A STUDY ABOUT ROTOR-STRUCTURE-SOIL SYSTEMS INTERACTION

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Abstract. *Rotating machinery are extensively used to very diferent purposes. One of the most important uses of these machines is in the energy generation, something critical at present, that is why there is a great interest in the development of these machines. There are a large number of studies about rotating machinery components, supporting structure and bearings, but the soil influence has not deserved the correspondent attention. The soil either is not considered in the model or the soil models are very simple and the results are not precise. In large rotating machines, the soil can have a great influence on its operation modes. Different soil profiles can cause significant changes in the dynamic behavior of the same machine. This work presents a study about the soil influence on the rotating machinery response as well as the interaction amongst rotor, flexible bearings and soil-foundation. The purpose of this work is to improve the dynamic analysis of soil profiles and verify how far the soil must be considered for a rotating machinery dynamic analysis. A computational simulation of the dynamic response of a Laval (Jeffcott) rotor with flexible bearings supported by a foundation placed on a soil is done. The rigid bidimentional foundation is rested on the soil. The soil models are the classical half-space and the stratified soil. The half-space model is a viscoelastic soil appropriated to the study of machines fixed on a homogeneous half space with a great depth. The stratified soil represents a viscoelastic soil where the lower part of the layer is supported by a bedrock. This model represents a soil where there is an abrupt increase in the stiffness in a specific depth. The damping effect of the system comes from the radiation, and it is associated to the energy dissipation of the system as waves emitted and non reflected.*

Keywords: *rotor dynamics, half-space soil, stratified soil, flexible bearings*

1. INTRODUCTION

There is a great interest in developing rotating machines for many purposes. Many components of these machines have been studied, and some improvement has been achieved, especially that concerning the interaction between machine and support structure. The dynamic behavior model for rotating machines does not usually consider the soil influence. Whenever the soil model is used, the results obtained do not represent the real characteristics of the soil.

Wu e Smith (1995) reported the existence of extensive studies in the past three decades. The studies showed that, in general, the soil structure interaction has the following effects: (1) reduction of the resonant frequencies of systems in comparison to those of the fixed-base structure; (2) partial dissipation of the vibrational energy of the structure in the soil through wave radiation; and (3) modification of the actual foundation motion when compared with the model that does not include the soil.

To describe realistic dinamic models of the soil and soil-foundation systems, it is necessary to develop numerical tools which should consider the Sommerfeld radiation conditions (Mesquita et al, 2006). It is dificult to do this using numerical methods in the time domain. So, the soil models in this work were done using the boundary element method (BEM), which is the most adequate numerical method to solve problems that involve non-limited dynamic sistems. (Dominguez, 1992).

This work is a preliminary invetigation of the soil influence on the operation of rotating machines, enhancing the effect of some basic caracteristics of a continuum element: the viscoelastic damping and the layer depth over a rigid bedrock. Thus, a simplified model of a Jeffcott rotor with flexible bearings was elaborated, enhancing the effects of the soil caracteristics on the dynamic behaviour of the foundation and of the rotor, even though this model does not represent real machine systems.

Two soil models are presented, the classic half-space model, presented by Gasch (2002), and the layer over a rigid bedrock (Mesquita et al, 2006), whose numerical model represents a soil that, at certain depth, has an abrupt increase in the stiffness.

2. MECHANICAL MODEL

The complete mechanical system (fig. 1) consistis of a Jeffcott rotor, a rigid foundation, flexible bearings and the soil. The Jeffcott rotor consistis of a rigid disc assembled on a cylindrical shaft whose stiffness is k_e. The geometric center of the disc does not coincide with the center of mass, and the eccentricity is *e*. Thus, the system is self-excited by the unbalancing force of the disc. The disc is located in the middle of the shaft, so it moves on its own plane, not considering the gyroscopic effect.

