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Elastic Suspension of Rotor with Quasi Zero Stiffness for Oil Pumping Units

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Abstract: Oil pumping units are very important for oil industry. Elastic suspensions are very promising for vibration isolation of rotors. Low natural frequency allows reducing vibration almost up to zero. Metamaterials for elastic suspensions are offered. A scheme of elastic suspension with metametarial with quasi-zero stiffness is presented. Modeling has shown high efficiency of this way of vibration reducing.

Key words: Elastic suspension, oil pumping unit, quasi-zero stiffness, vibration, metametarial, efficiency

INTRODUCTION

In industrial enterprises of oil and gas industry the majority of equipment failures are represented by refusals of oil pumping units. Consequently, the level of reliability and high level of safety of production processes are characterized by its technical state. Failures of pumping equipment can lead to accidents and hence, to significant economic and environmental damage.

In an oil pump the following groups of elements are distinguished: casing, foundation, rotating elements, impeller and bearings. Experience of the operation of machines shows that sources of increased vibration may be different:

- Increased imbalance of the rotating parts of the rotor
- Non-conservative forces of the oil layer in sliding bearings
- Defects in bearings
- Vibration of hydraulic origin
- Easing of interference on bearing shells
- Gripping of rotor blades, etc.

The most common defects of oil pumping units are connected with bearings:

- Vibration in bearings occurs due to
- Violation of geometry
- Gaps
- Variable compliance of the bearing elements
- Ovality with the frequency of the second rotary harmonic, etc.

However, even an ideally manufactured rolling bearing is a source of vibration. Elastic deformation of parts, slipping of rolling elements in places of contact with the rings, swirl of air cause vibration of even perfectly manufactured bearing. In addition, a qualitatively manufactured bearing can become a source of intense vibration and noise if it is set incorrectly.

Many causes of vibration and failure of the pump components are due to the rigid attachment of the rotor to the body of the machine by means of a bearing. In this case, the dynamic load is fully transmitted both to the machine itself and to other elements and surrounding equipment.

Vibration level and forces transmitted through bearing can be greatly decreased if an elastic suspension of a rotor is applied.

ELASTIC SUSPENSION OF A ROTOR

Rotating machines with imbalance transmit periodic force to their foundations which can cause unwanted oscillations of foundations and noise. To reduce these harmful effects elastic suspension are sometimes used.

If the machine is rigidly attached to a rigid foundation, then the body will remain stationary and the foundation will be transmitted full centrifugal force. In this case the force acting on the foundation equals:

$$F_{rigid} = me\omega^2 \quad (1)$$

Where:
m = Mass of a rotor
e = Eccentricity
ω = Cyclic speed (frequency of rotation)

To reduce the force acting on the foundation an elastic suspension of a rotor can be applied. In this case, the amplitude of the force transmitted to the foundation is:

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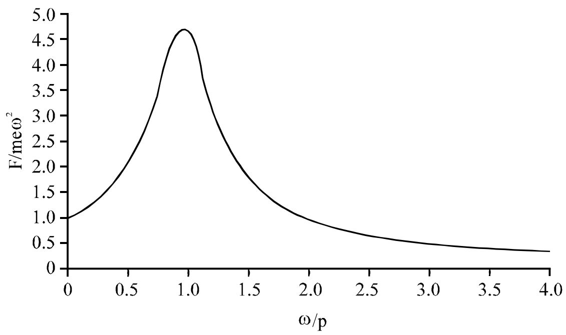

Fig. 1: Force acting on the foundation relative to cyclic speed ω and low natural frequency p

$$F_{elastic} = me\omega^2\sqrt{\frac{1+\frac{4n^2\omega^2}{p^4}}{\left(1-\frac{\omega^2}{p^2}\right)+\frac{4n^2\omega^2}{p^4}}} \quad (2)$$

Where:
p = Natural frequency of elastic suspension
n = Coefficient characterizing damping (Stephen and Young, 1955)

Figure 1 illustrates Eq. 2. As it follows from Eq. 2 low value of stiffness (i.e., low natural frequency p, i.e., $\omega/p<<1$) leads to small force transmitted to the foundation.

It is known that elastic suspension for some rotary machines is used. In case of large machines the elastic suspension is usually made with a help of steel springs. In small motors used in household appliances, the necessary elasticity of the supports is achieved by installing rubber rings between rigid supports and rotor bearings. The last ones are rigidly connected to the stator. An example of the elastic suspension is suspension of car engines.

