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Short Communication

Broadband acoustic transducer driven by magnetostrictive composite rod and electrostrictive stack

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Abstract

An acoustic transducer consisting of a magnetostrictive Terfenol-D composite and electrostrictive PMN-PT stack connected in mechanical series is presented. A broadband velocity response is possible in this transducer when the two sections are connected in electrical parallel. A linearly coupled electromechanical model is formulated through mechanical vibrations, classical electroacoustics, and linear piezoelectricity and piezomagnetism. The linear model is used to analytically calculate the head mass velocity of the transducer in response to white noise voltage excitation. The analytical solutions are shown to correlate well with measurements, while providing a framework for calculation of material properties under the same dynamic conditions found during operation, as opposed to quasistatic conditions.

1. Introduction

Downey and Dapino [1] demonstrated broadband response over the range 500 Hz–6 kHz from a hybrid transducer consisting of a mechanical series arrangement of a Terfenol-D section and a PMN-PT section (Fig. 1). This hybrid concept was originally developed by Butler and Clark [2] for achieving large front-to-back velocity ratios and electrical tuning, and later incorporated into a broadband 4×4 element array by Butler and Tito [3]. The transducer produces broadband head velocity response when the tail, center, and head masses have the ratio 2.5 : 2 : 1 and the two sections are connected in electrical parallel. Under these conditions, the intrinsic ninety degree phase shift between the magnetostrictive and piezoelectric velocities causes a significant response at the location between the resonance peaks where high attenuation would exist in a passive 2-dof resonator. Ignoring the zero-frequency translational mode, the transducer exhibits a double resonant frequency response with the lower frequency controlled by the Terfenol-D rod and the upper frequency controlled by the stiffer PMN-PT single crystal.

To achieve cancellation of motion at one end and maximization of motion at the other end, a mass ratio of 1 : 2 : 1 is necessary [4]. In that case, the phase difference between the magnetostrictive and piezoelectric velocities is combined with an additional ninety degree phase shift due to time delays in the transducer drivers [5]. A variant of this concept has been employed by Butler et al. [6] to increase the effective coupling coefficient

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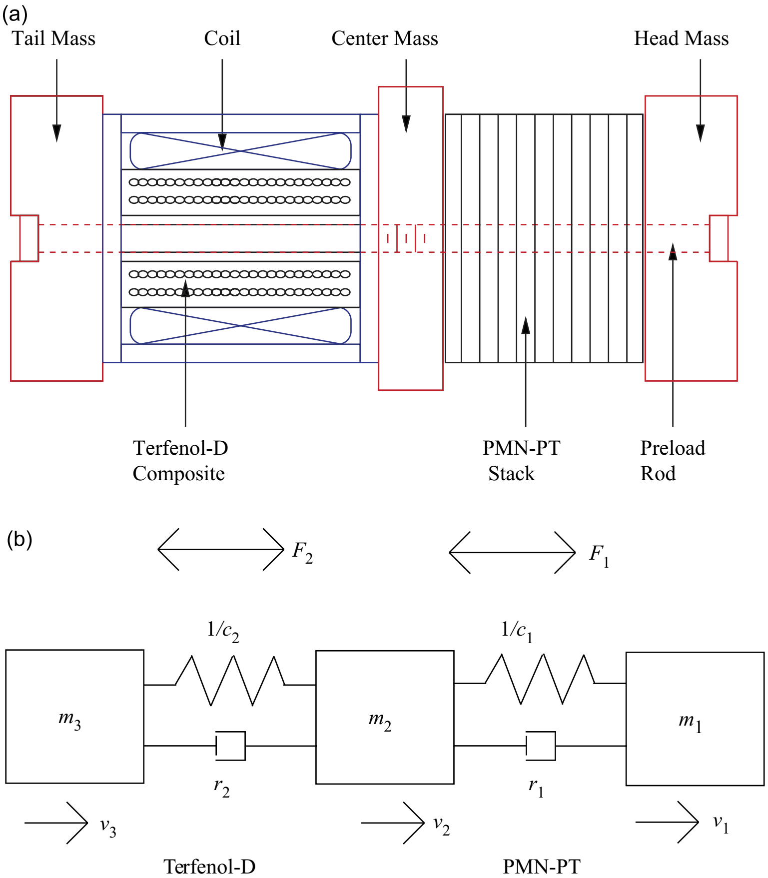

Fig. 1. (a) Tonpilz-type hybrid ferroelectric/ferromagnetic transducer; (b) lumped-parameter vibratory model representing the hybrid transducer.

