

Scaling of electromagnetic transducers for shunt damping and energy harvesting

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Keywords: energy harvesting, shunt damping, electromagnetic transducers

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 order of one for laboratory devices that weigh about 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, much 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 performance of such a device 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 the parameter with the size of the transducer is then investigated and the result contrasted with the corresponding result for a piezoceramic actuator.

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 [5, 6], which may be written as:

$$u = Z_{eb} i + T v \quad (1)$$

$$f = -T i + Z_{mo} v, \quad (2)$$

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. Z_{eb} is thus the device's blocked electrical impedance, Z_{mo} is its open circuit mechanical impedance and T its transduction coefficient, each of which are, in general, complex, frequency-dependant parameters.

Figure 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 Figure 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:

$$Z_{eb} = R_e + j\omega L_e, \quad (3)$$

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

$$T = Bl. \quad (5)$$

where R_e and L_e are the electrical resistance and inductance of the coil M , K and R_m are the mass, stiffness and mechanical resistance of the moving parts, B is the flux density and l is the length of 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 Figure 2, the two port parameters can then be shown to be:

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

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

$$T = \frac{-\omega^2 MBl}{j\omega R_m + K - \omega^2 M}. \quad (8)$$

Figure 3 shows the modulus of these two port parameters, as a function of frequency, for both cases with the assumed parameters listed in Table 1.

If the inertial device is operated above its natural frequency, ω_n , but below the frequency at which the inductance becomes important, $\omega_u = R_e/L_e$, then Z_{eb} is approximately equal to R_e , Z_{mo} is approximately equal to R_m and T is approximately equal to Bl . These approximations hold for well damped devices with $\zeta > 1/2$. For damping ratio lower than $1/2$ the cut off frequency above which these approximations are still valid is approximately given by $\omega_n/2\zeta$ [7]. For the device whose parameters are listed in Table 1, this frequency range is from approximately 30 Hz to 1 kHz, as confirmed by the results shown in Figure 3.

2. SHUNT DAMPING AND ENERGY HARVESTING

When used as either a shunt damper or an energy harvester, an electrical impedance, Z_{shunt} , is connected across the electrical terminals of the transducer, as shown in Figure 4. The difference between the two applications is that for shunt damping the objective is to modify the mechanical response of the device, whereas for energy harvesting the objective is to transfer as much power into the electrical shunt as possible, so that it may be stored and used for other purposes.

2.1 SHUNT DAMPING

The voltage across the terminals, u , is equal to $-Z_{shunt} i$, since i is defined to flow onto the transducer in Figure 1. The two-port equations (1) and (2), can then be used to show that the mechanical impedance presented by the transducer in this case is:

$$Z_m = Z_{mo} + \frac{T^2}{Z_{eb} + Z_{shunt}}. \quad (9)$$

Assuming the actuator is being used in the frequency range where Z_{eb} is resistive, and that the shunt is passive, the greatest increase in Z_m will be achieved if the shunt impedance is set to zero, i.e. the device is short circuit. In this case Z_m is equal to Z_{ms} , given by:

$$Z_{ms} = Z_{mo} \left(1 + \frac{T^2}{Z_{mo} Z_{eb}} \right). \quad (10)$$

If the electromagnetic transducer is mass-driven and at resonance, or if it is base-driven in the frequency range discussed in Section 1, so that T is approximately equal to Bl , Z_{eb} is approximately equal to R_e and Z_{mo} is approximately equal to R_m , then we can express the ratio of the short circuit mechanical impedance to the open circuit mechanical impedance as:

$$\frac{Z_{ms}}{Z_{m0}} = 1 + C_{em} , \quad (11)$$

where we define C_{em} to be the non-dimensional electromagnetic coupling coefficient given by

$$C_{em} = \frac{(Bl)^2}{R_m R_e} . \quad (12)$$

The ratio Z_{ms}/Z_{m0} is a measure of the extent to which shorting an electromagnetic actuator can affect its impedance and hence achieve shunt damping. The variation of Z_{ms}/Z_{m0} with C_{em} is shown in Figure 5.

It is clear that there will be little shunting effect on the mechanical impedance, if C_{em} is small compared to unity, but a considerable effect if C_{em} is large compared with unity. It is possible to synthesise electrical impedances that are not passive with special circuits, in which case the resistive part of the shunt impedance could be negative, cancelling out some of the resistive part of Z_{eb} , which would have a greater effect on Z_m than just short circuiting [1]. To have a significantly greater effect than just short circuiting, however, most of the resistive part of Z_{eb} would have to be cancelled [2], which makes the stability of the system rather sensitive to changes in Z_{eb} due, for example to variations in temperature.