Elastic suspension is studied by different scientists like Yang and Chieng (1997). Many scientists (Muminovic *et al*., 2013) study elastic suspensions controlled by magnetic forces (Six *et al*., 2005).

As it follows from Eq. 2 elastic suspension is very effective if the suspension has low stiffness and low damping. If n<<1, then force acting on the foundation equals:

$$F = \frac{me\omega^2}{\left|1-\frac{\omega^2}{p^2}\right|} \quad (3)$$

and if n<<1 and p<<ω then, force acting on the foundation equals:

$$F = mep^2 << F_{rigid} \quad (4)$$

So, the less natural frequency of elastic suspension the less force transmitted to the foundation. But in case of suspension with springs or rubber it is very difficult to achieve very low values of stiffness. Small stiffness leads to big deformations (sags) of suspension it is unacceptable from a practical point of view. So, the suspension has to have simultaneously high static stiffness in order to support high weigh of a rotor and low dynamic stiffness to have low natural frequency.

To solve this problems systems with quasi-zero stiffness (systems with high-static-low-dynamic stiffness (Alabuzhev *et al*., 1989) can be used.

SYSTEMS WITH QUASI-ZERO STIFFNESS

Systems with quasi-zero stiffness has flat area on its force characteristic (Alabuzhev *et al*., 1989). These systems provide a great advantage compared with usial elastic elements such as rubber or spring. They have much higher degree of reduction of dynamic forces transmitted due to extra low stiffness at a certain compression (Valeev and Kharisov, 2016). Low stiffness under a certain static load reduces allows to have very low natural frequency (<1 Hz) (Valeev *et al*., 2015).

It is already known that quasi-zero stiffness effect can be used for quality vibration isolations. Systems with quasi-zero stiffness are studied by Alabuzhev *et al*. (1989) who analyzed different types of passive systems with quasi-zero stiffness. Carrella studies systems with inclined springs and compressed beams (Carrella and Friswell, 2008; Carrella *et al*., 2007a, b). Quasi-zero stiffness may be also obtained by structures of dome type (Valeev and Kharisov, 2016; Valeev *et al*., 2015). The systems can be also achieved by pneumatic active elements as reported bt Sun *et al*. (2014) and Le and Ahn (2012). "Scissor-like" system with spring for obtaining quasi-zero stiffness is observed by Sun *et al*. (2014). Also, systems with quasi-zero stiffness of a passive type are proposed by Maciejewski *et al*. (2009) and Le and Ahn (2012).

DESIGN OF ELASTIC SUSPENSION WITH QUASI-ZERO STIFFNESS

Designing of elastic suspension with quasi-zero stiffness has a problem how to create such a effect

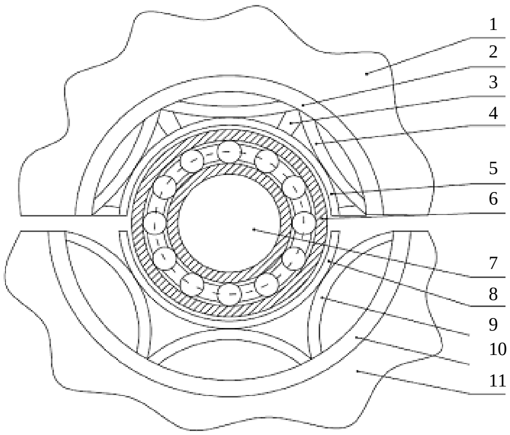

Fig. 2: Vibration insulating suspension with quasi-zero stiffness; 1: upper part of machine case; 2: exterior top semiring; 3: support for fastening the plates with negative stiffness; 4: plate with negative stiffness; 5: inner top semiring; 6: bearing; 7: shaft; 8: inner bottom semiring; 9: supporting plate; 10: exterior bottom semiring and 11: the bottom part of machine case

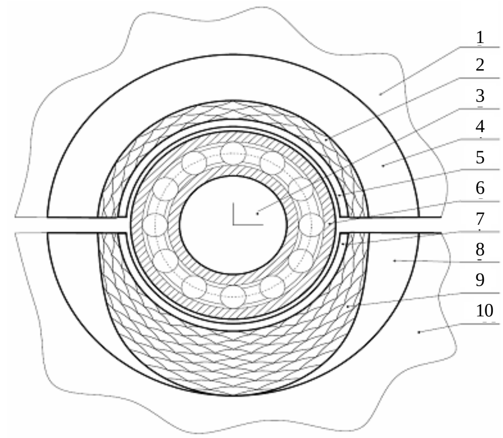

Fig. 3: Elastic suspension with quasi-zero stiffness; 1: Upper part of machine case; 2: upper insett of metamaterial with quasi-zero stiffness; 3: shaft; 4: top liner; 5: inner top semiring; 6: bearing; 7: inner bottom semiring; 8: bottom liner; 9: bottom insert of metamaterial with quasi-zero stiffness and 10: the bottom part of machine case

in very small volume around the bearing. Systems with quasi-zero stiffness of many researchers requires big dimensions.

