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Research Article

Non-stationary Operation Regimes of the Gas Bearings

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Abstract: This review provides of basic information on non-stationary operation regimes of the gas bearings. The causes and mechanisms of maintaining the oscillation of the rotor's gas suspensions are discussed. A brief review of linear, nonlinear and resonant vibrational effect is given. The questions on the oscillations in the layer of gas and liquid lubrication in the bearings are elaborated. A classification of non-stationary processes in gas bearings is given. Brief information on issues such as "frequency capture", "Sommerfeld effect", "a half-speed and fraction-speed vortex", "pneumatic hammer", "consumption oscillations in nozzles". The main tasks for the gas-static bearing's control system are formulated. The results of calculations of the reaction in gas-static rotor bearings on a single external influence. It is shown that when the external load, the impact of external forces and the gas pressure in the lubricating gap rotor motion seeks to limit discrete trajectories. Thus, the radius is changed stepwise precession and not continuously. Increasing supply pressure in the lubricating gap fluctuations can be suppressed by decreasing the diameter of the precession.

Keywords: Gas-dynamic bearing, gas lubrication, gas-static bearing, hybrid gas bearing, oscillations of lubrication, the half-rate vortex

INTRODUCTION

Types of gas-lubricated bearings: The modern tendency is gradual refuse from usage of oil lubrication systems in gas-turbine technology in favor of gas bearings.

There are three types of gas bearings used (Bulat *et al*., 2002; Bulat and Bulat, 2013a):

- Gas-Static (GSB), in which a lifting force, applied to the shaft is created by the supplying of the air in the gap between the stator
- Gas-Dynamic (GBD), in which the lift force arises due to the Bernoulli law
- Hybrid, combine in theirs design both of the effects

Gas-dynamic bearings are self-generating, i.e., require no external control or gas supply to create the lift force. At low speeds this bearing operates under the conditions of dry friction and contact with the shaft. The shaft begins to "float" and continues to operation without any contact with the bearing, when a sufficiently high speed is achieved. When the load changes, the size of the gap and lift force, which acts from the bearing's elements on the shaft is changed as well. To increase the range of supported loads, various elastic supporting structures: ribbons, petals and so on are used in gas-dynamic bearings. As a result, gas-dynamic bearing shows good performance in the conditions, where the machine is running in continuous operation regimes, rarely starts and stops and overloads and impact loads are absent. It is typical for ground power gas turbines.

For aircraft engines and various mechanical drives the tough starting conditions (low temperature), high frequency of stops and subsequent runs, the possibility of significant loads during aircraft maneuvers, impact loads and high vibration during operation of mechanical drives must be taken into account. For such conditions, gas-static bearings are better suited (Bulat and Bulat, 2013b). Operation of GSB is characterized by the presence if non-stationary processes, which can be divided into two large groups: vibrational and transient. Displacement of the shaft relatively to the geometrical axis can be characterized as a plane-parallel displacement, a cylindrical rotation of the rotor's center of mass and as a conic precession. Motions that combine these three types of displacements are called beats.

GSB control system: A system control that regulates the pressure and the consumption of the air, supplied into the gap between the stator and the rotor is required to use the GSB. The tasks that can be set to the control system are the following:

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- Assure the start and braking of the shaft (hanging the shaft during these regimes)
- Suppression of harmful non-stationary regimes
- Managing the passage through the critical frequencies and the parametric resonance areas, preventing the phenomenon of "frequency capture" or Sommerfeld (1902) effect
- Control the shaft during the aircraft maneuvers
- Control the shaft during the impact loads and high low-frequency vibration

It is known (Grassam and Powell, 1964) that the regulation of the air flow, supplied to the gap allows to achieve the maximal stiffness of the lubricating layer for a given consumption rate, load capacity and the supply pressure. Fluid automation (Korotkov, 1972; Dmitriev and Gradetsky, 1973) or high-speed controlled electromagnetic hydraulic resistances can be used as a regulator.

