Smart Structures and Systems, *Vol. 11, No. 6 (2013) 605-621*
DOI: http://dx.doi.org/10.12989/sss.2013.11.6.605

A full-range hybrid device for sound reproduction

Francesco Braghin, Francesco Castelli-Dezza, Simone Cinquemani* and Ferruccio Resta

Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 1, Milan, 20156, Italy

(Received June 6, 2012, Revised August 15, 2012, Accepted November 29, 2012)

Abstract. The paper deals with the design of a device for sound reproduction to be fixed to a supporting surface. The device is made up of two different types of acoustic actuators based on different technologies. This allows to reproduce sound in the range of frequencies from 20 Hz to 20 kHz. The generation of sound at high frequencies is demanded to a magnetostrictive actuator, while a more traditional magnetodynamics actuator is used to generate sound at low frequencies. The coupling between these two actuators leads to a device having small overall dimensions and high performance.

Keywords: acoustic actuator; magnetostrictive actuator; magnetodynamics actuator; sound reproduction; loudspeaker

1. Introduction

The quality of sound and the aesthetics of sound reproduction devices play a fundamental role in the customer's satisfaction. The possibility of completely hiding these sound reproduction devices into the furniture or behind walls is also considered very attractive. The drawback, at present, is that usually this solution shows up bad sound quality. For this reason, no high end invisible sound loudspeaker are available on the market. Recently, inertial proof mass actuators have been tested for sound reproduction (Lin and Meydan 2006, Zhou *et al*. 2008) and noise suppression (Gardonio and Diaz 2010, Diaz *et al*. 2008).

These devices consist of a mass suspended on a spring-damper element and driven by an external force. This force has the same time history of the audio signal to be reproduced. The inertia force generated by the proof mass is transmitted to the surface to which the actuator is fixed, thus setting the whole surface into vibration. In this way, the emitted pressure wave is planar and the sound is more uniform. Naturally, the quality of the sound strictly depends on the kind of surface. From a mechanical point of view, inertial actuators can be considered as ideal force generator above their resonance frequency. Below this frequency, regardless of the type of technology used to actuate the device (magnetodynamic, magnetostrictive, piezoelectric, etc.), the transmitted force is very low. However, considering the electromagnetic behavior of the system, as the imposed voltage is constant, the current decreases with the frequency, as the impedance grows (Fig. 1). This leads to a reduction of the transmitted force and to the impossibility of generating

*Corresponding author, Dr., E-mail : simone.cinquemani@polimi.it

http://www.techno-press.org/?journal=sss&subpage=8 ISSN: 1738-1584 (Print), 1738-1991 (Online)

sound. In practice it happens that an inertial actuator is usable in a band-limited of frequencies that is not able to fully cover the range of frequencies typical of hearing.

For this reason, multiple actuators are generally used (Cibelli *et al*. 2011).

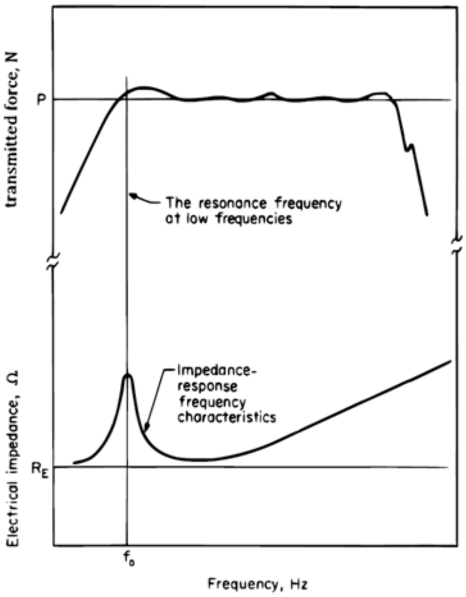

Fig. 1 Operating range of frequencies

Among the acoustic proof mass actuators, the most common are magnetostrictive, i.e., actuators that use magnetostrictive element to drive the proof mass and magnetodynamics, i.e., actuators that can generate a force exploiting the interaction between a constant and a variable magnetic fields (Benson 1988). The former are based on the giant magnetostrictive effect that is the property of certain materials called magnetostrictive materials (Clark *et al*. 1984, Huang *et al*. 2007, Dapino 2002), to change their size when subjected to a magnetic field (Engdahl 2000, Pons 2005, Dapino *et al*. 2000, Braghin *et al*. 2010, 2013).

Such actuators provide good to excellent sound quality in the medium-high frequency range (Braghin *et al*. 2011). In medium-low frequency range, instead, such actuators are not able to generate enough force, thus requiring the use of different actuators (to overcome the limitations in the frequency range, considerable technical complications (Pons 2005, Bartlet *et al*. 2001, 2012) are required).

