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Scaling of electromagnetic transducers for shunt damping and energy harvesting

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ABSTRACT

In order for an electromagnetic transducer to operate well as either a mechanical shunt damper or as a vibration energy harvester, it must have good electromechanical coupling. A simple two-port analysis is used to derive a non-dimensional measure of electromechanical coupling, which must be large compared with unity for efficient operation in both of these applications. The two-port parameters for an inertial electromagnetic transducer are derived, from which this non-dimensional coupling parameter can be evaluated. The largest value that this parameter takes is approximately equal to the square of the magnetic flux density times the length of wire in the field, divided by the mechanical damping times the electrical resistance. This parameter is found to be only of the order of one for voice coil devices that weigh approximately 1 kg, and so such devices are generally not efficient, within the definition used here, in either of these applications. The non-dimensional coupling parameter is found to scale in approximate proportion to the device's characteristic length, however, and so although miniaturised devices are less efficient, greater efficiency can be obtained with large devices, such as those used to control civil engineering structures.

1. Introduction

Electromagnetic transducers can be used for either shunt damping [1,2] or energy harvesting [3,4]. The objective of shunt damping is to increase the mechanical damping in a structure by attaching an electromechanical transducer, which dissipates electrical energy [5]. The transducer may be either piezoelectric [6] or electromagnetic [7] and applications have ranged from reducing the vibration in skis [8] to controlling motion in civil engineering structures [9,10]. The aim of a vibration energy harvesting system is also to convert mechanical energy to electrical energy, but in this case the electrical energy is stored, using a capacitor or battery, in order to be used for various purposes [11]. Typical applications are wireless sensors for structural health monitoring [12,13] or biological implants [14], which can then be autonomous since they require no external power source. These systems can also use either piezoelectric [15,16] or electromagnetic transducers [3].

The performance of an electromagnetic actuator in both of these applications is analysed here in terms of its two-port parameters. A single dimensionless parameter is found to govern the efficiency of the device when used for either shunt damping or energy harvesting. The scaling of this parameter with the size of the transducer is then investigated for voice coil actuators and the result contrasted with the corresponding result for a piezoceramic actuator.

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Assuming that the moving parts of an electrodynamic actuator all vibrate in phase and that it is linear, its response at a single frequency can be completely defined by the two-port network equations [17, 18], which may be written as

$$u = Z_{eb} i + T v \tag{1}$$

$$f = -T i + Z_{mo} v, \tag{2}$$

where u, i, f and v are the voltage across the device's terminals, the current through the device, the force generated by the device and its velocity, respectively. Z_{eb} is thus the device's blocked electrical impedance, Z_{mo} is its open circuit mechanical impedance and T is its transduction coefficient, each of which is, in general, a complex, frequency-dependent parameter.

Fig. 1 shows a block diagram of the transducer, represented in terms of the two-port parameters. There are two circuits, representing either the mechanical or electrical responses, each coupled via a generator representing the electromechanical coupling.

When the base of the transducer is fixed and the force acts on the moving mass, an electromagnetic actuator can be idealised as on the left hand side of Fig. 2. This model is widely used to represent the dynamics of shaker mounted on a rigid base, for example. Assuming the mechanical parts move as a single degree of freedom system, then the two-port parameters for the transducer in this case are

$$Z_{eb} = R_e + j\omega L_e, \tag{3}$$

$$Z_{mo} = j\omega M + \frac{K}{j\omega} + R_m, \tag{4}$$

$$T = Bl, \tag{5}$$

where R_e and L_e are the electrical resistance and inductance of the coil, respectively, M, K and R_m are the mass, stiffness and mechanical resistance of the moving parts, respectively, B is the flux density and l is the length of the wire moving in the field. The electrical and mechanical variables are assumed to be proportional to $e^{j\omega t}$ where ω is the angular excitation frequency. When operated at its natural frequency, $\omega_n = \sqrt{K/M}$, the open circuit mechanical impedance is equal to R_m and, since ωL_e is generally much less than R_e at this frequency, Z_{eb} is approximately equal to R_e.

If, however, the electromagnetic transducer is used as an inertial device, so that the force acts on its base and the mass vibrates freely, as on the right hand side of Fig. 2, the two port parameters can then be shown to be

$$Z_{eb} = R_e + j\omega L_e + \frac{j\omega (Bl)^2}{j\omega R_m + K - \omega^2 M}, \tag{6}$$

$$Z_{mo} = \frac{j\omega M\,(K + j\omega R_m)}{j\omega R_m + K - \omega^2 M}, \tag{7}$$

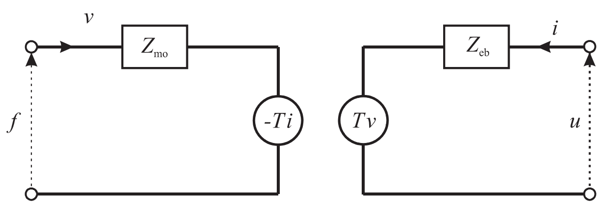

Fig. 1. Block diagram of an electromagnetic transducer in terms of its two-port parameters.

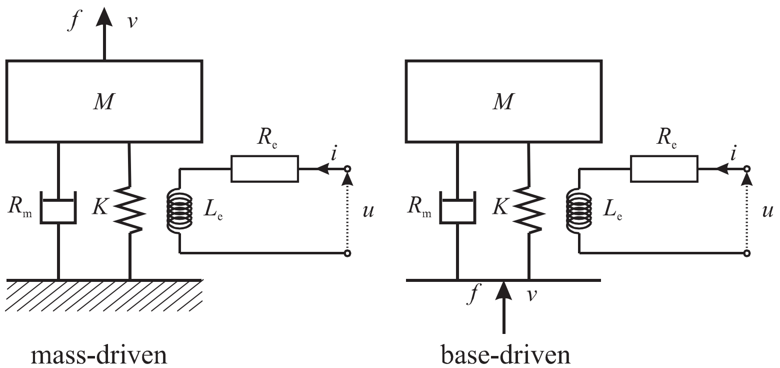

Fig. 2. Block diagram of an idealised electromagnetic actuator when driven by the moving mass, left, and when driven by the base structure, for an inertial device, right.