*
V, m\s	*0*	0	*20*	0	0	0	0	0	0	0	*0*
Case No.	11 (BC[3])	12	13	14	15	16	17	18	19		11 (BC[3])
P, MPa	*10*	10	10	10	10	10	10	0.1	0.1		*10*
f, Hz	*150*	*50*	*100*	150	150	150	150	150	150		*150*
U_a, μm	*50*	50	50	*20*	*80*	50	50	50	50		*50*
Working substance	*Perfect gas*	Perfect gas	Perfect gas	Perfect gas	Perfect gas	*Methane*	*Air*	Perfect gas	Perfect gas		*Perfect gas*
V, m\s	*0*	0	0	0	0	0	0	*10*	*20*		*0*

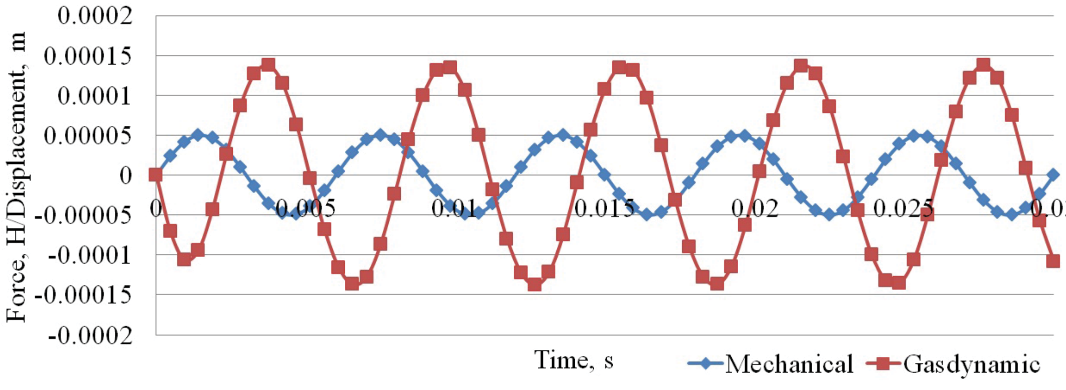
[1] – base case for calculation series No.4-10, 18,19;
[2] – base case for calculation series No.3;
[3] – base case for calculation series No.12-17;
Italicized text corresponds to the varying parameters.

VI. Analysis of Results

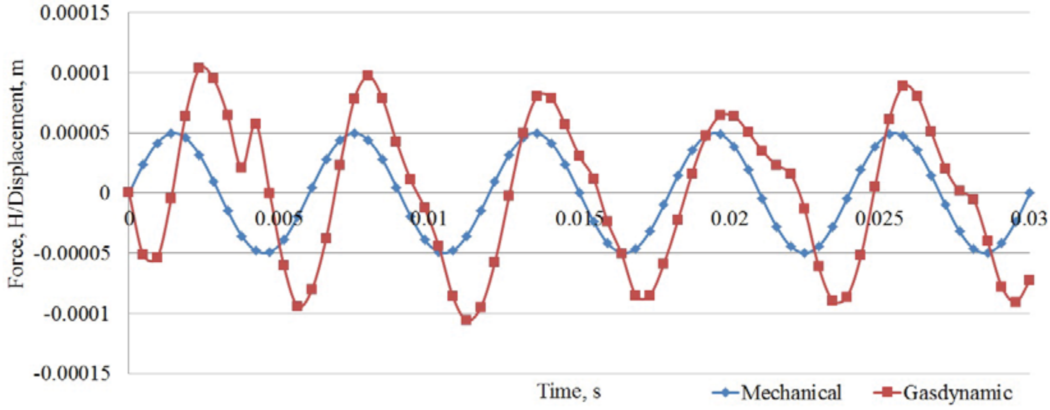
According to the plan, we performed series of calculation experiments and researched the factors affecting oscillatory processes in the working substance: pressure and speed of gas in LP, rotation velocity and movement amplitude of the shaft, different features of working substances.

A. Influence of Nominal Pressure on Oscillatory Processes in LP

The analysis of nominal pressure influence on oscillatory processes in LP was performed using the following time dependence of gas-dynamic forces and shaft displacement amplitude (Fig. 4).



(a)



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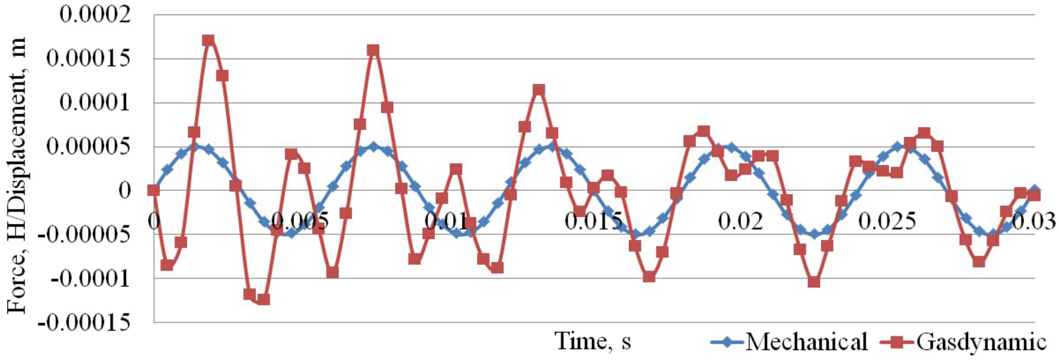


(c)

Fig. 4 Time dependence of gas-dynamic forces and shaft displacement amplitude, where: (a) 0.1 MPa; (b) 1 MPa; (c) 10 MPa