Magnetodynamic acoustic actuators are generally optimized to provide the best sound quality in the medium-low frequencies range (Benson 1988, Rashedin *et al*. 2006). The actuation force is generated by the interaction between a constant magnetic field, generally generated by a permanent magnet, and a variable one generated by a variable current flowing in a coil fixed to the supporting structure. This force drives the proof mass, typically the permanent magnet.

The simple coupling of a magnetostrictive and a magnetodynamic acoustic actuator does not guarantee a good sound quality in the audible frequency range. In fact their frequency ranges are usually overlapped thus leading to sound distortion that can be only partially connected using a cross-over filter (Cibelli *et al*. 2011).

This paper presents a hybrid actuator consisting of two stages in series (magnetostrictive to reproduce the higher frequencies and magnetodynamic to reproduce the mid-low frequencies) that allows good sound quality throughout the audible frequency range. The advantages of this solution are the small dimensions, the simple installation and the fact that the cross-over filter is mechanically obtained thus avoiding the overlap of frequency ranges. Finally the generated sound wave is more uniform, thus guaranteeing higher sound performances, since the two actuators force the structure in the same point. The device has been patented (Resta *et al*. 2012) because of its innovative character.

The paper is structured as follows: section 3 presents the mechanical model of the acoustic actuator and the achievable theoretical performance in terms of force that can be transmitted to the supporting surface; section 4 illustrates the design of the system and its correct sizing to reach the desired performances. Section 5 reports experimental results obtained by testing the device. Finally, conclusions are drawn in section 6.

2. Mechanical model of the device

The hybrid acoustic device is made up of two stages and can therefore be profitably modeled as a 2 d.o.f. system, as depicted in Fig. 2, where:

m_1 is the moving mass of the high frequency stage;
k_1 is the total stiffness of the elements supporting mass m_1;
r_1 is the equivalent viscous damping of the high frequency stage;
m_2 is the moving mass of the low frequency stage;
k_2 is the total stiffness of the elements supporting mass m_2;
r_2 is the equivalent viscous damping of the low frequency stage;
F_{mag} is the force exerted by the magnetostrictive element;
F_{el} is the electromagnetic force applied to both masses m_1 and m_2;
x_1 is the displacement of the mass m_1;
x_2 is the displacement of the mass m_2.

Considering the scheme shown in Fig. 2, the lower stage is designed to generate high frequency vibrations. It consists of a mass m_1 suspended on a bar of magnetostrictive material, that has a total stiffness equal to k_1, and that can deform as a result of a variation of the magnetic field passing through it. The deformation of the magnetostrictive bar generates a force F_{mag}, that acts both on the mass m_1 and on the support of the actuator (internal force).

On the other hand, the upper stage is designed to generate vibrations at mid-low frequencies. It consists of a mass m_2 suspended on deformable elements having overall stiffness equal to k_2. The mass m_2 is driven by the force F_{el} that is generated by the interaction between a constant and a variable magnetic fields. Note that the same force F_{el} also acts on mass m_1 (internal force).

The force generated by the deformation of the magnetostrictive material F_{mag} is a function of the current flowing in the coil surrounding the magnetostrictive bar itself. This force is equal to (Braghin *et al*. 2011)

$$F_{mag} \approx \frac{ndA}{s^H}\frac{I_1}{\delta L} = C_{mag} I_1 \tag{1}$$

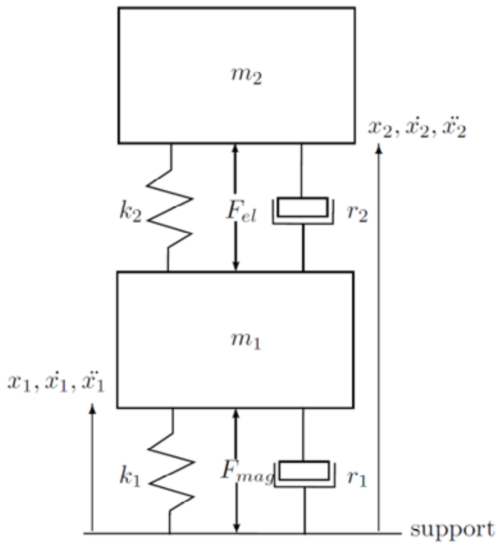

Fig. 2 Lumped parameter mechanical model

being I_1 the supplied current. The coefficient C_{mag} depends on the number of windings surrounding the magnetostrictive bar n, on the linear piezomagnetic cross-coupling coefficient and on the mechanical compliance at constant applied magnetic-field strength H of the magnetostrictive material (d and s^H), on the cross-section area and on the length of the bar (A and L) and on the length of the magnetic field lines ($dL \approx 2L$)

$$C_{mag} = \frac{ndA}{s^H \delta L}$$

The force F_{el} is generated by the interaction between the variation of a magnetic field, associated to a variation of current in the coil, connected to mass m_1, and a constant magnetic field, fixed with respect to mass m_2. This force is directly proportional to the current I_2 flowing in the windings

$$F_{el} = C_{el} I_2$$

where

$$C_{el} = Bl$$

is the power factor describing the state of magnetization of the system, being B the flux density and l the total length of the coil. Note that, since the currents flowing into the two coils are independent, forces F_{el} and F_{mag} are independent too.