2.2 ENERGY HARVESTING

When used for energy harvesting purposes, we assume that the transducer is subject to a constant excitation velocity, v . Since the voltage across the terminals is equal to $-Z_{shunt} i$, then using equation (1), the current generated is:

$$i = \frac{-Tv}{Z_{eb} + Z_{shunt}} . \quad (13)$$

The electrical power transferred to the shunt is:

$$W_e = \frac{1}{2} \text{Re}(i^* u) = \frac{1}{2} |i|^2 \text{Re}\{Z_{shunt}\} , \quad (14)$$

where Re denotes the real part of a complex quantity and $*$ indicates complex conjugate, so that:

$$W_e = \frac{|T|^2 |v|^2 \text{Re}\{Z_{shunt}\}}{2|Z_{eb} + Z_{shunt}|^2} . \quad (15)$$

The harvested power is maximised, in this case where a constant velocity excitation is assumed, if Z_{shunt} is equal to Z_{eb}^* . If the mass-driven actuator is driven at resonance or the base-driven actuator is again driven in the frequency range discussed at the end of Section 1, then Z_{eb} is equal to R_e , and so for maximum harvested power Z_{shunt} must also equal R_e , in which case:

$$W_e = \frac{|T|^2 |v|^2}{8 R_e} . \quad (16)$$

The mechanical power absorbed by the transducer is:

$$W_m = \frac{1}{2} \text{Re}\{v^* f\} = \frac{1}{2} |v|^2 \text{Re}\{Z_m\}, \quad (17)$$

where the mechanical impedance of the transducer is, in general, given by equation (9). If Z_{eb} and Z_{shunt} are again assumed to be equal to R_e , then using equation (9) the mechanical power is given by:

$$W_m = \frac{1}{2} |v|^2 \text{Re}\left\{Z_{mo} + \frac{T^2}{2R_e}\right\}. \quad (18)$$

Although there are many figures of merit that could be used for such transducers, we define the power harvesting efficiency, E , as the ratio of the electrical power harvested to the mechanical power supplied, so that:

$$E = \frac{W_e}{W_m} = \frac{|T|^2}{\text{Re}\{Z_{mo} + T^2/2R_e\} 4R_e}. \quad (19)$$

If the electromagnetic transducer is mass-driven at resonance, or it is base-driven in the frequency range discussed in Section 1, then T is approximately equal to Bl and $\text{Re}\{Z_{mo}\}$ to R_m , so that:

$$E = \frac{(Bl)^2}{4R_m R_e + 2(Bl)^2} = \frac{C_{em}}{4 + 2C_{em}}, \quad (20)$$

where C_{em} is again the electromagnetic coupling coefficient given by equation (12) [4]. The variation of E with C_{em} is also shown in Figure 5.

The efficiency of the energy harvesting device is clearly low if C_{em} is small compared to unity, but reaches a maximum value of 50% when C_{em} is large compared with unity. In this case the electromagnetic coupling is strong, little power is dissipated in the mechanical parts of the transducer and an equal power is dissipated in the internal electrical resistance and harvested on the external shunt.

3 SCALING OF COUPLING COEFFICIENT WITH DEVICE SIZE

If the cross-section area of the wire used in the coil of the electromagnetic actuator is A_w and the resistivity of the material is η , then the resistance of the coil is given by:

$$R_e = \eta \frac{l}{A_w}, \quad (21)$$

where l is the length of wire in the coil, which is given, approximately, by

$$l = \frac{V_c}{A_w}, \quad (22)$$

and V_c is the volume of the coil. The quantity l^2/R_e , which appears in the expression for the electromagnetic coupling coefficient, C_{em} , in equation (12), is thus given by