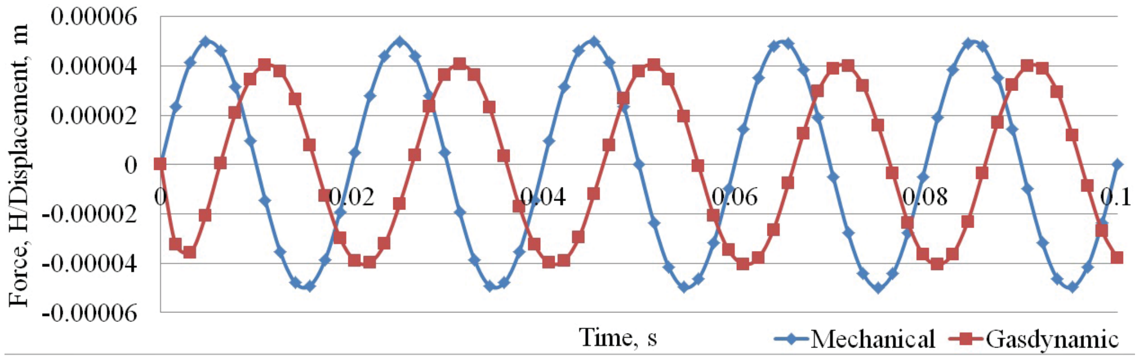
It is apparent that the increase of pressure (cases 1, 2, 4) causes the growth of gas-dynamic force oscillation amplitude and frequency. At the same time, the phase shift angle between gas-dynamic force oscillations and those of shaft displacement decreases. Along with this, the damping constant has maximum value of 0.245 under 1 MPa pressure in the gap.

B. Influence of Shaft Oscillations Frequency

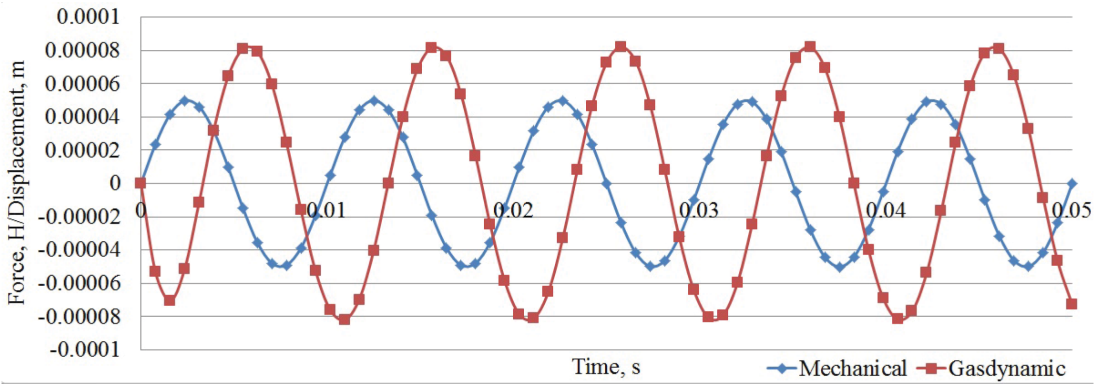
Evaluation of rotation velocity influence on properties of gas oscillations in LP was performed under P_{nom}=0.1 MPa and P_{nom}=10 MPa. The following time dependences of gas-dynamic forces and shaft displacement amplitude were obtained under P_{nom}=0.1 MPa – Fig. 5.

It is apparent that the increase of shaft oscillations frequency (cases 1, 5, 6) causes the growth of the amplitude, and gas-dynamic force oscillations frequency and the phase shift angle between oscillations of the gas-dynamic force and those of shaft displacement are not liable to variation. At the same time, the damping constant equals to 0.

The following time dependences of gas-dynamic forces and shaft displacement amplitude were obtained under P_{nom}=10 MPa – Fig. 6.



(a)



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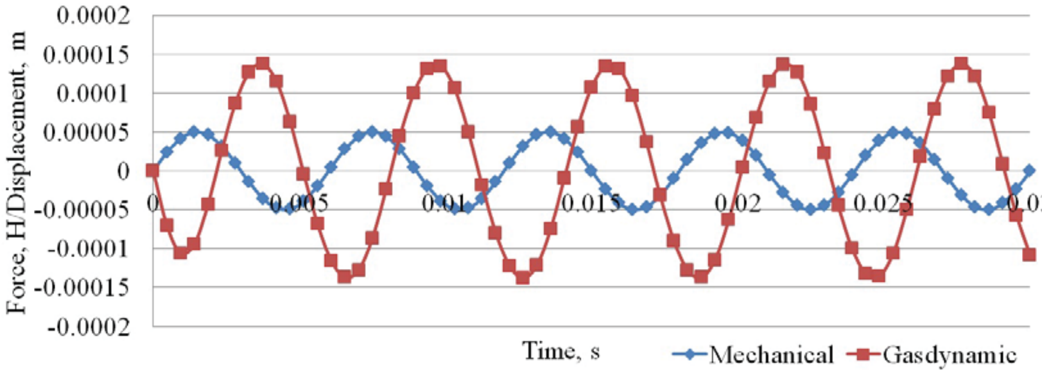
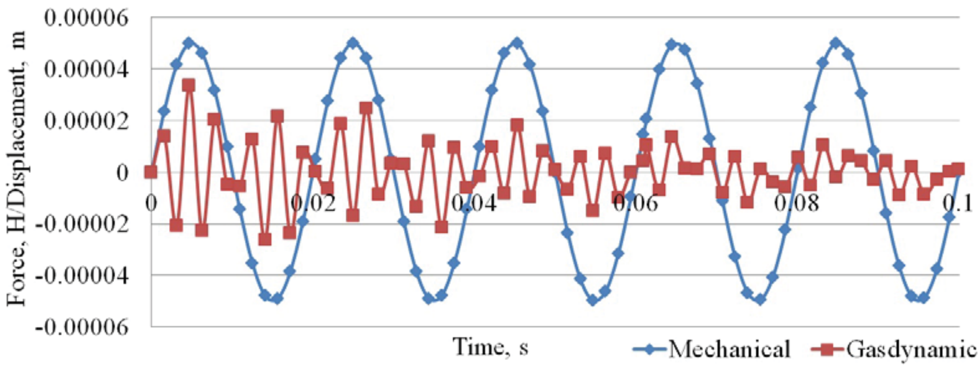
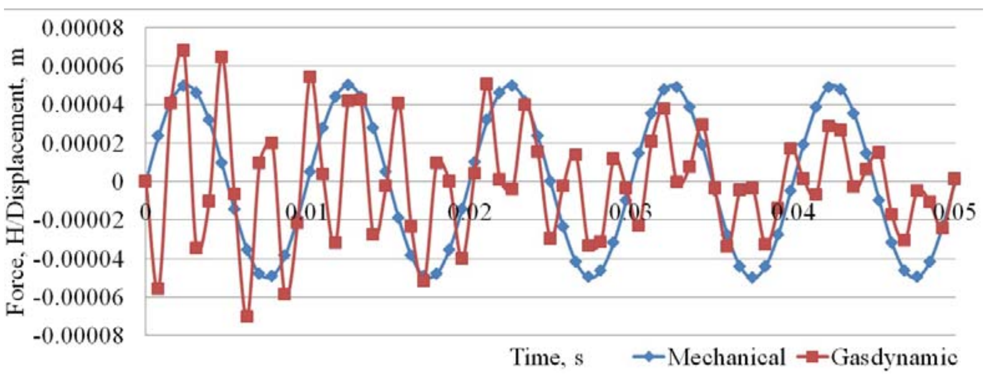