2.1 Equation of motion

Two differential equations of the two masses can be written in terms of absolute displacements. Vector $\underline{x}$ is defined as

$$\underline{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

where x_1, x_2 are the displacement of the mass m_1 and m_2 respectively. The equations of motion of the system are

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \underline{\ddot{x}} + \begin{bmatrix} r_1 + r_2 & -r_2 \\ -r_2 & r_2 \end{bmatrix} \underline{\dot{x}} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \underline{x} = \begin{bmatrix} C_{mag} \\ 0 \end{bmatrix} I_1 + \begin{bmatrix} -C_{el} \\ C_{el} \end{bmatrix} I_2$$

In the Laplace domain, they can be written as

$$\begin{bmatrix} m_1 s^2 + (r_1 + r_2)s + (k_1 + k_2) & -r_2 s - k_2 \\ -r_2 s - k_2 & m_2 s^2 + r_2 s + k_2 \end{bmatrix} \underline{X}(s) = \begin{bmatrix} C_{mag} \\ 0 \end{bmatrix} I_1(s) + \begin{bmatrix} -C_{el} \\ C_{el} \end{bmatrix} I_2(s)$$

2.2 Force transmitted to the support

Since it is impossible to describe the characteristics of the actuator from an acoustic point of view, as they depend on the type of surface that is set in vibration, the only parameter that can uniquely describe the performance of the actuator is the force that it is able to transmit to the support.

The relationship between the force transmitted to the support F_T and the currents I_1, I_2 flowing into the two coils can be obtained applying the principle of superposition, thus supposing the transmitted force is the consequence of the effects of the two stages alternatively:

$$F_T(s) = F_{T1}(s) + F_{T2}(s) = G_1(s) I_1 + G_2(s) I_2$$

where

$$G_1(s) = \frac{F_{T1}(s)}{I_1(s)}$$

$$G_2(s) = \frac{F_{T2}(s)}{I_2(s)}$$

Consider to power only the magnetostrictive actuator (I_2=0), the transmitted force F_{T1} is

$$F_{T1}(s) = F_{mag}(s) - r_1 s X_1(s) - k_1 X_1(s)$$
$$F_{T1}(s) = C_{mag} I_1(s) - (r_1 s + k_1) X_1(s)$$

where $X_1(s)$ can be reached from Eq. (7) imposing I_2=0

$$X_1(s) = \frac{det\begin{bmatrix} C_{mag}I_1(s) & -r_2s-k_2 \\ 0 & m_2s^2+r_2s+k_2 \end{bmatrix}}{det\begin{bmatrix} m_1s^2+(r_1+r_2)s+(k_1+k_2) & -r_2s-k_2 \\ -r_2s-k_2 & m_2s^2+r_2s+k_2 \end{bmatrix}}$$

The force transmitted to the support F_{T2}, when only the magnetodynamic is powered (I_1=0), is

$$F_{T2}(s) = -r_1sX_1(s) - k_1X_1(s)$$
$$F_{T2}(s) = -(r_1s+k_1)X_1(s)$$

where $X_1(s)$ can be reached from Eq. (7) imposing I_1=0

$$X_1(s) = \frac{det\begin{bmatrix} -C_{el}I_2(s) & -r_2s-k_2 \\ C_{el}I_2(s) & m_2s^2+r_2s+k_2 \end{bmatrix}}{det\begin{bmatrix} m_1s^2+(r_1+r_2)s+(k_1+k_2) & -r_2s-k_2 \\ -r_2s-k_2 & m_2s^2+r_2s+k_2 \end{bmatrix}}$$

From Eqs. (9)-(13) one can gets

$$G_1(s) = \frac{C_{mag}[m_1m_2s^4+(m_1r_2+m_2r_2)s^3+(m_1k_2+m_2k_2+r_2^2)s^2+2r_2k_2+k_2^2]}{\Delta(s)}$$

$$G_2(s) = \frac{C_{el}[m_2r_1s^4+m_2k_1s^3]}{\Delta(s)}$$

where

$$\Delta(s) = det\begin{bmatrix} m_1s^2+(r_1+r_2)s+(k_1+k_2) & -r_2s-k_2 \\ -r_2s-k_2 & m_2s^2+r_2s+k_2 \end{bmatrix}$$

The main mechanical parameters affecting the dynamics of the actuator are m_1, k_1, m_2, k_2. Figs. 3-6 show the theoretical transfer functions G_1 and G_2 obtained by varying these parameters. The mechanical coupling, designed to connect the two stages, allows each actuator to force the supporting surface in the desired frequency range.