$$\frac{l^2}{R_e} = \frac{V_c}{\eta}, \quad (23)$$

which is independent of the number of turns in the coil. The resistivity of the coil material does not depend of the scale of the transducer, but the volume of the coil clearly scales as the cube of characteristic length of the transducer, L , so that it scales as $[L^3]$ in the notation used in reference [8-10], for example. The magnetic flux density B is assumed to be saturated in a well-designed transducer, so this depends on the properties of the materials that the transducer is made from, but not its dimensions. Finally, the scaling of the mechanical resistance, R_m , depends on the detailed mechanism of mechanical damping in the transducer and we will infer this from experimental data. Table 2 lists the parameters of a number of different electromagnetic actuators, including their non-dimensional coupling coefficient. The variation of this parameter with the mass of the transducer is plotted in Figure 6. A least square fit to the data shown in Figure 7 suggests that the electromagnetic coupling coefficient scales as the mass raised to the power of about 0.35. Since the mass of the device clearly scales as $[L^3]$, the overall electromagnetic coupling coefficient, C_{em} , given by $(Bl)^2/R_e R_m$, thus must scale approximately in proportion to the characteristic length of the transducer, as $[L]$. Assuming that $(Bl)^2/R_e$ still scales as $[L^3]$, this result implies that R_m scales as about $[L^2]$ for these devices, rather than in proportion to $[L]$, as suggested in [11]. A reasonable fit to the data is thus that electromagnetic coupling coefficient is given by:

$$\frac{(Bl)^2}{R_m R_e} \approx \left(\frac{M_T}{M_0}\right)^{.35}, \quad (24)$$

where M_T is the total mass of the transducer and M_0 is a reference mass, given from Figure 6 as about 0.6 kg.

This scaling of the coupling coefficient for electromagnetic transducers is in contrast to the equivalent quantity for piezoelectric transducers, as discussed in the Appendix, which depends only on the material properties and is thus, to a first approximation, independent of L . It is shown in the Appendix that the equivalent coupling coefficient for piezoelectric transducers C_{piezo} , is related to the piezoelectric coupling factor, k_{piezo}^2 , by the expression:

$$C_{piezo} = \frac{k_{piezo}^2}{1 - k_{piezo}^2}, \quad (25)$$

We can thus define a coupling factor for a generic electromagnetic transducer, k_{em}^2 , as a function of the electromagnetic coupling coefficient, by analogy with the piezoelectric case as:

$$k_{em}^2 = \frac{C_{em}}{1 + C_{em}}, \quad (26)$$

which varies from 0 to 1 as C_{em} increase from 0 to ∞ . Figure 7 shows the variation of k_{em}^2 , with the actuator mass, assuming that C_{em} scales with mass as in equation (24), with a constant of proportionality obtained from Figure 6. Also shown on this graph is the value of k_{piezo}^2 for a PZT transducer, which is assumed to be independent of actuator mass, as discussed in the Appendix.

It can be seen that k_{em}^2 is smaller than k_{piezo}^2 for actuator masses below about 6 kg, whereas it is larger than k_{piezo}^2 for larger devices.

In order to assess the practicability of larger electromagnetic devices, it is also useful to estimate the scaling of some of its other properties with device size. Gardonio *et al.*[10], for example, show that the devices natural frequency, $\omega_n = \sqrt{K/M}$, scales as $[L^{-1}]$ and that the static displacement due to gravity, Mg/K , where g is the acceleration due to gravity, scales as $[L^2]$. As the actuator gets larger, its natural frequency tends to fall, as expected, but of more concern is that its static displacement due to gravity will become large rather quickly. This is not a concern if the device can be used horizontally, but if used vertically this static displacement can become larger than the size of the device itself and may ground the inertial mass. Although various self-levelling strategies can be adopted [12] these often require external power, which compromises energy harvesting performance, and so the static displacement may limit the size of the device that can be used in practice.

The operating frequency range of the inertial device has also been assumed to be from somewhat above the natural frequency, ω_n , to an upper frequency, ω_u , when the reactance of the device's inductance is equal to its electrical resistance, given by R_e/L_e . The dependence of R_e on the geometric and electrical properties of the coil is given by equation (21). If the coil has a radius r and height h , then since l is approximately equal to $\pi r N$, where N is the number of turns, and A_w is equal to rh/N , then:

$$R_e \approx \eta \frac{\pi N^2}{h}, \quad (27)$$

where η is the resistivity of the wire. The electrical inductance can also be approximated by that of a solenoid coil:

$$L_e = \mu \frac{A_s N^2}{h}, \quad (28)$$

where μ is the magnetic permeability and A_s is the area of the solenoid. A_s is equal to rh in this case so the inductance is approximately given by:

$$L_e \approx \mu N^2 r, \quad (29)$$

The upper limiting frequency ω_u , given by R_e/L_e is thus equal to:

$$\omega_u = \frac{\eta \pi}{\mu r h}, \quad (30)$$

which is independent of the number of turns, N , but scales as $[L^{-2}]$.