(c)

Fig. 5 Time dependence of gas-dynamic forces and shaft displacement amplitude under P_{nom}=0.1 MPa: (a) 50 Hz; (b) 100 Hz; (c) 150 Hz



(a)



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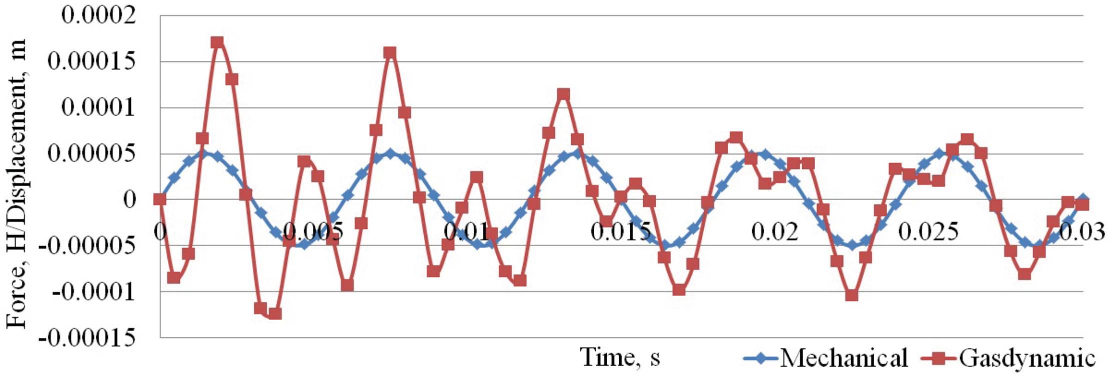


(c)

Fig. 6 Time dependence of gas-dynamic forces and shaft displacement amplitude under P_{nom}=10 MPa: (a) 50 Hz; (b) 100 Hz; (c) 150 Hz

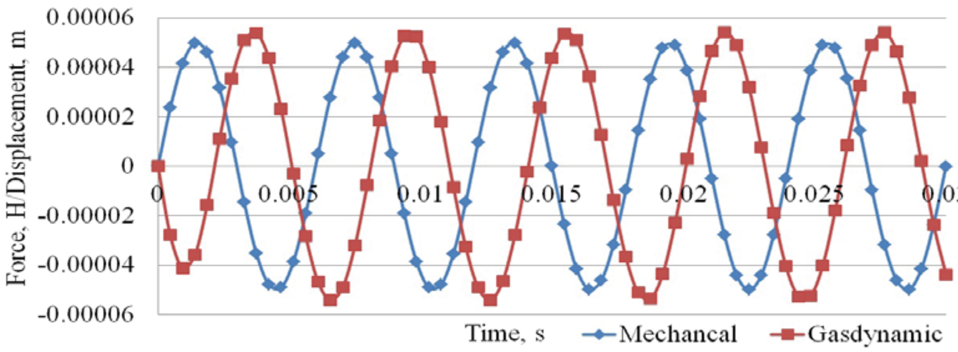
It is apparent that the increase of shaft oscillation frequency (cases 11, 12, 13) causes the growth of gas-dynamic force amplitude. Spectral analysis is required to determine oscillations frequency of gas-dynamic force and the phase shift angle between gas-dynamic force oscillations and those of shaft displacement. Along with this, the damping constant has maximum value of 1.012 under 50 Hz.