Types of non-stationary motions of the shaft: Study of non-stationary effects that arise due to the rapid rotation of the rotors on elastic supports, is associated with several inherent problems (Swanson *et al*., 2002):

- The shaft that have eccentricity passaging the "critical" rotation frequencies, at which the "capture" of the main frequency, caused by parametric resonance of the rotor occurs
- Stability and non-stability of the oscillatory motion of long rotor on elastic supports (Naraikin and Temis, 2004)
- Occurrence of the rotor's unstable precessing with increasing amplitude, known as "half-speed vortex" (Sheinberg *et al*., 1969)

There is another type of oscillation, called "pneumatic hammer". This regime was first discovered in systems with flat hydrostatic support (axial bearing).

Pneumatic hammer occurs in GSB due to immediate difference in the consumption rates of the gas that flowing into the lubricating gap from the supply holes and the gas, flowing out of a GSB into the environment.

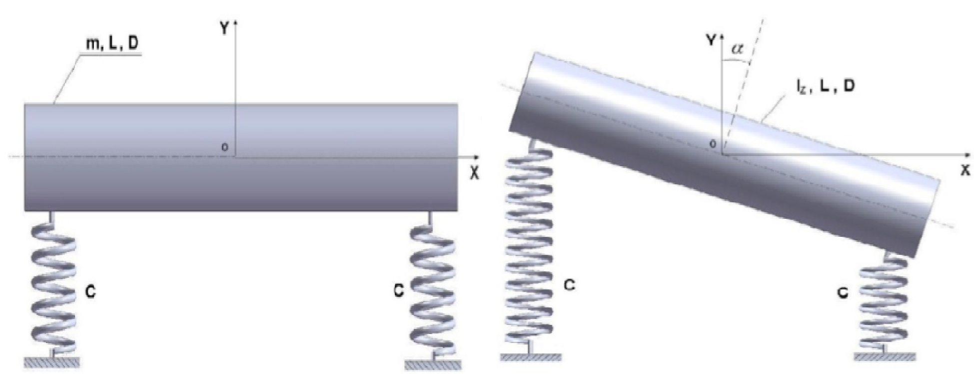
This regime belongs to the consumption auto-oscillations type. It is most typical for gas supply systems with pockets. Consumption oscillations can occur in GSB as well, while operating on supercritical regime, at which the supersonic jets flow from the nozzles into the lubricating layer and interact with the surface of the rotor's cylinder (Bulat and Uskov, 2012a, b). The described mechanism has much in common with the problem of pressure oscillations in the circulation areas, which arise in supersonic separated flows (Bulat *et al*., 2002; Zasukhin *et al*., 2011).

MODEL AND METHODS

Let's consider the problem, listed above, sequentially. Statement of the problem of calculation and experimental study of the gas flow in the lubricating layer thickness is described in Bulat and Bulat (2013c).

Oscillatory modes: Shaft on the elastic supports has several modes of its own oscillations (Fig. 1), i.e., oscillations, occurring under the effect of the shaft's mass inertia force and of the and its elasticity of its supports. The first two modes correspond to oscillations of the shaft as absolutely solid and rigid body (Fig. 1). Subsequent modes occur when the shaft is bent.

Shaft oscillations can occur due to the imbalance of the rotor masses. Rotors typically are unbalanced, i.e., axis of the inertia ellipse do not coincides with the axis of rotation. In such cases it is said that the eccentricity has place. Then the periodic dynamic load will be applied to the shaft. Since the frequency of the external forces, applied on the support is, in this case, equal to the frequency of rotor's rotation, such oscillations are called synchronous.



(a) (b)