The frequency range of operation of an inertial device is assumed to be above ω_n , which scales as $[L^{-1}]$, but below ω_u , which scales as $[L^{-2}]$, and this range thus becomes smaller as the size of the device is scaled up. The upper frequency range can be extended somewhat by using electrical circuit with a negative inductance to cancel the electrical inductance of the device. Similar circuits, but with negative capacitance are currently used to increase the frequency range over which shunt dampers using piezoelectric actuators can be used [13]. There are limitations to the use of such circuits, however, since the magnetic behaviour can be more complicated than that leading to the linear model in equations (3), (4) and (5), with parameters that can be frequency and amplitude dependent.

4 CONCLUSIONS

The efficiency of an electromagnetic transducer when used as either a shunt damper or an energy harvester has been shown, under realistic circumstances, to depend on a non-dimensional electromagnetic coupling coefficient, equal to $(Bl)^2/R_e R_m$. This coupling coefficient, which varies from zero for a poorly coupled transducer to infinity for a well coupled device, is shown to increase with the size of the electromagnetic transducer, approximately in proportion to its characteristic length. This is in contrast to a piezoelectric transducer, for which the corresponding coupling coefficient is independent of the size of the device. The coupling coefficient is related to the coupling factor widely used to characterise piezoelectric transducers, which varies from zero to unity.

Although an electromagnetic transducer can be used as either a shunt damper or energy harvester, there may also be applications where it is used simultaneously for both purposes. The harvested electrical energy could potentially be used to power a self-tuning shunt damper, for example, to give an entirely autonomous device [14, 15] which may even give enough power to drive a digital controller [13].

It has been demonstrated that, because of the scaling of the coupling coefficient with the transducer's size, such systems may be most efficient for electromagnetic devices weighing many kilogrammes, as used in civil engineering applications for example, but would not be very efficient for miniaturised device, even though it is such devices that have been most widely studied for energy harvesting.

ACKNOWLEDGEMENTS

This work is based on a paper presented at the ISMA conference in 2012 [16] and grew out of a previous conference paper on the possibilities of combined energy harvesting and shunt damping [14] with a wider authorship. We would like to thank Nicolas Loix of Micromega for supplying some of the parameters for their actuators and also Paul Reynolds and Donald Nyawako at the University of Sheffield for their measurements on the APS 400 actuator that allowed the parameters used here to be identified.

APPENDIX A

In order to compare the analysis above with that for piezoelectric transducers, we can write the two port equations for a single-layered piezoelectric transducer, of area A and thickness t as:

$$q = C_e u + Dw \quad (\text{A.1})$$

$$f = -Du + S_m w \quad (\text{A.2})$$

where q , u , f and w are the charge, voltage, force and extension of the actuator, and [17]:

$$C_e = \frac{\epsilon^T A(1 - k^2)}{t} \quad (\text{A.3})$$

$$D = \frac{d_{33} A}{S^E t} \quad (\text{A.4})$$

$$S_m = \frac{A}{S^E t}, \quad (\text{A.5})$$

where ϵ^T , S^E , d_{33} and k^2 are the permittivity, compliance, piezoelectric constant and electromechanical coupling factor of the piezoelectric material.

If the piezoelectric transducer is open circuit then for harmonic excitation the current, given by $j\omega q$ is equal to zero, so that unless ω is zero, then q must also equal zero, and so the open circuit stiffness is equal to:

$$\left. \frac{f}{w} \right|_{open\ circuit} = S_m \left(1 + \frac{D^2}{S_m C_e} \right), \quad (\text{A.6})$$

where S_m is the mechanical stiffness if the device is short circuited.

The stiffness, and hence the impedance, of a piezoelectric transducer is thus greater when it is open circuit than when it is short circuit, in contrast to an electromagnetic transducer, whose impedance is greater when short circuit than when it is open circuit, as shown in equation (11). Another difference is that whereas an electromagnetic device, being velocity controlled, can add damping when short circuit, the piezoelectric device, being displacement controlled, is dominated by its stiffness when either open or short circuit and so requires a resistive element in the shunt to provide

a damping impedance. Nevertheless, we can define an electromechanical coupling coefficient for this piezoelectric case, by taking the analogy between equation (A.6) and equation (10), as:

$$C_{piezo} = \frac{D^2}{S_m C_e}, \quad (A.7)$$

which can also be written, using the definitions in equations (A.3) to (A.5), as:

$$C_{piezo} = \frac{k_{piezo}^2}{1 - k_{piezo}^2} \quad (A.8)$$

where

$$k_{piezo}^2 = \frac{d_{33}^2}{S^E \epsilon^T} \quad (A.9)$$

is the electromechanical coupling factor of the piezoelectric material [17], which can vary from 0 to 1, but is typically 0.1 for PVDF and 0.7 for PZT. As k_{piezo}^2 varies from 0 to 1, the electromechanical coupling coefficient in this case C_{piezo} , varies from 0 to ∞ , being about 0.1 for PVDF transducer and 2.3 for PZT devices.