The rotor is supported by flexible bearings. The foundation consists of a rigid block, whose moment of inertia is $I_f = \rho_f abh_f\left(4a^2 + h_f^2\right)/12$ in relation to the center of gravity, where ρ_f is the density of the foundation, *a* is the half-width, *b* is the half-length, and h_b is the foundation height. The height of the bearings from the center of gravity of the foundation is h_b, the height of the center of gravity of the foundation from the soil surface is h_g. The degrees of freedom of the foundation are the rotating angle ϕ_y^f and the horizontal and vertical displacement, u_x^F and u_z^F, respectively. The degrees of freedom of the bearings are u_x^M and u_z^M. The rotor is described in the plane X-Z by the degrees of freedom u_x^R and u_z^R. The soil models considered are the homogeneous half-space and the layer over a rigid bedrock.

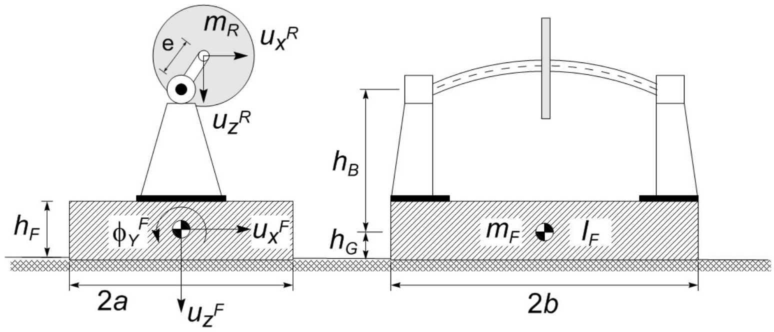


Figure 1. Mechanical model.

2.1. Half-space

The classic half-space model (fig. 2a) is used for analizing the behaviour of rotating machines on a homogeneous soil of great depth. This model takes into account a rigid massless bidimentional foundation, fixed to viscoelastic half-space. The soil is caracterized by the shear modulus *G*, the mass density ρ_S, and the Poisson's coeficient ν_S. In this work, the soil is considered viscoelastic and it is represented by a constant hysteretic model witch has a constant internal damping coefficient η_S (Barros & Mesquita, 1999). It is assumed that the foundation is attached to the soil. A vector with external forces acts on the foundation and it is caracterized by $\{F_e\} = \{F_Z^S, F_X^S, M_Y^S\}^T$. The displacement vector of the rigid massless foundation is $\{u_S\} = \{u_Z^S, u_X^S, \phi_Y^S\}^T$.

2.2. The layer over a rigid base model

This model of the soil (fig. 2b) is adequate to represent the soil, which has an abrupt increase in the stiffness at a depth *d*. This model consists of a viscoelastic layer with a depth *d*, where the lowest part of the layer rests on a rigid base. The properties of the layer of the soil are the same as those of the half-space.

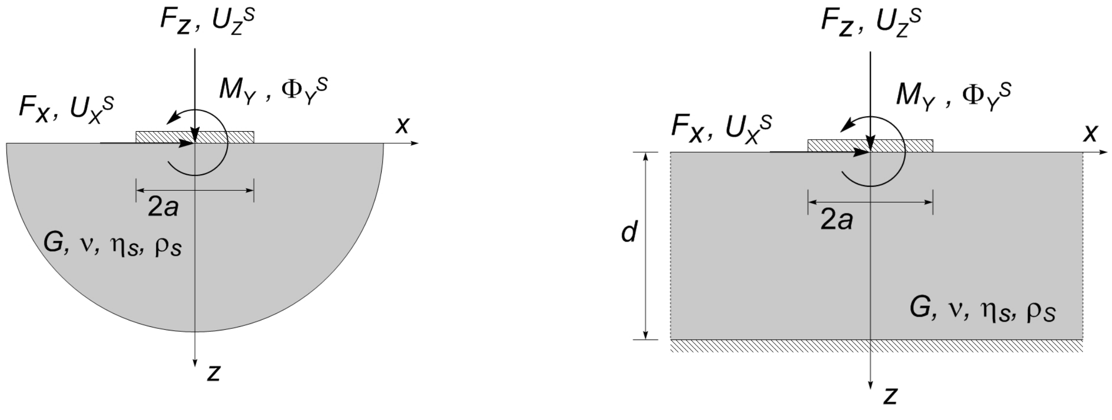
2.3. Soil compliance functions

For stationary problems, in the frequency domain ω, the dynamic interaction between a rigid foundation and the soil is usualy described by the flexibility matrix $[N_S(\omega)]$, or by the compliance matrix $[K_S(\omega)]$ that relates the external forces vector to the vector which contains the degrees of freedom of the rigid massless foundation, measured from the center of the soil-foundation interface, $[K_S(\omega)]\{u_S\} = \{F_e\}$. The compliance matrix of the rigid foundation interacting with the soil, in the frequency domain, is synthesized using the boundary element method (BEM), (Barros and Mesquita, 1999). In soil dynamics, the circular frequency parameter ω is replaced with the adimentional frequency parameter A_0, defined as:

$$A_0 = \frac{\omega a}{c_S} \quad \mathbf{(1)}$$

In this equation, c_S is the shear wave velocity of the soil, expressed as a function of the shear modulus G and the soil density ρ_S:

$$c_S = \sqrt{\frac{G}{\rho_S}} \tag{2}$$



(a) (b)

Figure 2. Soil profiles: (a) half-space; (b) Layer over a rigid base model

The parameters A_0 and c_S, in the Gasch et al (2002) half-space model, are used for calculating the soil stiffness and the damping concentrated parameters. The parameters used in the model that uses the boundary element method are considered when determining the impedance matrix of equation (3) below. The compliance matrix of the rigid fundations can be calculated for distinct soil profiles. These soil profiles can include the homogeneous half-space, multiple horizontal layers, and isotropic or anisotropic soils. So, the soil reaction forces acting on the plane X-Z and the moment in Y coupled to the displacement in the X direction, are incorporated to the movement equations as external forces acting on the system. The resultant compliance matrix presents the following structure:

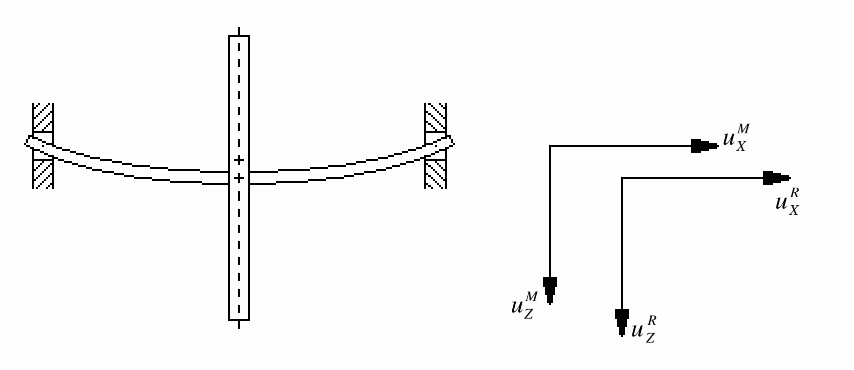
$$\begin{bmatrix} K_{wz} & K_{wx} & K_{wy} \\ K_{uz} & K_{ux} & K_{uy} \\ K_{\varphi z} & K_{\varphi x} & K_{\varphi y} \end{bmatrix} \begin{Bmatrix} u_z^S \\ u_x^S \\ \varphi_y^S a \end{Bmatrix} = \begin{Bmatrix} F_z^{\ S} \\ F_x^{\ S} \\ M_y^{\ S} / a \end{Bmatrix} \tag{3}$$

It is usual to present the compliance matrix of the rigid massless foundations in the normalized form:

$$Ga\left[K_S(A_0)\right]\left\{u_S\right\} = \left\{F_e\right\} \tag{4}$$

3. MOTION EQUATIONS OF THE COMPLETE SYSTEM

3.1 Rotor-bearings



Four degrees of freedom are used to describe this system. u_Z^R and u_X^R are the movement of the geometric center of the rotor in vertical and horizontal directions respectively, and u_Z^M and u_X^M are the movement of the bearing housing in vertical and horizontal directions respectively. The motion equations of the system are:

$$\left(-\Omega^2 \begin{bmatrix} m_R & 0 & 0 & 0 \\ 0 & m_R & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} + i\Omega \begin{bmatrix} (d_I+d_A) & 0 & -(d_I+d_A) & 0 \\ 0 & (d_I+d_A) & 0 & -(d_I+d_A) \\ (d_I+d_A) & 0 & -(d_I+d_A-2d_{MZZ}) & 2d_{MZX} \\ 0 & (d_I+d_A) & -2d_{MXZ} & -(d_I+d_A-2d_{MXX}) \end{bmatrix} + \begin{bmatrix} k_E & -\Omega d_i & -k_E & \Omega d_i \\ \Omega d_i & k_E & -\Omega d_i & -k_E \\ k_E & -\Omega d_i & -k_E & \Omega d_i \\ \Omega d_i & k_E & -\Omega d_i & -k_E \end{bmatrix} \right) \begin{Bmatrix} u_Z^R \\ u_X^R \\ u_Z^M \\ u_X^M \end{Bmatrix} = \begin{Bmatrix} m_R e\Omega^2 \\ -i\, m_R e\Omega^2 \\ 0 \\ 0 \end{Bmatrix}$$

3.2 Rotor bearings foundation system

Seven degrees of freedom are used to describe the system. Creating a vector for the degrees of freedom of the rotor-bearings-foundation system, $\{u_{RF}\}\{u_Z^R \quad u_X^R \quad u_Z^M \quad u_X^M \quad u_Z^F \quad u_X^F \quad \phi_Y^F\}^T$ For the time domain, the movement equations of the system, can be written as:

$$[M_{RF}]\frac{d^2\{u_{RF}\}}{dt^2} + [D_{RF}]\frac{d\{u_{RF}\}}{dt} + [K_{RF}]\{u_{RF}\} = \{F_0(t)\} \qquad \textbf{(5)}$$

In equation (5), the vector of forces $\{F_0\}$ consists of external forces acting on the rotor and the soil reactions. The explicit form of these equations, in the frequency domain is:

$$\left(-\Omega^2 \begin{bmatrix} m_R & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_R & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_F & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_F & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_F \end{bmatrix} + i\Omega \begin{bmatrix} (d_I+d_A) & 0 & -(d_I+d_A) & 0 & -(d_I+d_A) & 0 & 0 \\ 0 & (d_I+d_A) & 0 & -(d_I+d_A) & 0 & -(d_I+d_A) & 0 \\ (d_I+d_A) & 0 & -(d_I+d_A-2d_{MZZ}) & 2d_{MZX} & -(d_I+d_A) & 0 & 0 \\ 0 & (d_I+d_A) & 2d_{MXZ} & -(d_I+d_A-2d_{MXX}) & 0 & -(d_I+d_A) & 0 \\ 0 & 0 & 2d_{MZZ} & 2d_{MZX} & 0 & 0 & 0 \\ 0 & 0 & 2d_{MXZ} & 2d_{MXX} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(d_{MZX}+d_{MXX})u_0^M & 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} k_E & -\Omega d_i & -k_E & \Omega d_i & -k_E & \Omega d_i & 0 \\ \Omega d_i & k_E & -\Omega d_i & -k_E & -\Omega d_i & -k_E & 0 \\ k_E & -\Omega d_i & (2k_{MZZ}-k_E) & \Omega d_i + 2k_{MZX} & -k_E & \Omega d_i & 0 \\ \Omega d_i & k_E & -\Omega d_i + 2k_{MXZ} & (2k_{MXX}-k_E) & -\Omega d_i & -k_E & 0 \\ 0 & 0 & 2k_{MZZ} & 2k_{MZX} & 0 & 0 & 0 \\ 0 & 0 & 2k_{MXZ} & 2k_{MXX} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(k_{MZX}+k_{MXX})u_0^m & 0 & 0 & 0 \end{bmatrix} \right) \begin{Bmatrix} u_Z^R \\ u_X^R \\ u_Z^M \\ u_X^M \\ u_Z^F \\ u_X^F \\ \phi_Y^F \end{Bmatrix} = \begin{Bmatrix} m_R e\Omega^2 \\ -i m_R e\Omega^2 \\ 0 \\ 0 \\ -f_S^Z \\ -f_S^X \\ -M_S^Y \end{Bmatrix} \qquad \textbf{(6)}$$

In equations (6), d_I and d_A are the respective internal and external dampings of the rotor. In this work, the external damping of the rotor is considered null and the height of the center of gravity of foundation is also null, $h_g=0$. Under these conditions, the degrees of freedom of the rigid foundation, obtained from the center of the soil-foundation interface, coincide with the vector of the foundation displacements, obtained from its geometrical center, $\{u_S\} = \{u_Z^S, u_X^S, \phi_Y^S\}^T = \{u_F\} = \{u_Z^F, u_X^F, \phi_Y^F\}^T$.

