Understanding Electrodynamic Dampers

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***Abstract* – This paper presents general analytical tools to predict the damping and stiffness coefficients of electrodynamic dampers. Special attention will be drawn to the different cases when the conductor is either rotating or non-rotating.**

***Index Terms* – Electrodynamic damper, electrodynamic bearing, eddy current, inductance, rotating damping.**

I. Introduction

Electrodynamic vibration dampers are often considered in the design of rotating machinery as a contactless and hydrocarbon-free replacement for viscous dampers. Their simple geometry based on combinations of magnets and conductors in relative motion makes them an attractive and flexible choice for as well radial, axial and torsional damper applications. However, at the present very little knowledge is available, with few exceptions, on how to optimise these dampers. Furthermore, their influence on rotor dynamics is not yet fully understood. This paper presents general analytical tools to predict the damping and stiffness coefficients from an arbitrarily geometry based on electrical model parameters such as resistance and inductance. Special attention will be drawn to the different cases when the conductor is either rotating or non-rotating.

II. Damper Layouts

Several damper topologies are possible, and they can be divided into categories based on for instance type of magnetization and functionality:

a) Axial flux radial damper, Fig. 1
b) Radial flux radial damper, Fig. 2
c) Axial flux axial damper
d) Radial flux axial damper
e) Axial flux torsional damper
f) Radial flux torsional damper

To further categorize these dampers it is helpful to use subcategories based on type of magnet polarity depending on wether it is a homopolar or a heteropolar arrangement. Finally it is important to know if the conductor is rotating or not. If it is, then this type of dampers is normally referred to as electrodynamic bearings, which will be explained later.

Using the terminology above, Fig. 1 shows a homopolar axial flux radial damper with stationary conductor, and Fig. 2 shows a homopolar radial flux combined radial and axial damper with rotating conductor, or simply “induction bearing”. These two dampers have been chosen since they represent two rather different dampers, and yet, using the general tools provided in this paper the reader would be able to analyse both.

The magnet arrangements in Fig. 1 and Fig. 2 are homopolar, which is the preferred arrangement in radial and axial dampers, since it prevents unwanted eddy currents and losses from being induced.

Heteropolar magnets though, are the preferred layout in torsional dampers. These dampers are also the kind of dampers which are best known: any permanent magnet motor with short circuited stator winding can be used for this purpose, and the corresponding electric and mechanical models are well known and will not be considered further in this paper.

Finally, damper magnets are preferably permanent magnets, but also electromagnets can be used. The advantage with the latter is that they can be controlled using either a simple switch, or by an advanced regulating system. The analysis below is limited to permanent magnets and DC electromagnets.

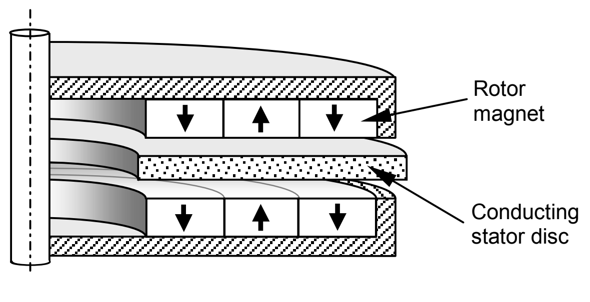

Fig. 1. Axial flux radial damper with moving magnets.

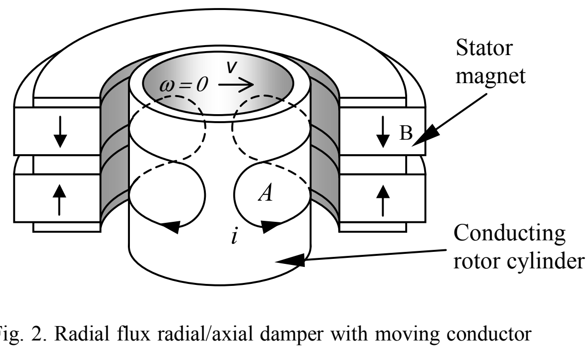

Fig. 2. Radial flux radial/axial damper with moving conductor and enhanced radial stiffness.