Since k_{piezo}^2 depends only on the piezoelectric material, and not on the transducer dimensions, then k_{piezo}^2 and hence C_{piezo} for a piezoelectric transducer, does not depend on the size of the transducer, in contrast to the case for the electromagnetic actuator above.

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FIGURES

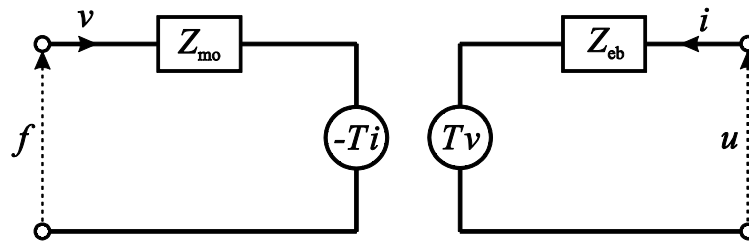


Figure 1: Block diagram of an electromagnetic transducer in terms of its two-port parameters

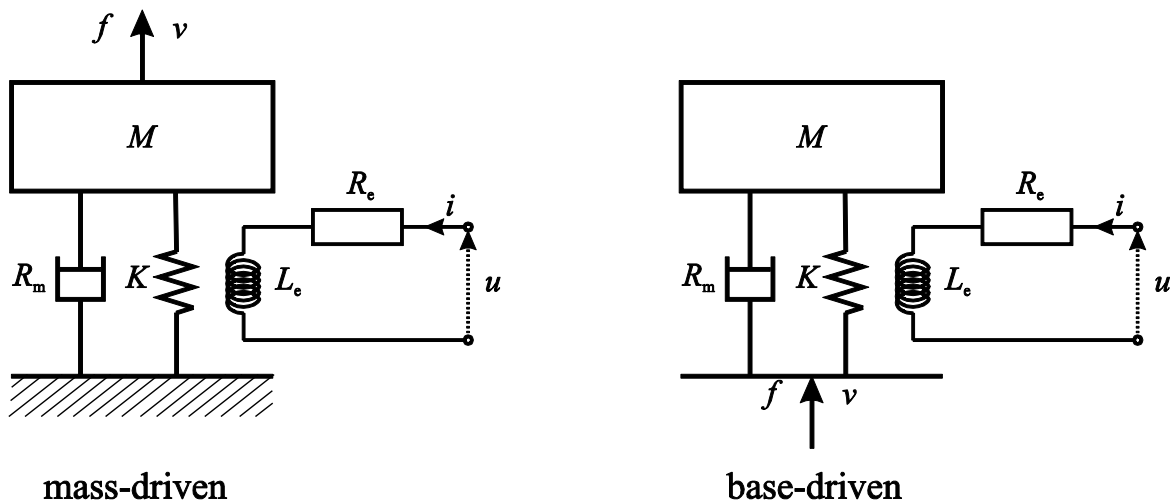


Figure 2: Block diagram of an idealised electromagnetic actuator when driven by the moving mass, left, and when driven by the base structure, for an inertial device, right.