After transforming the equation (6) for the frequency domain, and after replacing the soil reaction forces with the equations defined in (3) and (4), the following complete system equation was obtained:

$$\left(-\Omega^2 \begin{bmatrix} m_R & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_R & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_F & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_F & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_F \end{bmatrix} + i\Omega \begin{bmatrix} (d_I + d_A) & 0 & -(d_I + d_A) & 0 & -(d_I + d_A) & 0 & 0 \\ 0 & (d_I + d_A) & 0 & -(d_I + d_A) & 0 & -(d_I + d_A) & 0 \\ (d_I + d_A) & 0 & -(d_I + d_A - 2d_{MZZ}) & 2d_{MZX} & -(d_I + d_A) & 0 & 0 \\ 0 & (d_I + d_A) & 2d_{MXZ} & -(d_I + d_A - 2d_{MXX}) & 0 & -(d_I + d_A) & 0 \\ 0 & 0 & 2d_{MZZ} & 2d_{MZX} & 0 & 0 & 0 \\ 0 & 0 & 2d_{MXZ} & 2d_{MXX} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(d_{MZX} + d_{MXX})u_0^M & 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} k_E & -\Omega d_i & -k_E & \Omega d_i & -k_E & \Omega d_i & 0 \\ \Omega d_i & k_E & -\Omega d_i & -k_E & -\Omega d_i & -k_E & 0 \\ k_E & -\Omega d_i & (2k_{MZZ} - k_E) & \Omega d_i + 2k_{MZX} & -k_E & \Omega d_i & 0 \\ \Omega d_i & k_E & -\Omega d_i + 2k_{MXZ} & (2k_{MXX} - k_E) & -\Omega d_i & -k_E & 0 \\ 0 & 0 & 2k_{MZZ} & 2k_{MZX} & K_{WZ} & 0 & 0 \\ 0 & 0 & 2k_{MXZ} & 2k_{MXX} & 0 & K_{UX} & K_{UY} \\ 0 & 0 & 0 & 2(k_{MZX} + k_{MXX})u_0^m & 0 & K_{\phi X} & K_{\phi Y} \end{bmatrix} \right) \begin{Bmatrix} u_Z^R \\ u_X^R \\ u_Z^M \\ u_X^M \\ u_Z^F \\ u_X^F \\ \phi_Y^F \end{Bmatrix} = \begin{Bmatrix} m_R e\Omega^2 \\ -i m_R e\Omega^2 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \quad \mathbf{(7)}$$

The computer programs used for modeling the soil had been developed by Mesquita et al (2002) in Fortran language. The solution of the complete system linear equation was obtained in the frequency domain by the Gauss method.

4. RESULTS

The study of the soil damping coefficient influence is showed below. The parameters listed in table 1 were considered, where h_B is the bearing height, a is the foundation half-width, m_R is the rotor mass, m_F is the foundation mass, ρ_s is the soil density; d is the layer stratified soil depth.

The parameters considered are similar to those found in the literature (Gasch, 1984; Gasch et al, 2002).

Table 1. Parameters used in the simulations.

PARAMETERS	VALUES
h_B/a – distance from bearing center to foundation mass center	0,0
$M_{RF} = m_R/m_F$ - relation between rotor and foundation masses	0,5
$B_f = m_F/\rho_s a^2$ - relation between foundation and soil masses	1
d/a - layer stratified soil depth	2,0; 4,0; 6,0; 10,0

The rigid massless rotor, disregarding other components, presents a amplitude displacement peak when its rotation frequency coincides with the natural frequency of rotor (fig 3).