III. Principles of Operation

All electrodynamic dampers work according to the Faraday Induction Law. This means that a part of a conductor, or actually any material of a certain area A, moving relative to a magnetic flux gradient will be exposed to an induced voltage U proportional to the flux change through that area:

$$U = N\frac{d\Phi}{dt}. \tag{1}$$

This is true both for rotating and non-rotating conductors. For a linear damper, which shall replace a viscous one, the flux gradient is designed to be constant within the operating range of the conductor, which includes the conductor thickness and the airgap, but not necessarily the gap required for the emergency bearing g_e. Fig. 3 shows the flux distribution for the damper in Fig. 2, and is given as an example only. The constant gradient allows a voltage constant k_u to be defined such that

$$U = k_u \cdot v, \tag{2}$$

where v is the velocity to be damped, for instance the radial velocity defined in Fig. 2. If the conductor consists of a wound coil with N turns, then the area A is well defined, and k_u can be calculated. If, on the contrary, the conductor is a solid disc or cylinder, the number of turns is one, but the area is unknown and has to be estimated. This is the most difficult part in the analysis, and requires knowledge about the eddy current paths. Guidelines for how to find the shape of these currents are given in the analysis part.

Once the current paths have been found, the resistance R and the inductance L can be calculated for each eddy current circuit. With U, R and L known, the current/currents $i(t)$ follows from

$$U(t) = Ri(t) + L\frac{di(t)}{dt}. \tag{3}$$

The induced currents interact with the magnetic flux $\bar{B}$, both with the radial and the axial flux components, so that the damping force $\bar{F}_D$, or actually the total force if it includes other force components than purely damping ones, can be found by integrating the Lorenz force over the entire conductor volume

$$\bar{F}_D = \oiiint_V \bar{J} \times \bar{B}\, dV. \tag{4}$$

The analytical expression directly tells which force contributions that depend on eccentricity and which are speed dependent, that is which terms that can be recalculated into stiffness terms and damping terms respectively.

This far the principles of operation have been described in very general terms. However, the author has found it very helpful to apply a traditional electromechanical actuator model in order to visualize and to understand how the damping and stiffness components and their corresponding cross coupling terms relates to Eq. 1-4. The model will be used in the next section.

IV. Analysis

The general explanation of electrodynamic dampers presented above will now be narrowed down to cover more specific details necessary for the understanding of these dampers. Special focus will be given to the damper with rotating conductor in Fig. 2. Obviously, if one can find analytical expressions for this damper, then it is trivial to put the rotational velocity to zero, and the result will be applicable to dampers with stationary conductor as well, with respect to some geometrical data that might have to

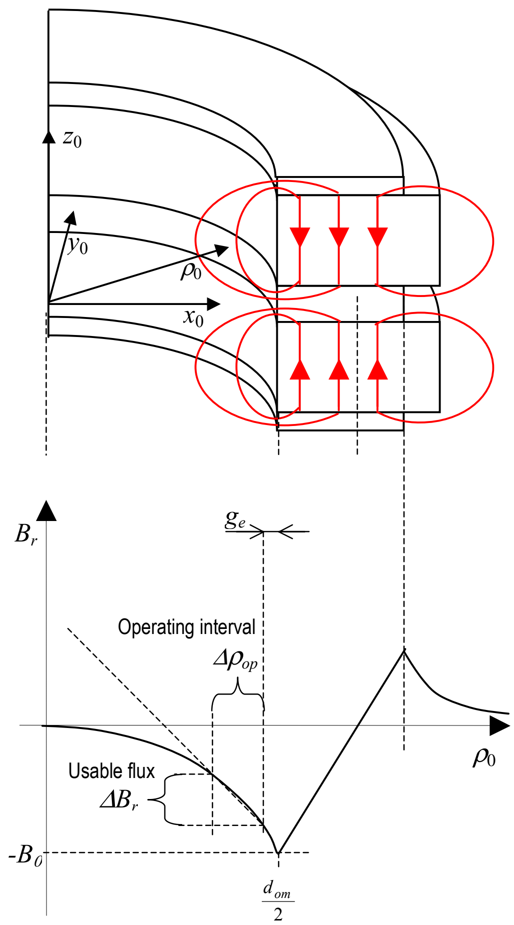

Fig. 3. Radial flux density distribution.

be recalculated as well. For more information on the latter damper, a variant of it was analysed by [1]. (The first successful commercial damper of this type was likely the one patented by [4] in 1989.)