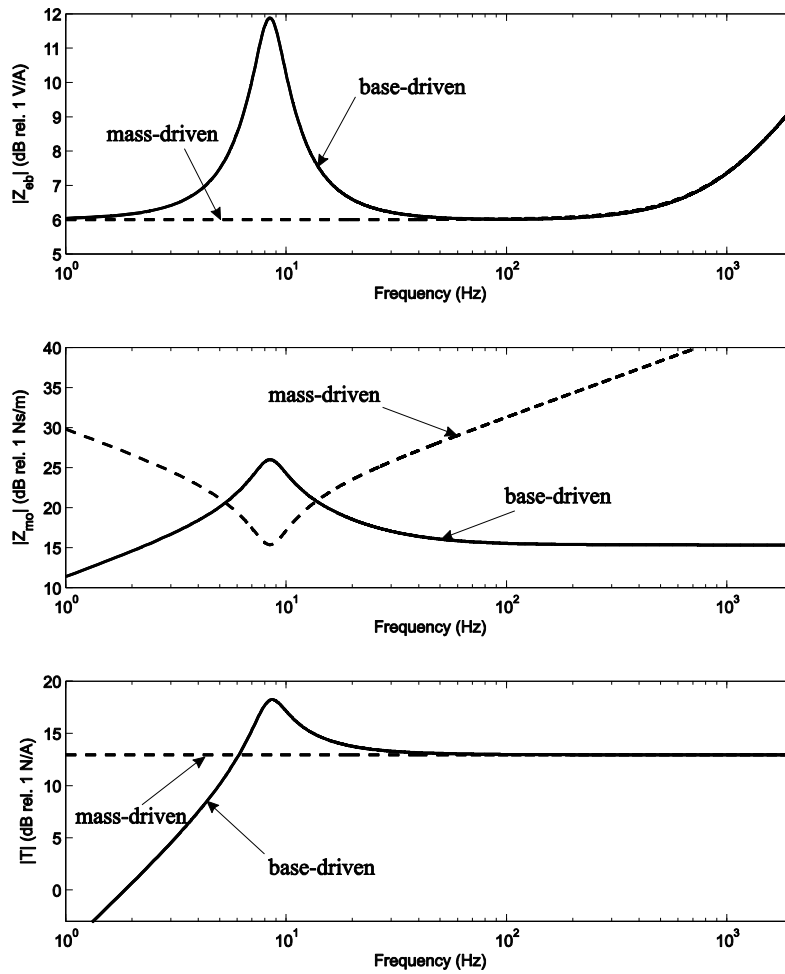


Figure 3: The modulus of the blocked electrical impedance $|Z_{eb}|$, open circuit impedance $|Z_{mo}|$ and transduction coefficient $|T|$ for an electromagnetic transducer with the force acting on the mass, mass-driven, dashed lines, and the force acting at the base, base-driven or inertial, solid lines, with the example parameters in the Table 1.

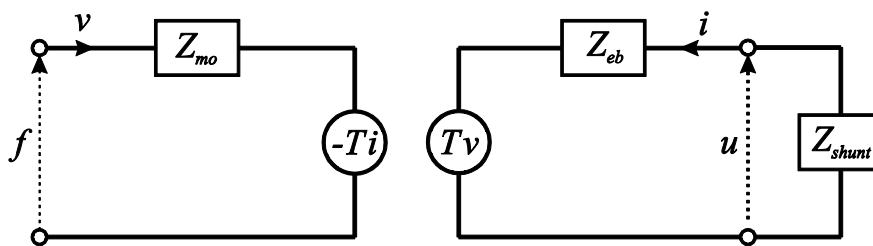


Figure 4: Block diagram of an electromagnetic transducer with a shunt impedance, Z_{shunt} , across its electrical terminals.