C. Influence of Shaft Vibrations Amplitude

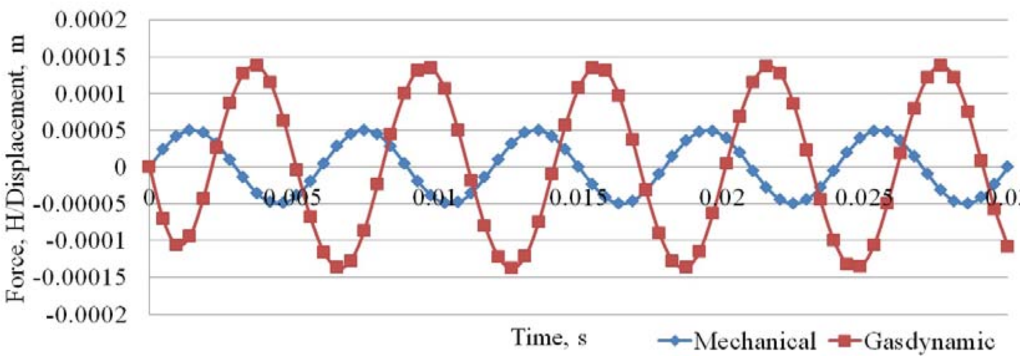
Evaluation of influence of shaft vibrations amplitude on properties of gas oscillations in LP was performed under P_{nom}=0.1 MPa and P_{nom}=10 MPa. The following time dependences of gas-dynamic forces and shaft displacement amplitude were obtained under P_{nom}=0.1 MPa – Fig. 7.

It is apparent that the increase of shaft vibrations amplitude (cases 1, 7, 8) causes the increase of the amplitude, and gas-dynamic force oscillations frequency and the phase shift angle between oscillations of the gas-dynamic force and those of shaft displacement are not liable to variation. At the same time, the damping constant equals to 0.

The following time dependences of gas-dynamic forces and shaft displacement amplitude were obtained under P_{nom}=10 MPa – Fig. 8.



(a)



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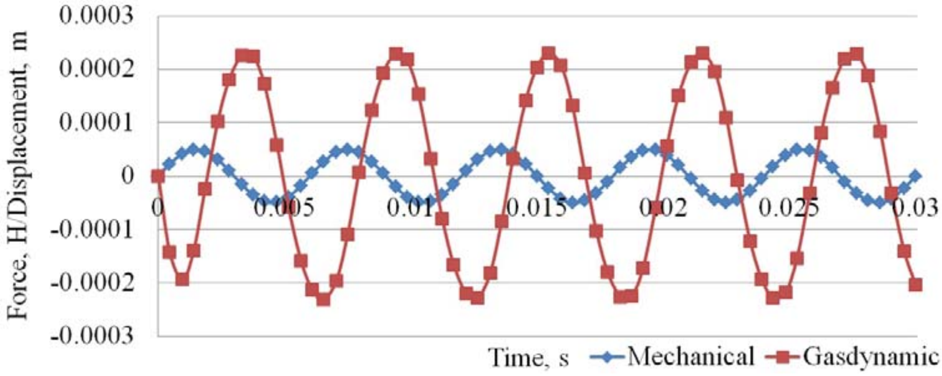
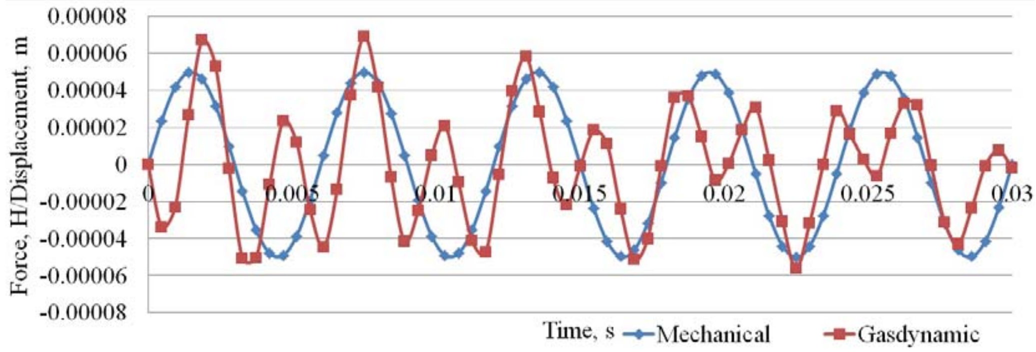
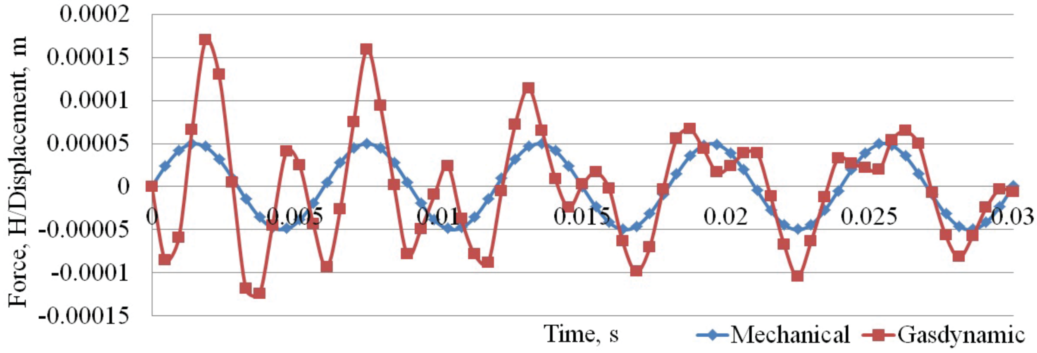


(c)

Fig. 7 Time dependence of gas-dynamic forces and shaft displacement amplitude under P_{nom}=0.1 MPa: (a) 20 µm; (b) 50 µm; (c) 80 µm



(a)