To simplify the analysis it is convenient to use a model of a voltage controlled electromechanical actuator, characterized by parameters like the resistance R, the reactance ωL and the force/current constant k_i transforming the current to the damping force F_D such that

$$F_D = k_i \cdot i(t) . \tag{5}$$

The input voltage U is zero (short circuit) and the induced back-EMF is now referred to as E.

The analysis of the model parameters will begin with the back-EMF. The axially oriented magnets in Fig. 3 produce a radial flux via flux concentrating iron pole shoes, some of it penetrating the conductor surface. The maximum (absolute) flux density at the pole surface is B_0 and it is directed radially inwards. If the flux space gradients $dB_r / d\rho_0$, expressed in stator fixed cylindrical coordinates ρ_0, z_0, ϕ_0 can be considered constant along the operating range $\Delta\rho_{op}$ of the damper, then the induced voltage

$$\begin{aligned} E &= N \cdot \oiint_A \frac{dB_r}{dt} da = N \cdot \oiint_A \frac{dB_r}{d\rho_0} \cdot \frac{d\rho_0}{dt} da = \\ &= v \cdot N \frac{dB_r}{d\rho_0} \oiint_A \cos(\phi_0 - \phi_v) da = v \cdot k_u \end{aligned} \tag{6}$$

is proportional to the lateral velocity v, defined in Fig. 2. This proportionality is of fundamental importance if the properties of the damper shall resemble those of a viscous one. In Eq. 6 we have used that the radial velocity varies sinusoidally around the perimeter of the conductor and has a maximum value equal to v in the direction of motion ϕ_v. For the damper in Fig. 1 the interesting flux gradient is of course the radial gradient of the axial flux, $dB_z / d\rho_0$.

To evaluate Eq. 6 the area A, which is illustrated in Fig. 2, has to be estimated. In the previous section it was found that in the case of solid conductors this is not a trivial task. The shape of the surrounding eddy current is mainly determined by the type of motion the conductor performs, axial, radial or rotational. Let us for the analysis initially assume that both rotors in Fig. 1 and Fig. 2 move in radial direction, and that the rotor in Fig. 2 has not yet started to rotate.

As a starting point, it is now apt to find the current path that encloses the largest flux change for this type of motion. Typically the eddy currents follow the perimeter of the magnets, but in the case of homopolar arrangements the currents are broken up into at least two separate circuits, see Fig. 2. For this particular cylindrical arrangement an analysis has been done in detail by the author [2]. For the disc in Fig. 1 a similar analysis would, depending on disc diameters, result in at least two, likely six, flat kidney shaped current circuits.

However, a FEM-code is still of great value to illustrate and to help find these current paths. (Unfortunately, most codes are not suited for problem formulations involving radial translations. However, the circular whirl motion and the rotation can be transformed into one another, so that a 3D-software with either time-step or Minkowski transform can be used to simulate the problem [2]. This was done in order to find the current paths in Fig. 2, 4 and 5.)

Finally, the force/current constant k_i can, in the case of a non-ferromagnetic conductor, be found by integrating the Lorenz force over the whole conductor volume including all eddy currents. Thus

$$k_i = \frac{1}{I} \left| \oiiint_V J \times B \, dV \right| \tag{7}$$

assuming that all eddy currents are equal. If they are not,

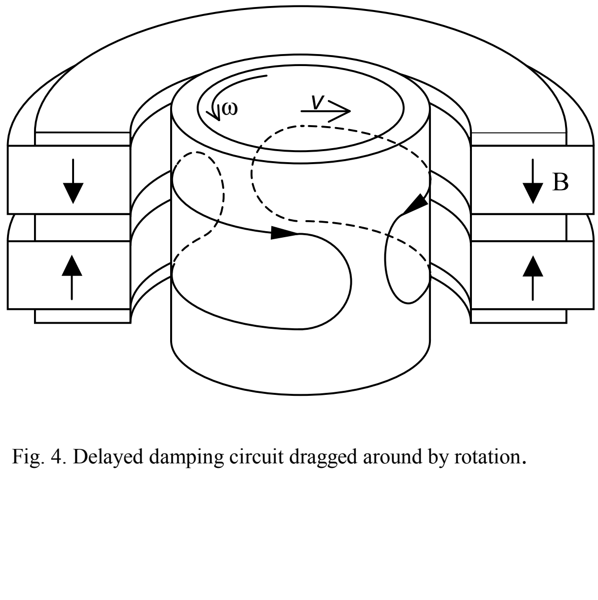

Fig. 4. Delayed damping circuit dragged around by rotation.