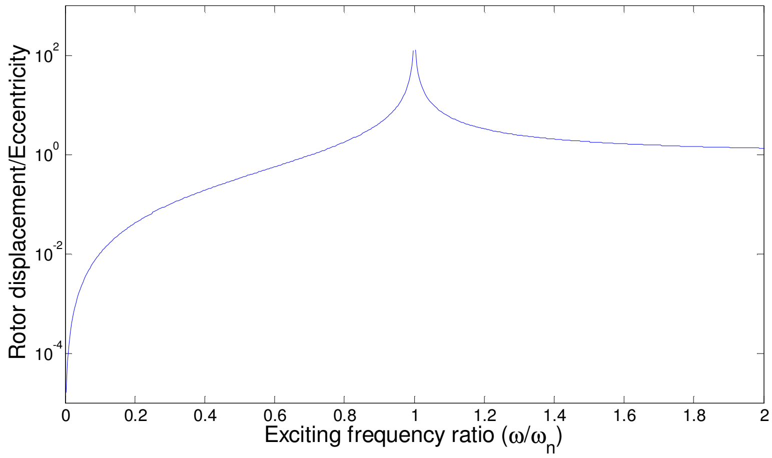
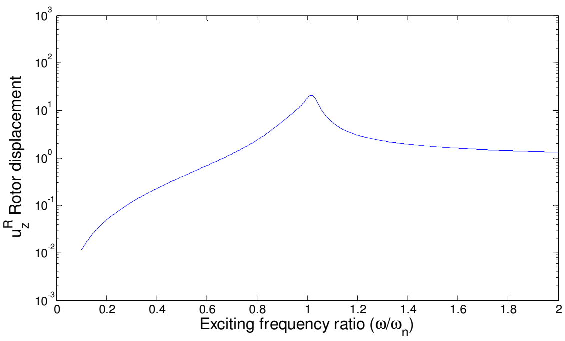


Figure 3. Rotor displacement amplitude to excitation frequency (Ramalho, 2006)

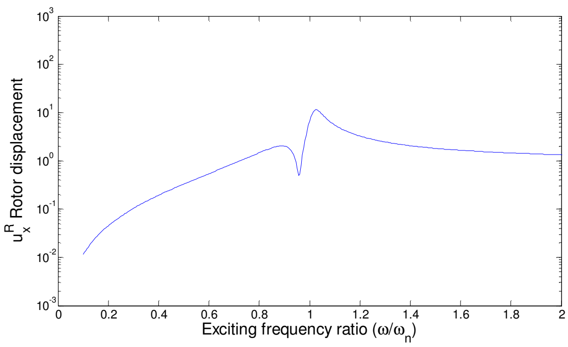
The data used to calculate the bearing coefficients, depending on the frequency, are:

PARAMETERS	VALUES
Bearing load	750 Kg
D_e - Shaft external diameter	18.0 cm
L - axial length	9.9cm
C_d - diametral clearance	135 µm
µ - oil viscosity	14.32 Pa.s

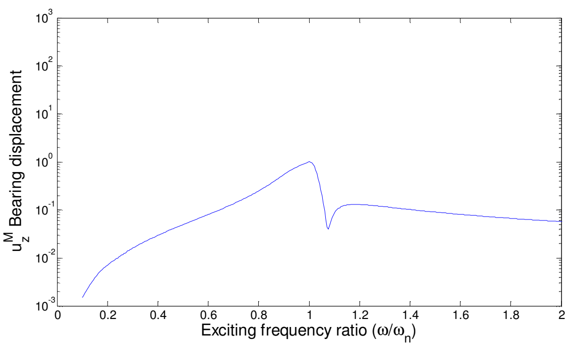
The study of the soil influence on the rotor, considering the bearing stiffness and damping, is showed bellow. The behaviour of the rotor with bearings, not considering the soil influence, presents the following answer:



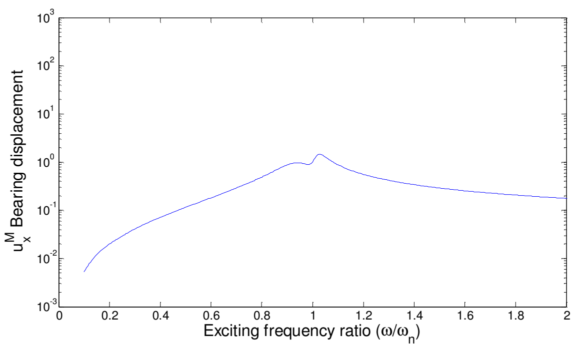
(a.1) Rotor-vertical-direction



(a.2) Rotor-horizontal direction



(b.1) Bearing-vertical direction

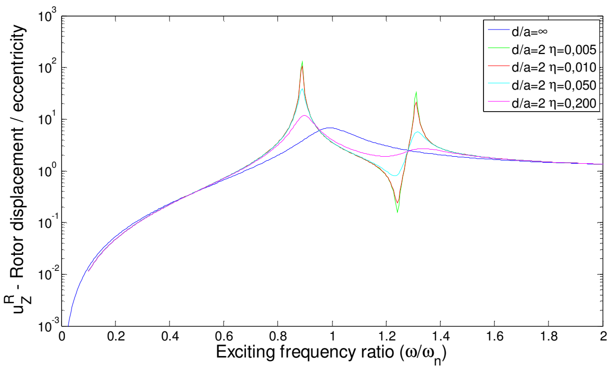


(b.2) Bearing-horizontal direction

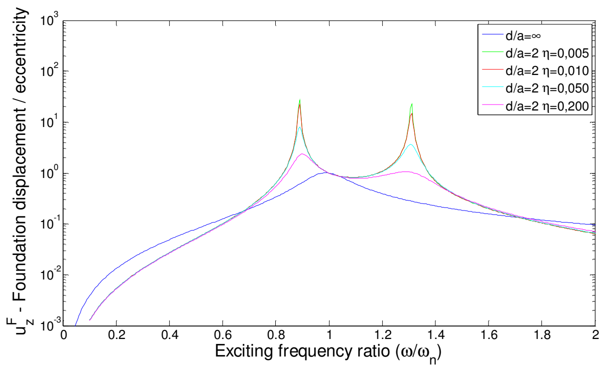
Figure 4. Behaviour of the rotor (a) and of the bearing (b) in vertical (1) and horizontal (2) directions.

It was observed that there is a bifurcation in the amplitude of the rotor only in the horizontal direction, as expected. The bearing presents a bifurcation mainly in the vertical direction.

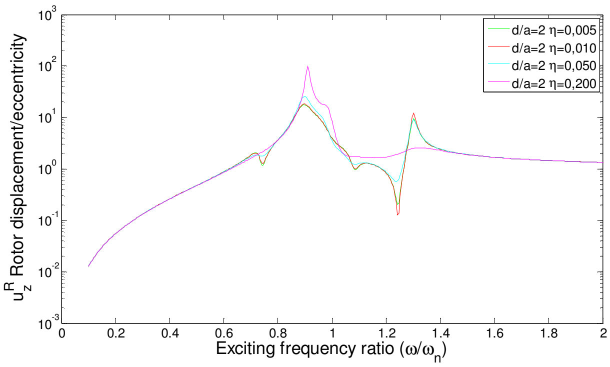
Considering the model that includes the rotor, the foundation and the soil, the behaviour of the system presents the following characteristics:



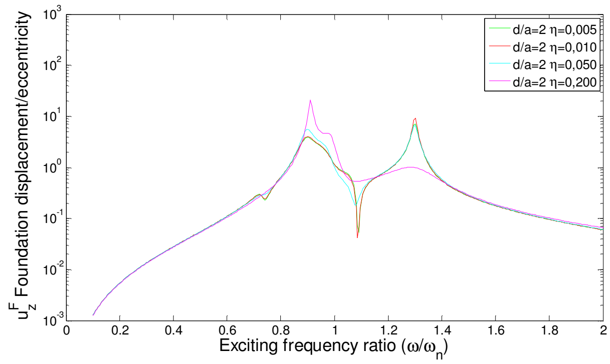
(a.1)Rotor-d/a=2- rigid bearings



(b.1) Foundation-d/a=2-rigid bearings



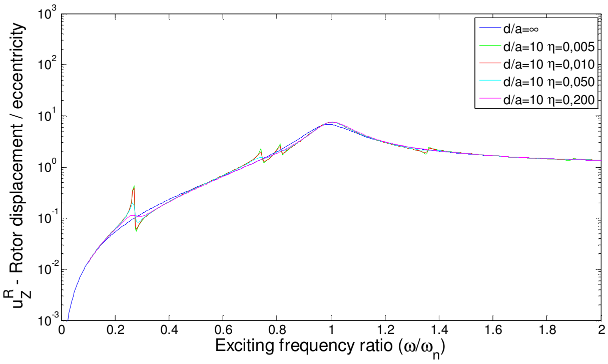
(a.2) Rotor-d/a=2-flexible bearings



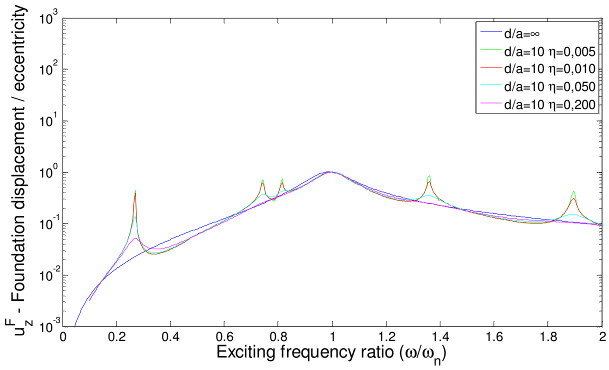
(b.2) Foundation-d/a=2-flexible bearings

Figure 5. Comparison of the behaviour of the rotor (a) and the foundation (b), with rigid (1) and flexible (2) bearings, for a depth layer d/a=2.

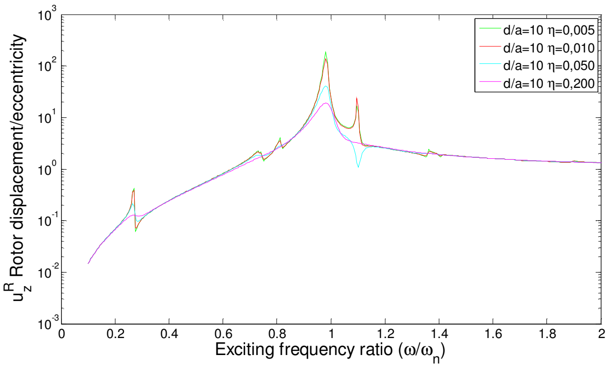
The foundation, with flexible bearings, has a more expressive vibration at the natural frequency that can be noticed as well in the rotor dynamic response. This increase in the vibration is observed in the rotor as well.



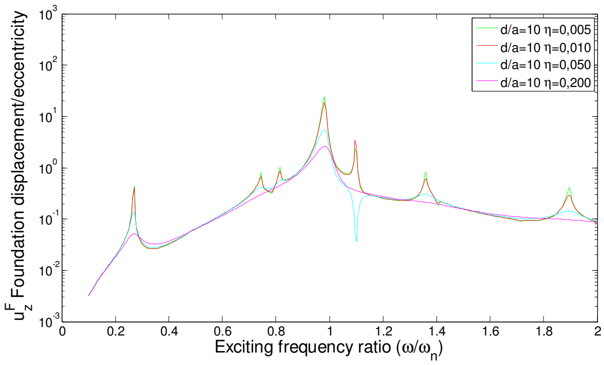
(a.1)Rotor-d/a=10-rigid bearings



(b.1) Foundation-d/a=10-rigid bearings



(a.2)Rotor-d/a=10-flexible bearings



(b.2)Foundation-d/a=10-flexible bearings

Figure 5. Comparison of the behaviour of the rotor (a) and the foundation (b), with rigid (1) and flexible (2) bearings, for a depth layer d/a=10.

When the layer of the soil is bigger, the increase of the vibration amplitude of the rotor and the foundation is less expressive, when comparing to the smaller layer.

5.CONCLUSIONS

It was observed that the bearings play an important role in the rotor-foundation interaction analysis, making this effect more or less significant.

A parametric sensitivity study would be interesting because there are many parameters in the model. It would be interesting observe what parameters are more or less important in the behaviour or the system rotor-bearing-foundation-soil, focusing the study in these parameters.

6. ACKNOWLEDGEMENTS

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