Fig. 3 shows the transfer functions G_1 and G_2 obtained by varying the mass m_1. The increase of the mass m_1 cuts down the second peak reducing the range of operation of the low frequency stadium and increasing the range of the magnetostrictive actuator. The stiffness k_1 is equal to

$$k_1 = \frac{A}{s^H L}$$

where A is the cross section area of the magnetostrictive bar, sH=$3.3\cdot10^{-11}$ m^2/N is the material compliance and L its total length. Considering a bar of Terfenol-*D* with a square cross section area A=9 mm^2, then k_1 only depends on the length of the magnetostrictive rod. The transfer function G_1 and G_2 can therefore be displayed as a function of L instead of k_1 (Fig. 4).

The increase of the suspended mass m_2 leads to a shift of the first resonance peak to lower frequencies (Fig. 5). Similarly, the chance of the overall stiffness k_2 mainly affects the operating frequency range of the electromagnetic actuator (Fig. 6) an increase in stiffness reduces the bandwidth of the hybrid device. To have a uniform sound in the desired frequency range, it is very important to have the amplitude of the transfer function G_1 (magnetostrictive) in mid-high frequency very close to the magnitude of G_2 (magnetodynamic) in the mid-low frequency range.

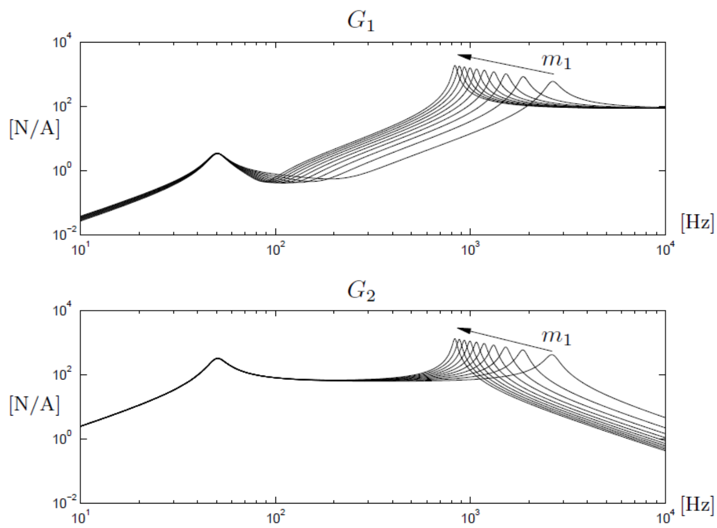

Fig. 3 Transfer functions G_1 and G_2 obtained by varying the suspended mass m_1

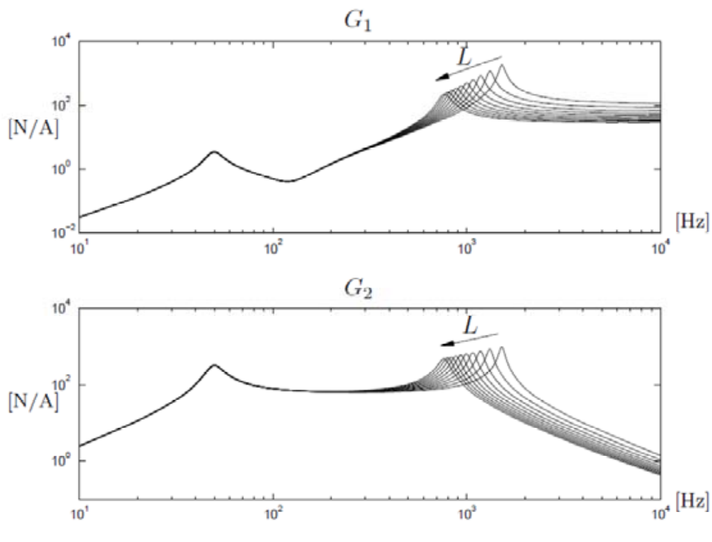

Fig. 4 Transfer functions G_1 and G_2 obtained by varying the length L of the magnetostrictive rod

Regardless of the design parameters values, it can be noted as the type connection between the two actuators ensures a mechanical crossover filter. Indeed, the force transmitted from the magnetodynamic actuator is significant only at low frequencies, especially between the first and second eigenfrequencies of the device. Otherwise, the magnetostrictive actuator can transmit forces only at frequencies higher than the second eigenfrequency of the system. This behavior is positive since it avoids the frequency ranges overlap.