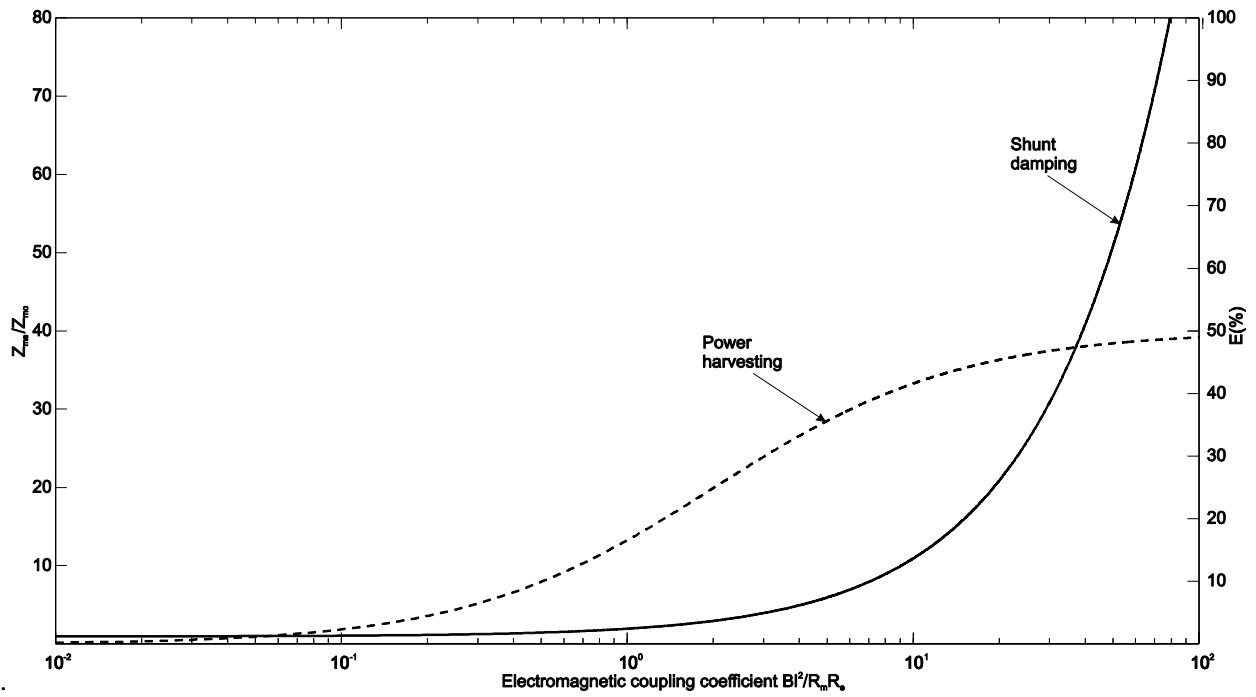


Figure 5: variation of the ratio of the electromagnetic transducer's mechanical impedance when short circuit and open circuit, Z_{ms}/Z_{mo} (solid line) as function of the electromechanical coupling coefficient $C_{me} = (Bl)^2/R_m R_e$, and the corresponding variation of the efficiency of the transducer as an energy harvester E , given by the ratio of the electrical power harvested to the mechanical power supplied

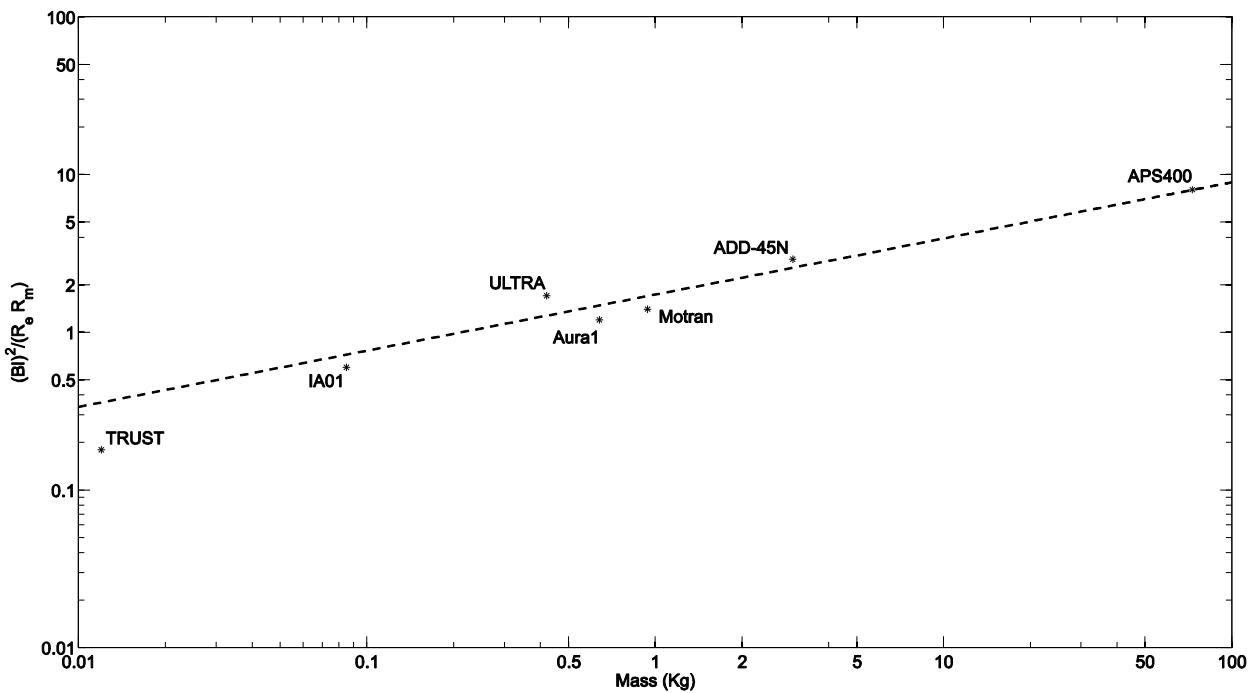


Figure 6: The log of the non-dimensional electromagnetic coupling coefficient, $(Bl)^2/R_e R_m$, for different transducers, plotted as a function of the log of their mass. The best linear fit to this data is shown as the dashed line, which suggests that $(Bl)^2/R_e R_m$ scales as mass to the power of about 0.35.