Fig. 1: The first (a) and the second (b) oscillation modes of the shaft

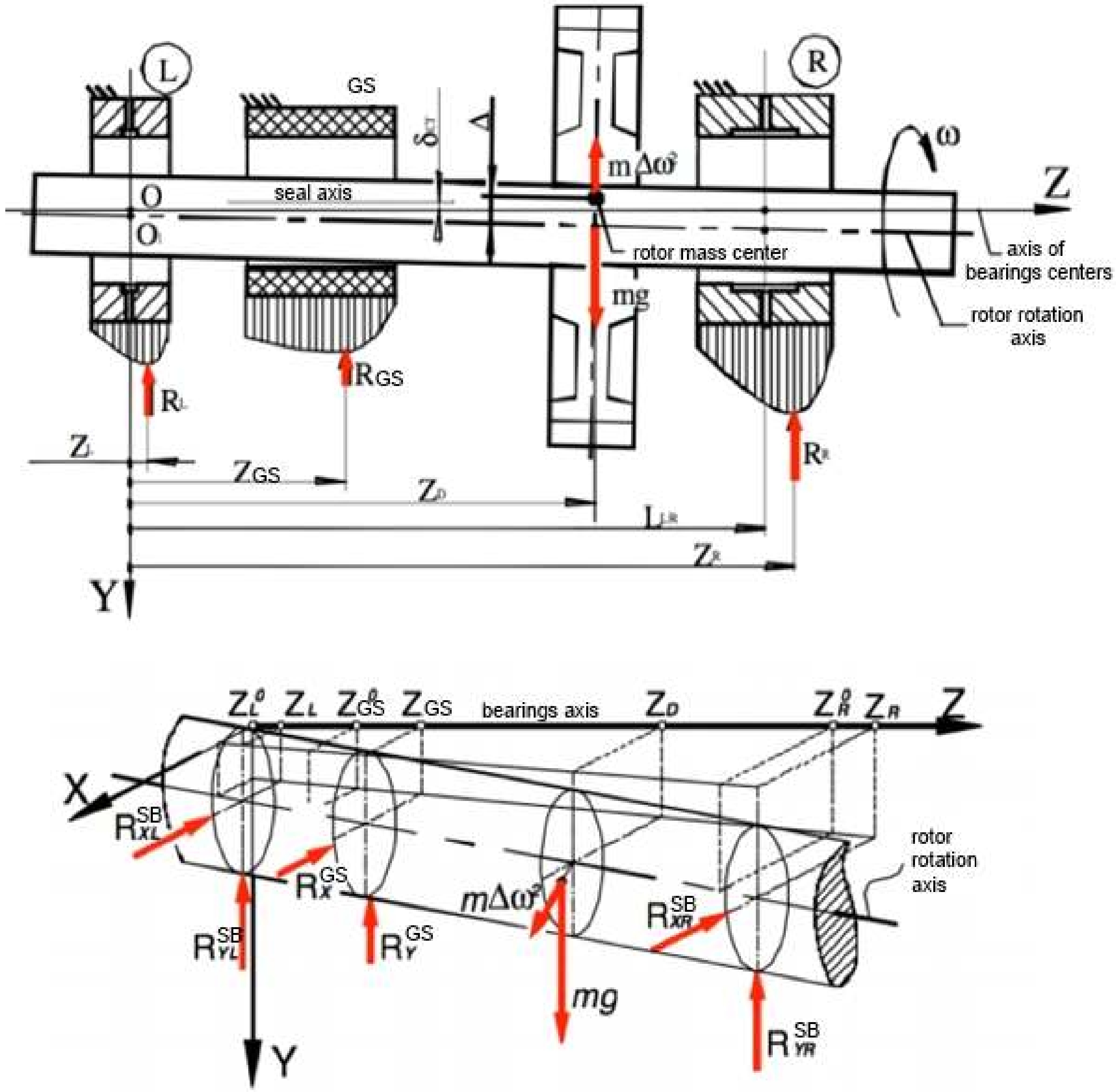


Fig. 2: Calculation scheme and the system of forces acting on the shaft, rotating with angular velocity ω, having eccentricity Δ
R_L: Left bearing; R_R: Right bearing; GS: Gap Seal; O: Coordinate system origin; Z_L: Coordinate of the left sleeve bearing reaction forces resultant; Z_{SB}: Coordinate of the gap seal reaction force resultant; Z_D: Coordinate of the rotor mass center; Z_R: Coordinate of the right sleeve bearing reaction forces resultant; L_{LR}: Distance between the centers of the right and left sleeve bearings; R_{XL}^{SB}, R_{YL}^{SB}: Reaction of the left sleeve bearing in the axial direction x, y; R_X^{GS}, R_Y^{GS}: Reaction of the gap seal in the axial direction x, y; R_{XR}^{SB}, R_{YR}^{SB}: Reaction of the right sleeve bearing in the axial direction x, y

Unsteady motion of the shaft: Unsteady motion of the shaft is determined by internal and external factors. The internal include the weight of the rotor, its axis eccentricity, dynamic and static unbalance. The external are: variable external forces and vibrations and vibrations resulting from the imbalance of the rotor and transmitted through the machine supports. Consider a horizontally disposed rotor having axial symmetry and rotating with constant angular velocity ω in two different bearings (Fig. 2).