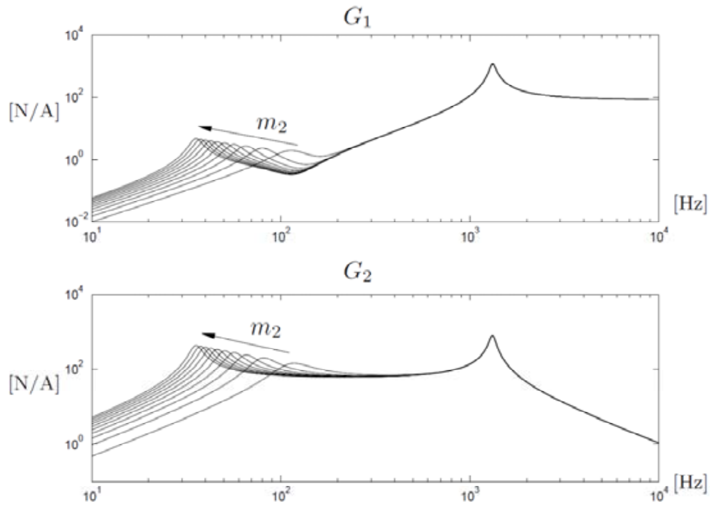

Fig. 5 Transfer functions G_1 and G_2 obtained by varying the suspended mass m_2

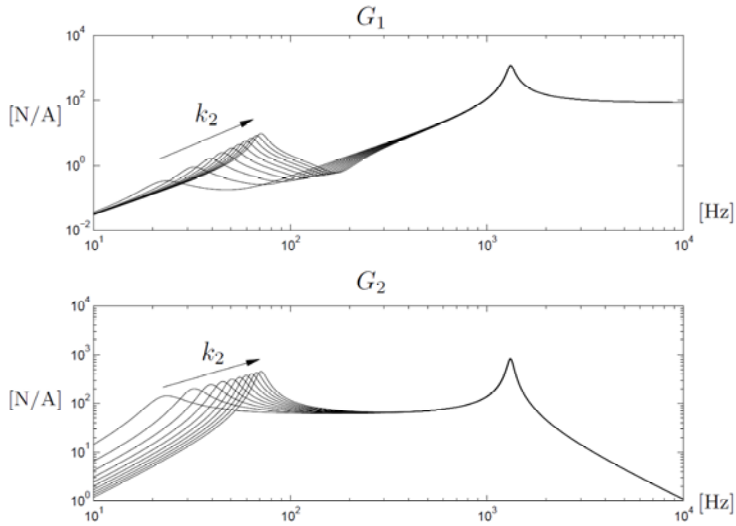

Fig. 6 Transfer functions G_1 and G_2 obtained by varying the stiffness k_2

3. Design and sizing

The 3D model of the hybrid device is shown in Fig. 7. It couples a magnetostrictive and a magnetodynamic actuator all coaxial with respect to the main axis *X*. The lower part is designed to house the electronic board necessary for the amplification of the signals sent to the windings of the two stages.

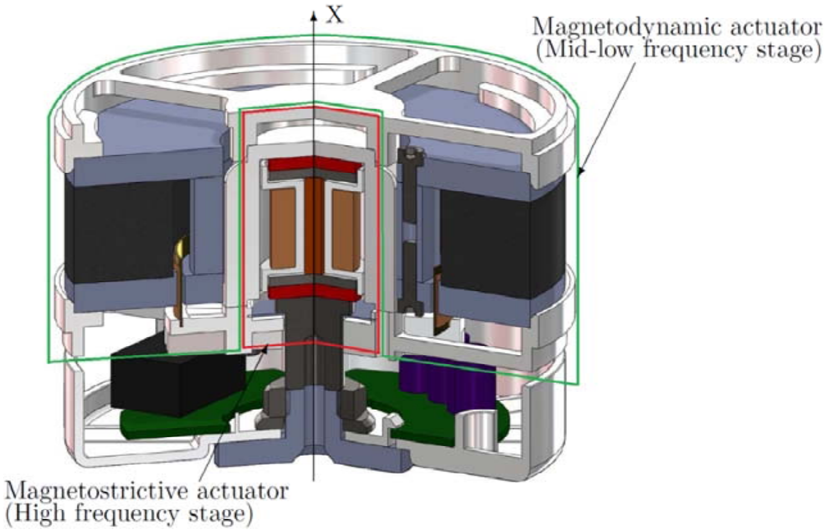

Fig. 7 Section of the 3D model of the hybrid device

3.1 High frequency stage

As already said, the stage designed to reproduce the high frequency content of the input signal is based on the properties of magnetostrictive materials. Fig. 8 shows a section of the 3D model of the high frequency stage of the actuator, while Fig.9 recalls the mechanical model of the device highlighting the high frequency stage. The actuator consists of a giant magnetostrictive rod, made of Terfenol-D, surrounded by a coil and subjected to a constant magnetic field generated by permanent neodymium iron boron magnets placed at the ends of the bar. When the supplied current flows through the coil, the variation of the magnetic field that passes through the magnetostrictive material produces a change in the magnetic field opposing this variation. This leads to the subsequent alignment of the magnetic domains of the material and thus to the elongation/contraction of the magnetostrictive rod that is associated to the generation of a high force.