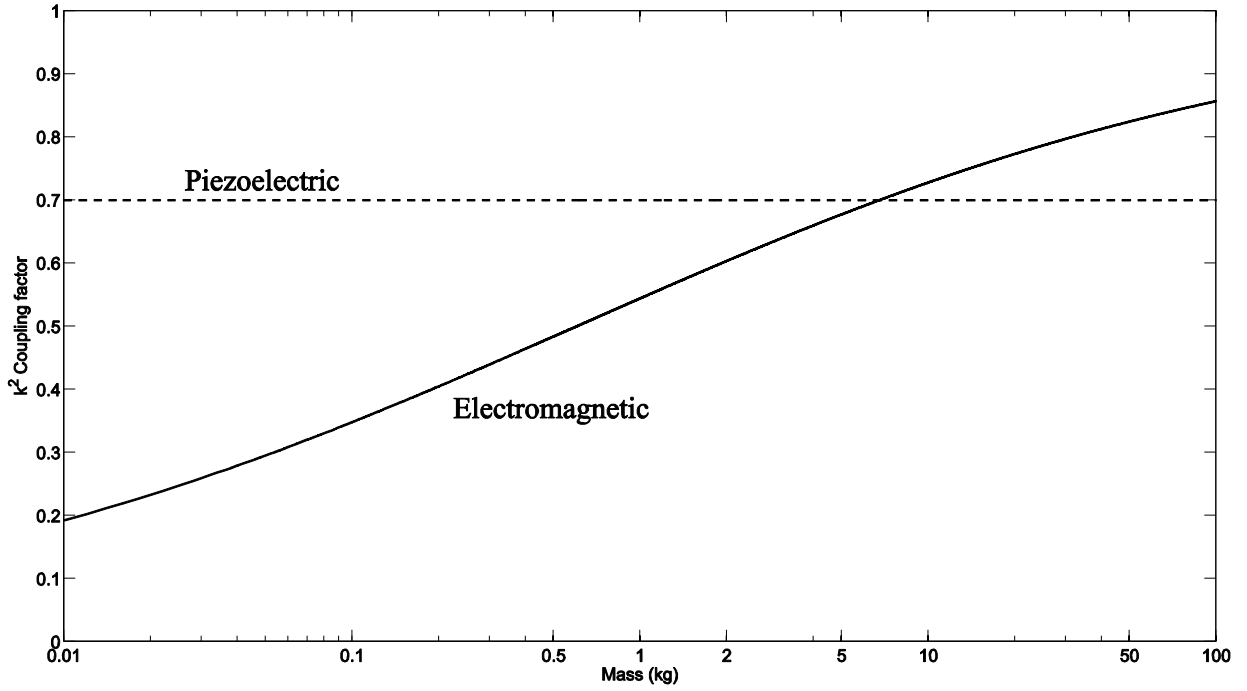


Figure 7: The effective electromechanical coupling factor as a function of the actuator mass for both electromagnetic transducers, using equation (25) and for piezoelectric transducers, assuming a PZT device.

TABLES

Table 1: Parameters of an example electromagnetic actuator, mostly taken from the datasheets for the Micromega Dynamics ADD-45N device

Moving mass (M)	2.2 kg
Suspension Stiffness (K)	6130 Nm^{-1}
Suspension damping ratio (ζ)	0.15
Suspension mechanical resistance (R_m)	35 Nsm^{-1}
Electrical resistance (R_e)	4 Ω
Electrical inductance (L_e)	0.6 mH
Force constant (Bl)	20 NA^{-1}
Total mass	3 Kg
Peak force	45 N
Resonant frequency ($\omega_n/2\pi$)	8.4 Hz

Table 2: The parameters of a number of electromagnetic inertial actuators

Type	Bl (NA ⁻¹)	R_e (Ω)	R_m (Nsm ⁻¹)	$(Bl)^2/R_eR_m$	Total mass (kg)
APS 400	37	3.0	53	8.0	73
Micromega (ADD-45N)	20	4	35	2.9	3
Motran (IFY 30-100)	10	1.6	44	1.4	0.94
Aura	7	4.4	9	1.2	0.64
Ultra	7.1	3.2	9.4	1.7	0.42
Micromega (IA-01)	1.6	3.0	1.4	0.6	0.085
TRUST headphone actuator	0.74	8	0.38	0.18	0.012