Let's call them as "left" and "right", with L and R indexes. Let's as well consider the motion of the rotor with mass m in the fixed coordinate system OXYZ with the origin O in the middle of the left bearing and the OZ axis passing through the center of the right bearing bushing. Mass center C located eccentrically relative to the supports and displaced relative to the axis of rotation by a small amount J and relative to the origin at distance ZD. The rotor has eccentricity e. We assume that the rotor is completely rigid, i.e., unaffected by flexural and torsional deformations.

The equations of motion of the rotor in this case take the form:

$$\begin{cases} m\left[\frac{Z_D}{L_{LR}}\left(\ddot{X}_R-\ddot{X}_L\right)+\ddot{X}_L\right] \\ = R_{XR}^{SB}+R_{XL}^{SB}+R_X^{GS}+m\omega^2\Delta\sin\omega t; \\ m\left[\frac{Z_D}{L_{LR}}\left(\ddot{Y}_R-\ddot{Y}_L\right)+\ddot{Y}_L\right] \\ = R_{YR}^{SB}+R_{YL}^{SB}+R_Y^{GS}+m\omega^2\Delta\cos\omega t+mg; \\ \frac{J_0\omega}{L_{LR}}\left(\dot{X}_R-\dot{X}_L\right)+JT\omega^2\sin[2(\omega t-T)] \\ = R_{XL}^{SB}Z_D-R_{XR}^{SB}(L_{LR}-Z_D)-R_X^{GS}(Z_{GS}-Z_D); \\ \frac{J_0\omega}{L_{LR}}\left(\dot{Y}_R-Y_L\right)+JT\omega^2\sin[2(\omega t-T)] \\ = R_{YL}^{SB}Z_D-R_{YR}^{SB}(L_{LR}-Z_D)-R_Y^{GS}(Z_{GS}-Z_D) \end{cases}$$

where,
J = Center mass offset relative to the axis of rotation
J_0 = Initial displacement of the center of mass relative to the rotational axis
T = Period oscillations

RESULTS AND DISCUSSION

Gas-dynamical causes of the shaft oscillation: There is a known phenomenon called "half-speed vortex", which is caused by a loss of stability by the lubricating layer, confined between two moving cylindrical surfaces as a result of viscous friction forces effect. This phenomenon is typical for gas-dynamic full-scope bearing, but at high velocities occurs in GSB as well. It is accompanied by the rotor's precession at the frequency equal to half of the rotor's rotational frequency about its axis.

The possibility of oscillations' occurrence under the influence of hydrodynamic lubrication forces is the immediate consequence of the Reynolds equations (Ustinov, 2001), which describe the dynamics of the lubricating layer. Such fluctuations were first noticed in the sleeve bearings with oil lubrication, therefore they are traditionally called oil vibrations.

The conclusion about the decisive role of hydrodynamic forces in the initiation of the oil vibration is obvious from Newkirk and Taylor's experiments (Reynolds, 1886): in the presence of separating oil layer between the friction surfaces, the shafts vibrate. Reducing the amount of oil, supplied to the bearing the oscillations decay.

Parametric resonance and sommerfeld effect: As the frequency of rotation approaches one of the natural frequencies (modes) of the oscillation, the phenomenon of parametric resonance occurs. If supports are perfectly rigid then, as the parametric resonance is being passed, the oscillations amplitude increases to infinity, therefore the damping is required. If the rotor is relatively rigid and the supports are compliant, the amplitude of the oscillations and the width of the resonance zone depend on the ratio of the rotor's imbalance degree and the compliance of supports (Newkirk and Taylor, 1925) (Fig. 3).