The magnetostrictive rod is preloaded by a mechanical spring due to the fact that the tensile strength of the material is limited (≈28 MPa) and the efficiency and coupling factors are considerably higher under compression. Normally the elastic element has a low stiffness compared with the magnetostrictive bar. Since the magnetostrictive rod and the elastic element are in parallel, the preloading mechanism does not appreciably affect the total stiffness. Table 1 shows main parameters of the designed device.

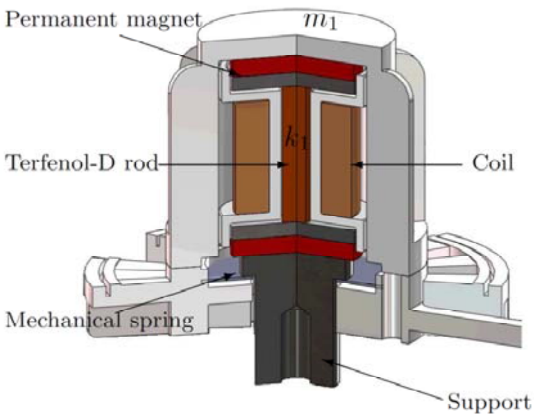

Fig. 8 3D model

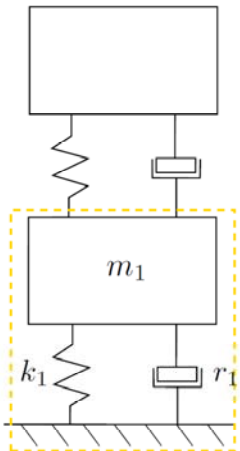

Fig. 9 Mechanical model

Table 1 Main features of the magnetostrictive actuator

Suspended mass (m_1)	300 g
Magnetostrictive material	Terfenol-D
Rod length (L)	20 mm
Rod stiffness (k_1)	$1.36 \cdot 10^7$ N/m
Number of windings	400

3.2 Mid-low frequency stage

The mid-low frequency stage uses a more traditional technology based on the interaction between a constant magnetic field, generated by permanent magnets, and a variable magnetic field, resulting from a current flowing in a coil. Fig. 10 shows a section of the 3D model of the mid-low frequency stage of the actuator, while Fig.11 recalls the mechanical model of the device. The mass m_2 is formed by a toroidal element that surrounds the magnetostrictive actuator and is suspended with respect to the high frequency stage through beams with an overall stiffness equal to k_2. The sizing of these elements has been done through a finite element analysis software Abaqus. The design parameters considered were the number of flexible elements, their shape and their cross-section area.

The mass m_2 consists of a toroidal permanent magnet, made of ferrite and of ring elements, made of ferromagnetic material. Parts are arranged in order to create an air gap in which the coil, powering the stage, can be placed. Windings are supported by a structure that is fixed to the high frequency stage. When the coil is powered, the interaction between the varying magnetic field and the constant one, generates a force F_{el} that acts on both masses m_2 and m_1.

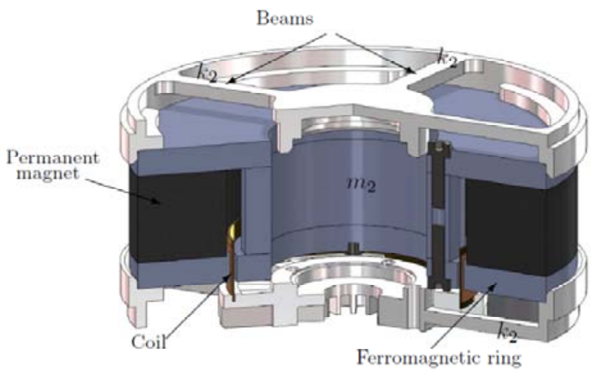

Fig. 10 3D model

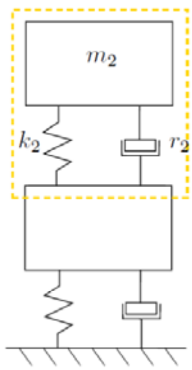

Fig.11 Mechanical model

To assess the state of magnetization of the system, a finite element analysis was carried out. Fig. 12 shows the magnetic field lines in a section of the prototype obtained from the simulation. Note how the field lines cross the air gap where the coil is placed thus ensuring a sufficient magnetic flux density (estimated equal to 0.8 T). The analysis also shows the magnetic field generated in the internal part of the device where the magnetostrictive element is placed. It completely crosses the bar of magnetostrictive material, thus ensuring a proper operation of the device. Table 2 shows the main features of the mid-low frequency range.