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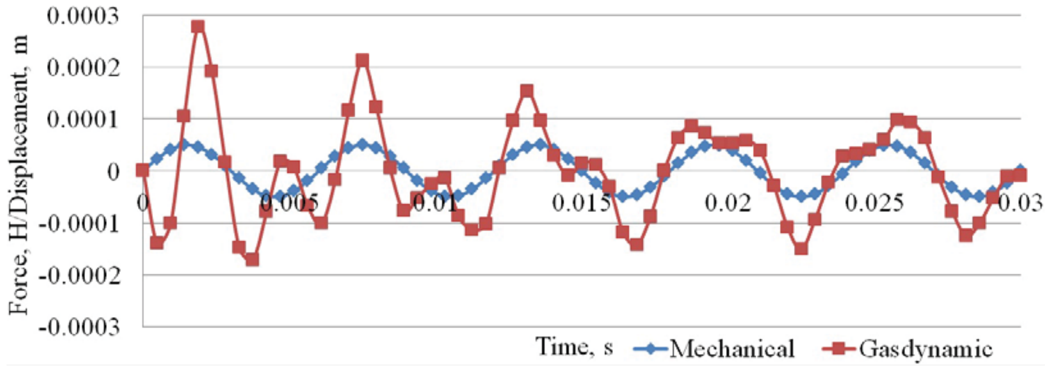


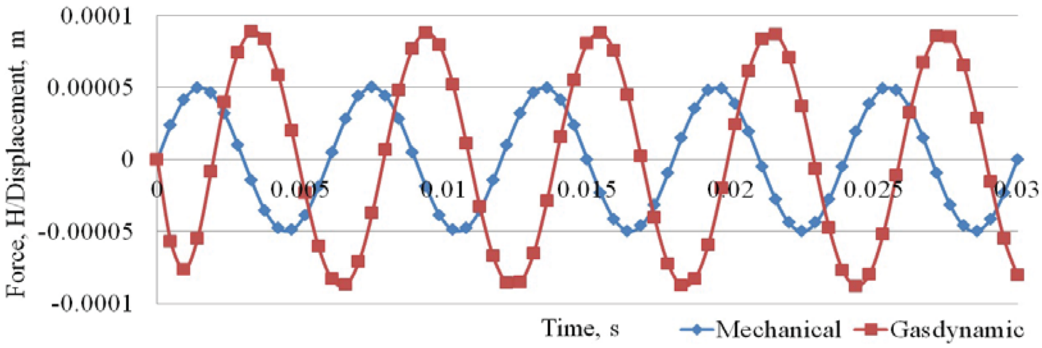
(c)

Fig. 8 Time dependence of gas-dynamic forces and shaft displacement amplitude under P_{nom}=10 MPa: (a) 20 µm; (b) 50 µm; (c) 80 µm

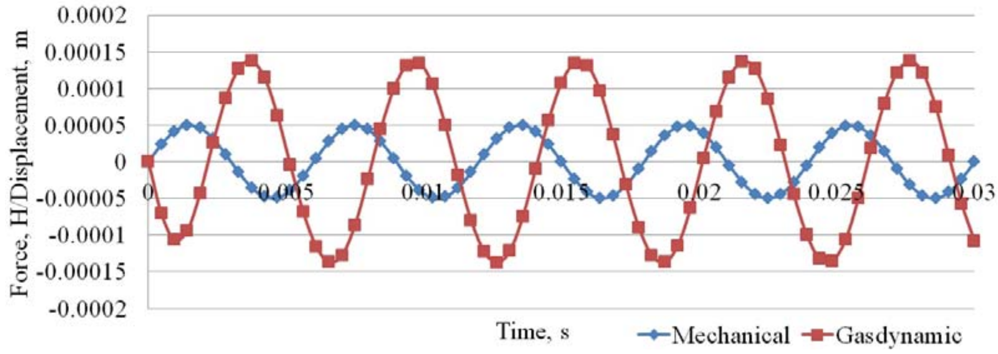
It is seen that the increase of shaft oscillation frequency (cases 11, 14, 15) causes growth of gas-dynamic force amplitude. A spectral analysis is required to determine oscillations frequency of gas-dynamic force and the phase shift angle between gas-dynamic force oscillations and those of shaft displacement. Along with this, the damping constant increases from 0.092 to 0.251.

D. Influence of Working Medium

Evaluation of influence of a working substance on properties of gas oscillations in LP was performed under P_{nom}=0.1 MPa and P_{nom}=10 MPa. The following time dependences of gas-dynamic forces and shaft displacement amplitude were obtained under P_{nom}=0.1 MPa – Fig. 9.



(a)



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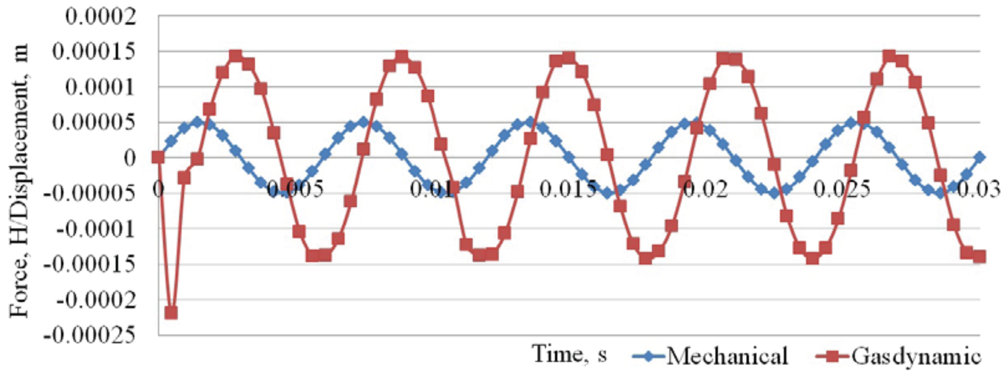


(c)

Fig. 9 Time dependence of gas-dynamic forces and shaft displacement amplitude under P_{nom}=0.1 MPa: (a) methane; (b) perfect gas; (c) air

It is seen that change of a working substance (cases 1, 9, 10) causes gas-dynamic force oscillations amplitude to reach its minimum value in methane, and maximum – in the air. Along with that, frequency remains unchanged and the phase shift in the air changes from 3π/4 to π/2. At the same time, the damping constant equals to 0.