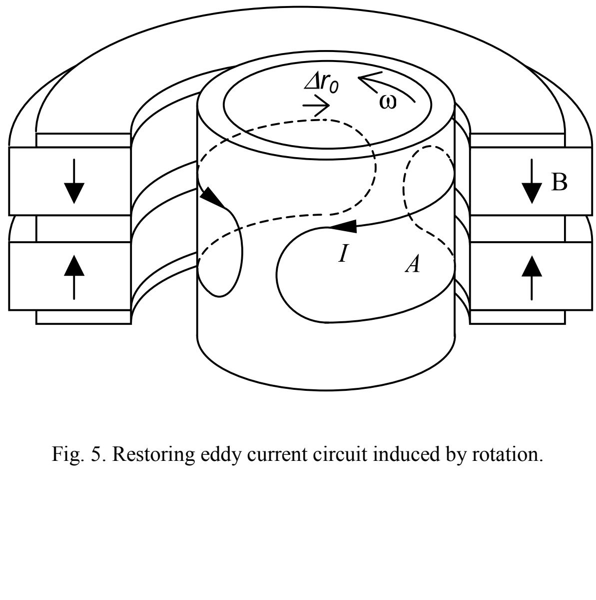

Fig. 5. Restoring eddy current circuit induced by rotation.

they have to be treated individually, as is done in [2]. From electromechanical theory it is known that the voltage constant k_u equals the current constant k_i, which offers an alternative way to calculate the forces, especially if the rotor is partly ferromagnetic so that the Lorenz force is not applicable.

V. Damping and Stiffness Coefficients

A. Stationary Conductor

Consider the simplest motion of all; the rotor moves with constant low speed v. Then the effect of the inductance is negligeble which implies a simple solution to the damping force. The current, which is constant, is

$$I = E / R \tag{8}$$

and the force

$$F_D = k_i \cdot I = \frac{1}{R} k_i k_u \cdot v \tag{9}$$

which is proportional to the velocity v so that a damping coefficient c can be defined as

$$c = \frac{1}{R} k_i k_u = \frac{k_u^2}{R} \quad \left[\frac{Ns}{m} \right]. \tag{10}$$

A far more important motion is whirl. If the frequency is so high that the inductance cannot be neglected, the current $i(t)$ will raise according to Eq. 3. For a harmonic excitation like whirl, where

$$E(t) = \hat{E} \sin(\omega t), \tag{11}$$

the first effect of the inductance is that it delays the current and thus also the damping force an angle

$$\varphi = \arctan \frac{\omega L}{R}. \tag{12}$$

This in turn represents a stiffness component, which will increase with increasing frequency. At very high frequency, or in the case of a superconductor with almost zero AC-resistance, the phase shift tends to $\pi / 2$ and almost all damping is turned into stiffness. Thus for non-zero vibrational frequencies an electrodynamic damper will always provide both stiffness and damping. The second effect is that the inductance will reduce the damping coefficient at higher frequencies and act as a high pass filter for vibrations.

B. Rotating Conductor

If the conductor rotates, some cross coupling effects are introduced. If the inductance once again is neglected, one can apply the well-known theory of rotating damping known among others from [3]. Ref. [1] and [2] studied the case including the inductance, and found that the cross coupling stiffness $k_c = \omega c$ predicted by [3] is delayed φ radians resulting in a pure stiffness term k and another, redefined cross-coupling stiffness k_c that decreases at higher speed, thus allowing stable operation at high speeds without necessarily reaching the instability threashold predicted by [3]. Ref. [1] and [2] also found that the damping coefficient is reduced at higher speeds, compared to the non-rotating case, and that a cross-coupling term is added to the damping matrix.

Ref. [2] has developed analytical expressions for the different damping and stiffness coefficients, and they are experimentally validated for a damper/bearing similar to the configuration in Fig. 2.

VI. Results

It is shown that all electrodynamic dampers offer both damping and stiffness properties. In the particular case of rotating conductors the stiffness is enhanced, and some cross coupling terms are introduced.

It is believed that increased knowledge in this field will enable technical solutions to vibration problems which today can not be properly solved using either active control nor using passive viscous or rubber dampers.

Acknowledgment

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