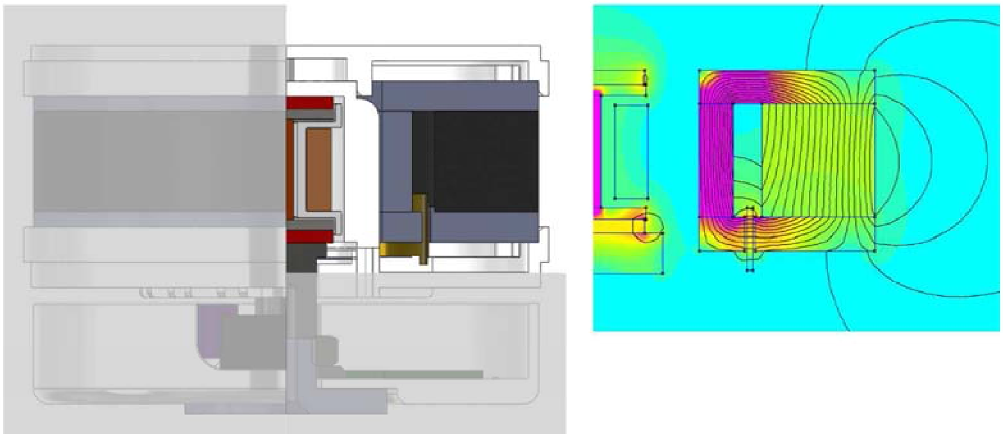

Fig. 12 Finite element analysis of magnetic field

Table 2 Main features of the low frequency voice coil

Wire diameter	0.3 mm
Overall length of the voice coil wire	10.5 m
Height of the voice coil	10.04 mm
Number of windings	60
Number of windings layers	2
Voice coil resistance	2.62 W

4. Experimental tests

Fig. 13 shows the prototype of the hybrid two stages acoustic actuator. The device is 71 mm height and has an external diameter of 102 mm. The test-bench used to test the device is shown in Fig. 14. The actuator is mounted on a small plate connected to a load cell fixed to the ground. This configuration coincides with the operating one. The actuator is driven by supplying currents (I_1 and I_2) at different operating frequencies. Currents I_1 and I_2 are independent. Their amplitudes is 1 A and the frequency varies from 20 Hz to 20 kHz. During the tests, voltages (V_1 and V_2) and supplied current (I_1 and I_2) are acquired as well as the accelerations of the two masses ($\ddot{x}_1$ and $\ddot{x}_2$) via uniaxial current (I_1 and I_2) piezoelectric accelerometers. The force transmitted to the ground (F_T) is also acquired through the installed load cell.

Fig. 13 First prototype

Fig.14 Experimental setup

The experimental transfer functions between the supplied current (I_1 and I_2) and the transmitted force (F_T) are obtained for the actuator under test. Fig.15 shows the calculated theoretical transfer functions, while Fig. 16 shows the experimental ones. Experimental transfer function G_2 can be plotted only for frequencies lower than 10 kHz. After this value the transmitted force is too small to be measured.