The following time dependences of gas-dynamic forces and shaft displacement amplitude were obtained under P_{nom}=10 MPa (Fig. 10).

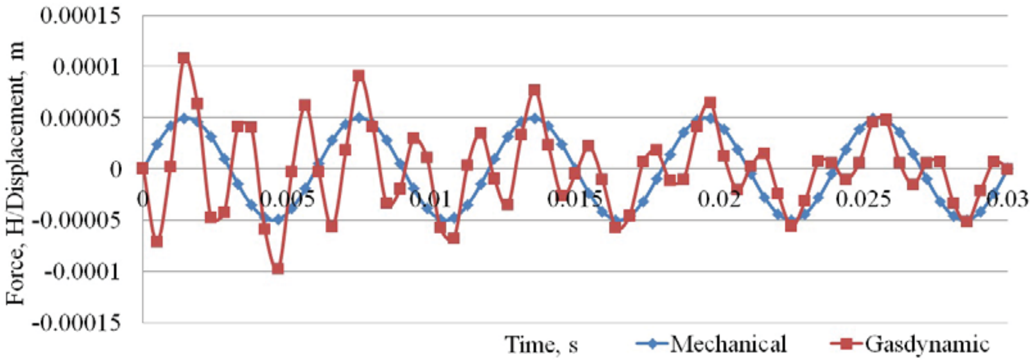
It is apparent that change of a working substance (cases 11, 16, 17) causes gas-dynamic force oscillations amplitude to reach its maximum value in methane, and minimum – in the air. A spectral analysis is required to determine oscillations frequency of gas-dynamic force and the phase shift angle between gas-dynamic force oscillations and those of shaft displacement. In addition, the air demonstrates surging.

E. Influence of Leakage Speed through LP

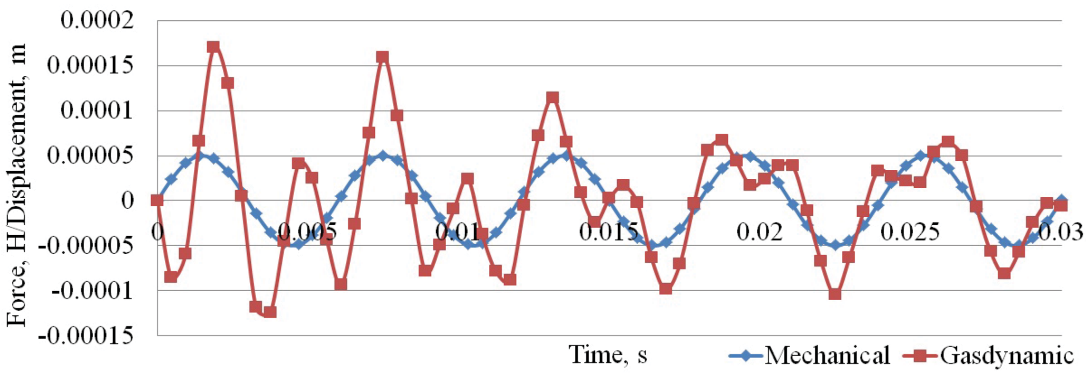
Evaluation of influence of leakage speed on properties of gas oscillations in LP was performed under P_{nom}=0.1 MPa and P_{nom}=1 MPa. The following time dependences of gas-dynamic forces and shaft displacement amplitude were obtained under P_{nom}=0.1 MPa – Fig. 11.

It is apparent that the increase of leakage speed from 0 to 20 m/s through LP (cases 1, 18, 19) causes the gas-dynamic force oscillating amplitude to decrease by 3 orders, at that oscillation frequency and the phase shift to increase 2 times and stabilize.

The following time dependences of gas-dynamic forces and shaft displacement amplitude were obtained under P_{nom}=1 MPa – Fig. 12.



(a)