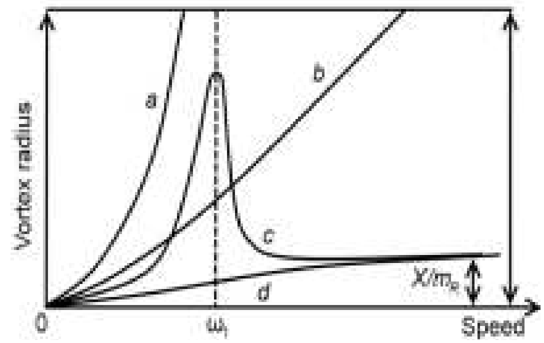


Fig. 3: The influence of the deformation on parametric resonance
a) Great imbalance, small damping, b) great imbalance, big damping, c) small imbalance, small damping, d) small imbalance, big damping, ω-resonance frequency

If the rotor's drive power is low, the Sommerfeld effect, also known as the effect of "frequency capture" can occur. The essence of this effect lies in the "transformation" of the rotor's rotational energy into energy of oscillation, whose amplitude increases. When the engine power is insufficient, the application of extra rotational moment does not increase the angular velocity of rotation, but only leads to an increase in amplitude of the oscillations. The influence of this effect is particularly noticeable for poorly-damped objects and obstructs the rotor from the passing of the resonance zone during acceleration and deceleration.

Reaction rotor gas-static bearings to external influence: Load on the shaft can be changed by vibration of the support of the aggregate, which uses a gas lubricated rotor, maneuver of the aircraft or single impact. Single impact force causes a displacement of the shaft.

Let us consider the reaction of the rotor supplied by the gas-static bearings on a single external influence which was set by the rotor axis displacement (red dots in Fig. 4). Figure 4 is a phase portrait of the motion of the rotor supplied by the gas-static bearings for different values of the initial disturbance. The ordinate is the acceleration of the rotor's center of mass. It is seen that depending on the magnitude of the initial disturbance further movement tends to one of two stable limit cycles, i.e., stable precession amplitude of the shaft changes stepwise. It is clear that a further increase in starting offset will form new limit cycles. The higher pressure of the blowing is, the lower the average amplitude of the oscillations will be. Thus, increasing of blowing pressure can "suppress" oscillations.