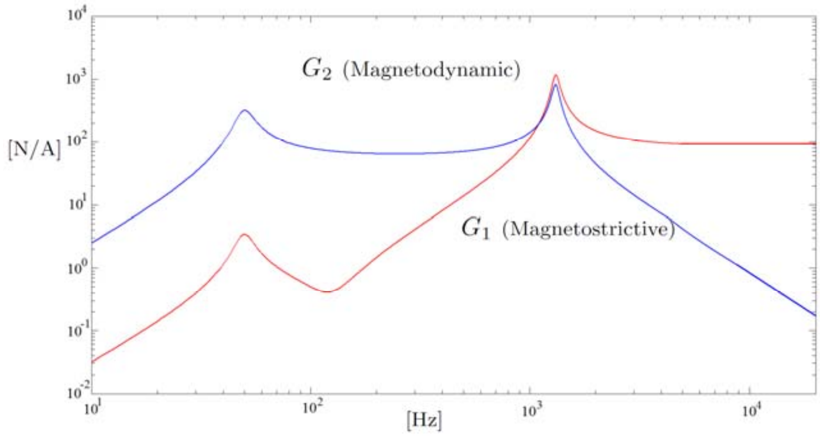

Fig. 15 Theoretical transfer functions G_1, G_2 for the prototype under test

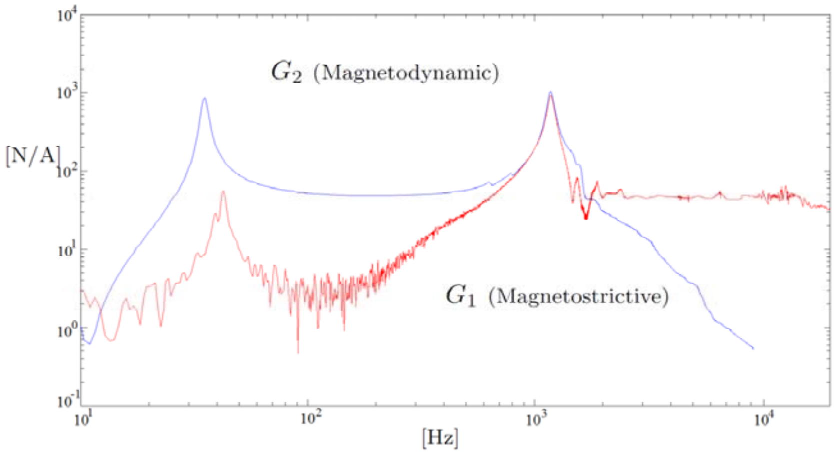

Fig. 16 Experimental transfer functions G_1, G_2 for the prototype under test

Comparing the two graphs it is observed that the dynamic behaviour of the actuator is substantially well described by the numerical model proposed. Obviously, since the actuator under test is a prototype, the realization of the parts used and their assembly impose limits on the device performance. The sound quality is guaranteed by a substantial linearity of the device in the frequency range of audible. The dynamic behaviour of this device allows to obtain mechanically the effects of a crossover filter and ensures that each actuator works properly in the range of frequencies for which it has been designed. The magnetodynamic acoustic actuator covers a range

of frequencies between 40 Hz-1000 Hz, thought its effect can be heard from 20 Hz to approx. 1200 Hz. On the other hand, the magnetostrictive actuators is effective at frequencies above the second eigenfrequency. The result is a device that can reproduce an audio signal in the range of frequency between 20 Hz to 20 kHz. Obviously, since an acoustic actuator based on proof-mass device works exciting the surface on which it is bound, the quality of the sound strictly depends on the kind of surface used and the point of application on the surface. This limit is not to be construed as the need to redesign the actuator each time it is applied on a different surface, but as the fact that the choice of the surface (and the point of application on the surface) is a parameter which significantly affects the acoustic performance.

Thickness	5-10mm	10-15mm	15-20mm	20-25mm	25-30mm	30-40mm	40-50mm
Plasterboard	YES	YES	YES	YES	YES	YES	YES
Wood	YES	YES	YES	YES	YES	YES	YES
Plywood	YES	YES	YES	YES	YES	YES	YES
Wood veneered	YES	YES	YES	YES	YES	YES	YES
Wood particle board	YES	YES	YES	YES	YES	YES	YES
Fiberglass	YES	YES	YES	YES	YES	YES	YES
Carbon fiber	YES	YES	YES	YES	YES	NO	NO
MDF	YES	YES	YES	YES	YES	NO	NO
Glass	YES	YES	YES	YES	YES	NO	NO
Plexiglass	YES	YES	YES	YES	NO	NO	NO
Aluminium	YES	YES	YES	NO	NO	NO	NO
Polystyrene	YES	YES	NO	NO	NO	NO	NO
Iron	YES	NO	NO	NO	NO	NO	NO
Steel	YES	NO	NO	NO	NO	NO	NO
Corck	NO	NO	NO	NO	NO	NO	NO
Concrete	NO	NO	NO	NO	NO	NO	NO
Marble	NO	NO	NO	NO	NO	NO	NO

Fig. 17 Experimental transfer functions G_1, G_2 for the prototype under test

5. Conclusions

A new hybrid device for sound reproduction with coaxial magnetostrictive and magnetodynamic actuators has been presented: the magnetostrictive one is responsible for the generation of sound at high frequencies, while the magnetodynamic is devoted to the generation of mid-low frequencies thus exploiting the best characteristics of both actuators in the whole audible frequency range. The mechanical model of the new acoustic device has been presented and the influence of design parameters on the performance of the actuator assessed. The particular configuration used to connect the two stages of the device ensures high performance in terms of force transmitted to the supporting structure, and thus high sound efficiency. A prototype of the hybrid device has been produced and tested showing the good expected performances.

Effects of surface

As discussed in the introduction, the quality of sound strictly depends on the kind of surface used to support the acoustic actuator. This limit, proper of all the acoustic actuators based on proof-mass devices, has not to be construed as the need to redesign the actuator each time it is applied on a different surface. On the contrary, it must be considered as the need to choose the right surface (and the right point of application on the surface) as this parameter affects significantly the acoustic performance.

Table depicted in Fig. 17 gives a qualitative overview of surfaces suitable for sound reproduction as a function of their thickness.

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