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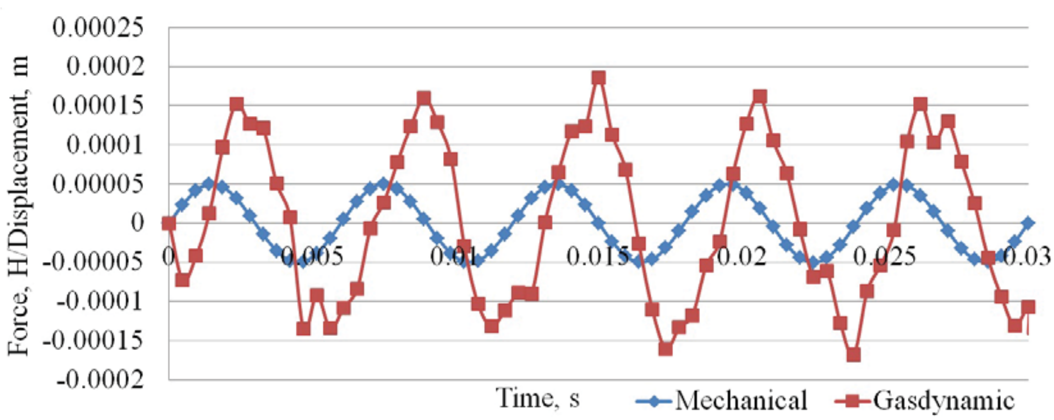
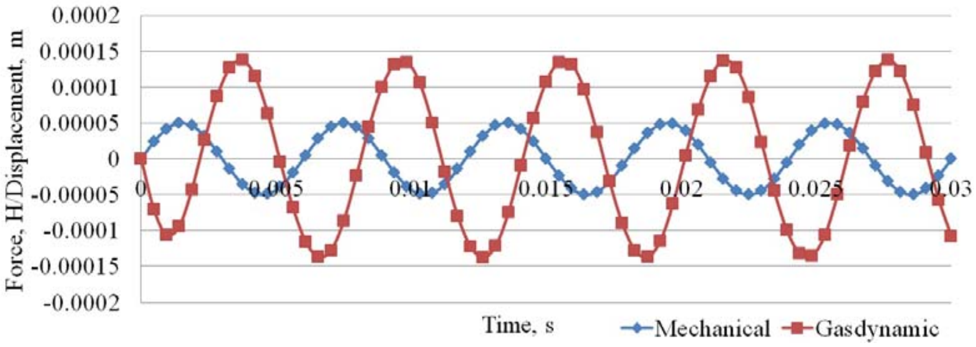
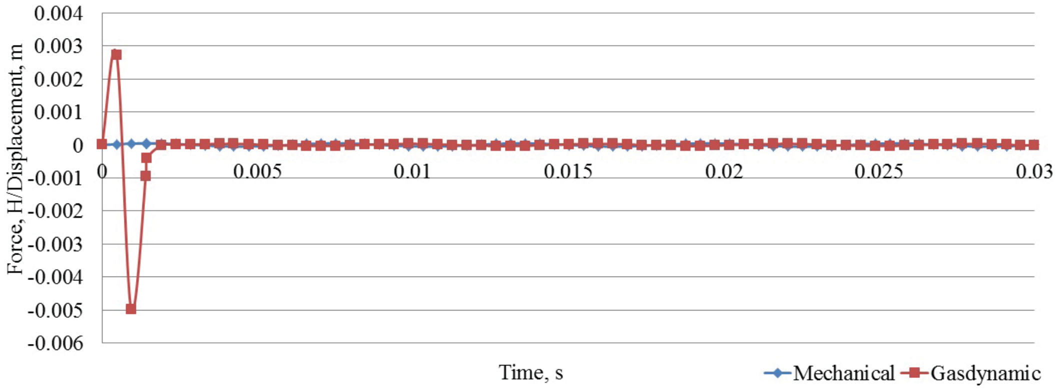


(c)

Fig. 10 Time dependence of gas-dynamic forces and shaft displacement amplitude under P_{nom}=10 MPa: (a) methane; (b) perfect gas; (c) air



(a)



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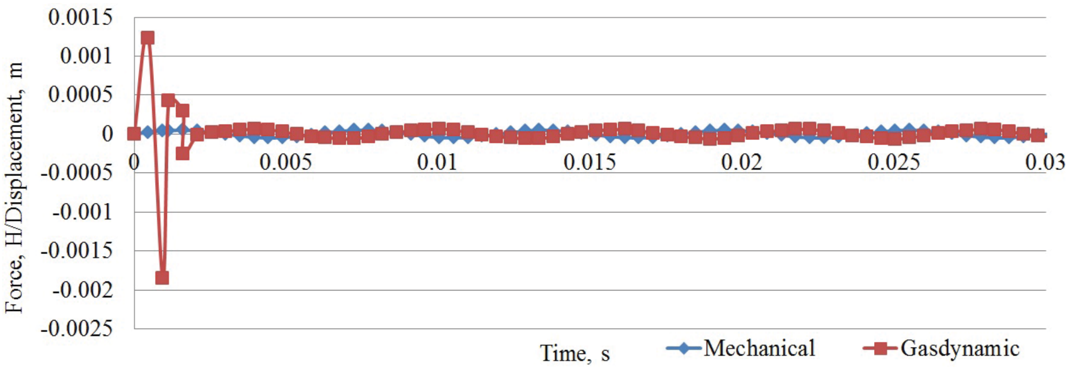
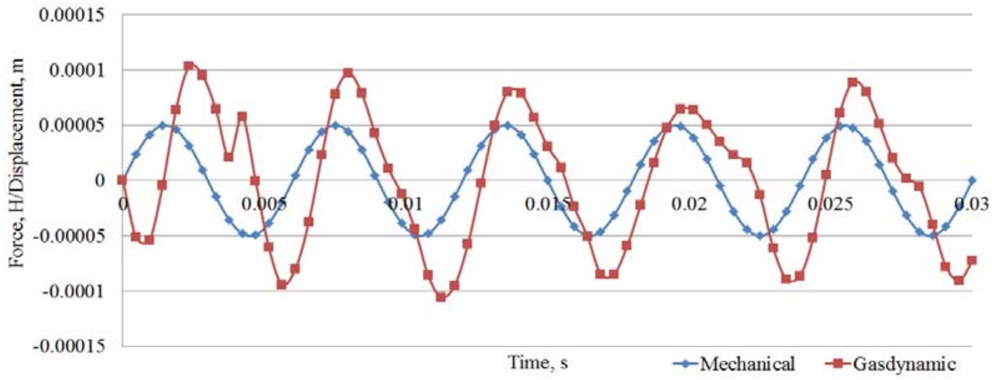
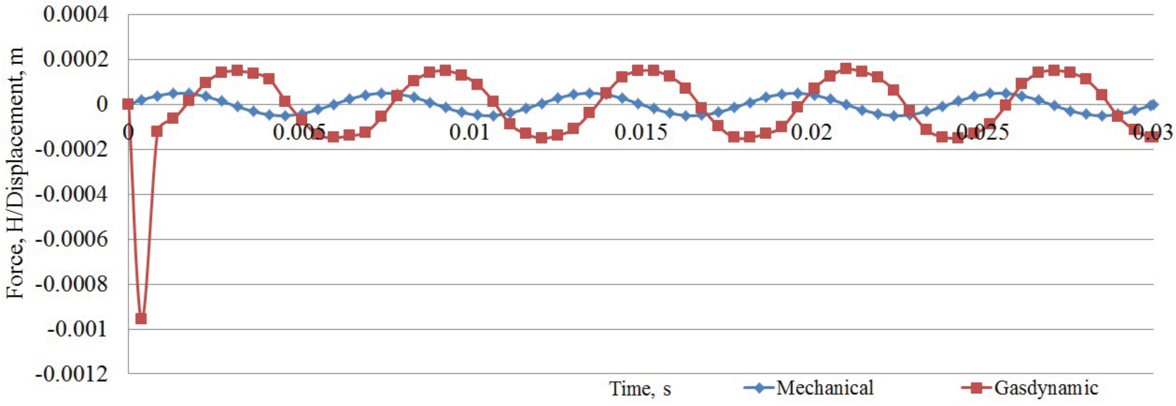