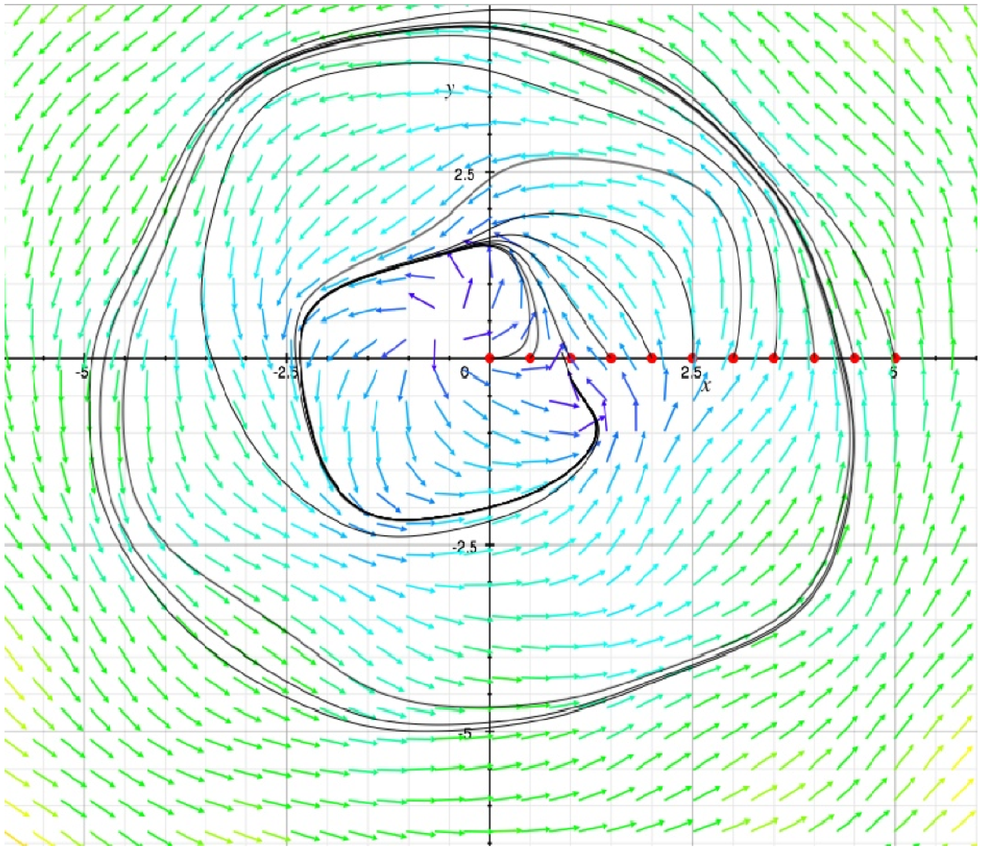
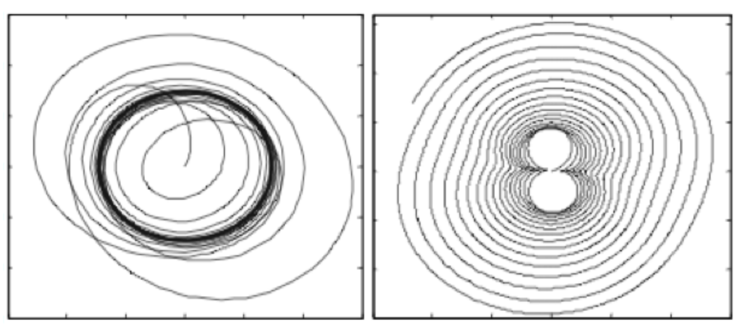
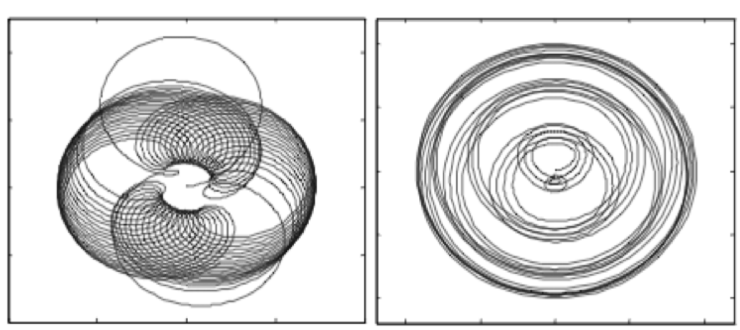


Fig. 4: Phase portrait of quasi-periodic oscillations cylindrical GSB depending on ham initial perturbation



(a) Stable synchronous precession (b) Unstable synchronous precession



(c) Bi-harmonic precession (d) Beating

Fig. 5: Types of the rotor's oscillatory motion in the compliant support

Superposition of different types of oscillations: The described types of oscillations may overlap each other, forming asynchronous fractional-synchronous oscillations. All of them can be summarized to four types of the rotor's oscillatory motions (Fig. 5).

CONCLUSION

Thus, all kinds of non-stationary processes in GSB can be reduced to transients (hanging the rotor in the air suspension, the acceleration and deceleration of the rotor when starting and stopping the engine) and oscillatory modes. The latter are divided into:

- **Forced:** Caused by external force (overload during the aircraft maneuvering, external low-frequency vibrations)
- **Natural:** Arises due to the imbalance of the rotor
- Hydrodynamic (oil vibration)
- Consumption (pneumatic hammer, oscillations during supercritical regimes of gas flowing from the nozzles of GSB)

The resulting motion of the shaft is determined by the superposition of the transient and oscillation processes listed above.

To achieve the desired mode of the plant, it must be possible to control the speed of the rotors in a wide range, including the resonant and above-resonant zones.

Air supply control system in the GSB must counter the basic types of oscillation motions; provide the control of consumption through the nozzles in order to obtain the maximal stiffness of the lubricating layer away from parametric resonance areas, as well as the necessary degree of damping when passing the critical frequencies.

The most important conclusion from the above studies is that the average amplitude of the oscillations of the shaft changes stepwise depending on the initial disturbance and the pressure of blowing. The higher pressure of the blowing is, the lower the average amplitude of the oscillations will be. Thus, increasing of blowing pressure can "suppress" oscillations.

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