It is known that quasi-zero stiffness can be used for elastic suspension of rotor. An example of such an application is shown in Fig. 2 (Valeev *et al.*, 2010; Le and Ahn, 2011).

But this scheme has several disadvantages because it requires elastic thin steel plates with very high precision. Also, installation of this type of suspension is very difficult. Elastic suspension with quasi-zero stiffness can be achieved with a help of metamaterial with quasi-zero stiffness.

A metamaterial is a composite material whose features are not provided due to properties of constituent material. The features of it are provided by artificial periodic structure. Modify of geometric shapes of internal structure allows to get special properties impossible to be in nature. At this time it is known that with a help of metamaterials it is possible to get negative or magnetic permeability. Such materials are also offered for obtaining special properties connected with acoustics, electrics, optics, electromagnetics, etc.

Modern 3D-additive technologies allow creating materials with complex fine internal structure. So, it is possible to manufacture materials with special vibration isolating properties. Providing special form of internal structure of material allows getting nonlinear force characteristics.

Due to 3D-additive technologies and idea of metamaterial this mean of vibration isolation can be very thin. One layer of material can be less than several millimeters. Moreover, creating metamaterial with different layers allows getting metamaterial with a set of properties.

On Fig. 3 scheme of proposed elastic suspension with quasi-zero stiffness is shown. Computer modeling a cell of the metamaterial with a help of ANSYS have been made.

Thickness equals $h = 0.3$ mm. Material-elastic plastic of type Flex with Youn's Modulus $E = 74$ MPa. Width $b = 10$ mm; length-$L = 5$ mm; thickness $h = 0.42$ mm. For these parameters optimum load equals 1.61 N. Stress distribution at optimum load is presented on Fig. 4. Maximum stress equals 11.9 MPa, so, relative deformation is 16%. It is very appropriate because such a material can have deformation up to 100%. So, margin of safety is quite big (more than 6) that is good for vibration isolating materials. It is achieved that optimum load of the whole metamaterial is 0.028 N/mm^2 or 2.8 ton/m^2. This value is enough for non-heavy industrial equipment. Natural frequency equals 0.3 Hz. These results allow assessing efficiency of the proposed metamaterial. Manufacturing of the metamaterial with a help of spring steels allow to get high loads and hence, to support heavy rotors (Fig. 4).

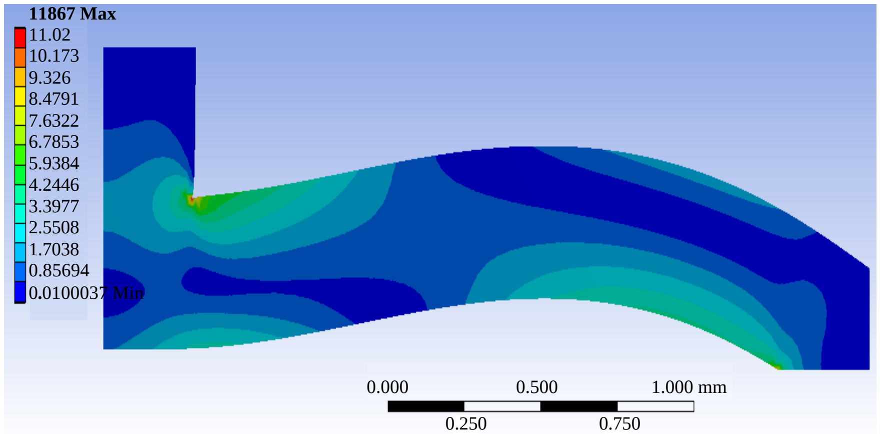

Fig. 4: Computer model of the cell of metamaterial

CONCLUSION

Application of elastic suspension is a very effective but complex way of reducing vibration level. There are active suspensions with magnetic forces are known but schemes of passive are not enough studied, especially with quasi-zero stiffness. In the study a scheme of elastic suspension with metametarial with quasi-zero stiffness is presented. Modeling has shown high efficiency of the conctruction. Such a suspensions allows to improve vibration isolation system of a oil pumping unit. It leads to decrease of vibration level and increase of reliability of durability of equipment.

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