(c)

Fig. 11 Time dependence of gas-dynamic forces and shaft displacement amplitude under P_{nom}=0.1 MPa: (a) 0 m/s; (b) 10 m/s; (c) 20 m/s



(a)



(b)

Fig. 12 Time dependence of gas-dynamic forces and shaft displacement amplitude under P_{nom}=1 MPa: (a) 0 m/s; (b) 20 m/s

Apparently, comparison of cases 2 and 3 shows that the increase of leakage speed from 0 to 20 m/s in LP causes gas-dynamic force oscillating amplitude to decrease by almost 4 orders. Along with that, the phase shift angle increases from π/72 to π/2. At the same time, the oscillations become persistent.

VII. Method Description

To perform LP gas-dynamic calculations, the following method (Fig. 13) was developed:

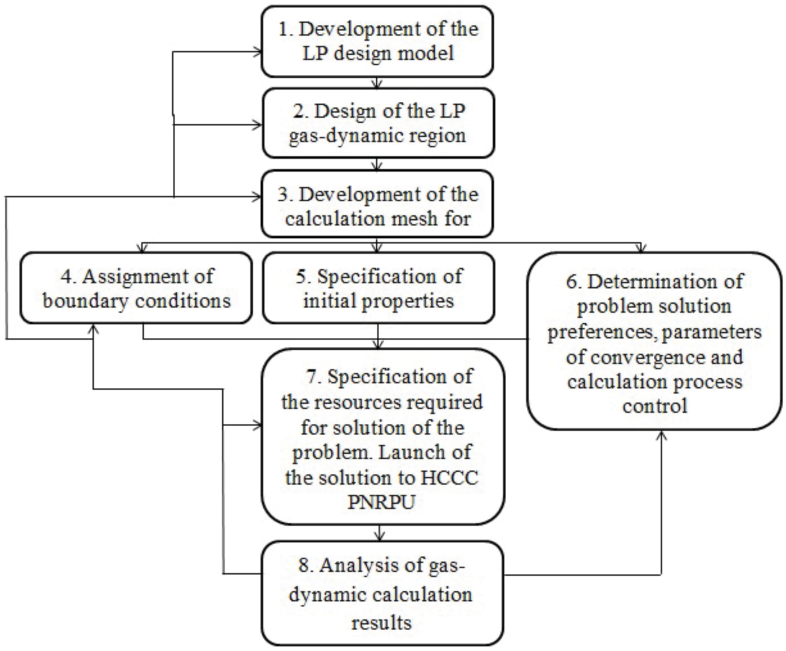


Fig. 13 LP gas-dynamic calculation method (considers shaft vibrations)

1. Development of the LP design model. The shaft is a cylinder with a defined external diameter. The labyrinth ring is a cylindrical surface with the diameter that is equal to the internal diameter of the labyrinth packing.
2. Design of the LP gas-dynamic region. The region is a ring with the internal diameter that is equal to the shaft diameter, the external diameter that is equal to the LP internal diameter, and the width that is equal to the labyrinth packing gap width.
3. Development of the calculation mesh for the LP gas-dynamic region.
4. Assignment of boundary conditions for the computational region. Assign:

- the "Wall" boundary condition to the side surface of the LP;
- the "Symmetry" boundary condition to the ring surface of the gas-dynamic gap in the plane perpendicular to the shaft axis;

- the "Wall" boundary condition to the side shaft surface with the special mesh option Mesh Motion "Specified Displacement".

5. Specify properties of the gas flowing through the LP. Choose working substance features from the material library of the ANSYS CFX software package.
6. Determine problem solution preferences, parameters of convergence and calculation process control in the ANSYS CFX software package assigning the Solver Control and Output Control options.
7. Specify the resources required for solution of the problem. This calls for test calculations performed with the help of the PNRPU high-capacity computer complex. High rates and pressures of the flow increase calculation time.
8. Process gas-dynamic calculation results to present required characteristics in the form of fields, graphs, tables, vectors, flow lines.
9. Analysis of results.

VIII. Conclusion

We discovered the phase shift between shaft oscillations and gas-dynamic force affecting the shaft in vibrations.

It may be expected that the phase shift from 0 to π/2 will cause the growth of shaft vibrations.

Flow rate through LP proved to influence greatly on pressure oscillations amplitude and the phase shift angle between shaft displacement and the gas-dynamic force affecting the shaft in vibrations.

The decrease of leakage speed causes the growth of the gas-dynamic force oscillating amplitude and narrowing of the phase shift angle from π/2 to 0. Consequently, it is expected that vibrations will intensify with the LP wear, which is confirmed by experimental results.

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