(ratio of mechanical energy stored to electrical energy supplied) relative to that of the individual drivers. A self-tuning Terfenol-D/PZT-4 transducer was shown to have an effective coupling coefficient 25% greater than that of a conventional Tonpilz type transducer [7].

A coupled electromechanical model was formulated [1] which combines linear mechanical vibrations, classical electroacoustics, and linear piezoelectricity and piezomagnetism. Use of this linear model for control applications is justified because doped PMN-PT crystals exhibit linear electrostriction when driven with a suitable bias electric field, even at large ac inputs, and Terfenol-D is quasilinear when magnetically biased. The model also permits extraction of material properties from dynamic impedance measurements, i.e., under conditions similar to those found in operation. The model differs from that by Butler and Tito [3] in that the electromechanical transducer equations are expressed in terms of the applied voltage rather than force terms representing the actuation forces produced by the individual sections. This permits direct correlation of the model with physical transducer inputs.

Chief intent of this communication is to replace the monolithic rod used in Ref. [1] with a composite driver element consisting of Terfenol-D particles embedded in an epoxy vinyl ester resin. The composite shows enhanced dynamic response due to reduced eddy current losses and improved linearity due to reduced magnetic hysteresis, while being less costly to manufacture than monolithic material. Disadvantages of the composite relative to monolithic material, namely higher compliance, lower magnetostriction, and higher required magnetic field, can be mitigated through careful model-based design and control of the hybrid transducer. To that end, the electrical impedance and velocity response of the transducer are analytically quantified. Model results are compared with dynamic experimental measurements for purposes of model parameter identification and validation. Quasistatic measurements are used for determination of suitable bias points.

2. Analytical framework

The transducer's double resonant frequency response is described by the second and third modes of the 3-dof linear vibratory system of Fig. 1(b). Here, m represents mass, r is damping coefficient, c is mechanical compliance, v is velocity, and F is force produced by the active elements in response to magnetic or electric fields. The subscripts 1 and 2 on F, r, and c denote the PMN-PT and Terfenol-D sections, respectively. The subscripts 1, 2, and 3 on v and m denote the head, center, and tail masses, respectively. In the Laplace (s) domain, the mechanical impedances have the form

$$Z_{m,M} = \frac{F_2}{v_1} = \frac{As^4 + Bs^2 + C}{sc_2m_3(r_1c_1s + 1)}, \tag{1}$$

$$Z_{m,E} = \frac{F_1}{v_1} = \frac{As^4 + Bs^2 + C}{sc_1(m_2m_3c_2s^2 + (m_2 + m_3)(r_2c_2s + 1))}, \tag{2}$$

for the PMN-PT stack and Terfenol-D rod, respectively, where

$$A = m_1m_2m_3c_1c_2,$$

$$B = m_3(m_1 + m_2)c_2(r_1c_1s + 1) + m_1(m_2 + m_3)c_1(r_2c_2s + 1),$$

$$C = (r_1c_1s + 1)(r_2c_2s + 1)(m_1 + m_2 + m_3).$$

Largest frequency bandwidth is achieved using a head:center:tail mass ratio of approximately 1 : 2 : 2.5, and having the PMN-PT stack stiffness $1/c_1$ be much higher than that of the Terfenol-D composite rod, $1/c_2$. Using these mass values, the dynamic response can be approximated by two dominant modes, the third being a zero-frequency rigid translation. The PMN-PT section controls the upper resonance, in which the tail mass decouples from the system and the head and center masses vibrate in opposite direction. The Terfenol-D section controls the lower resonance, in which the head and center masses are lumped together and vibrate in the opposite direction of the tail mass.

To couple the vibratory model with the electrical regime, a two-port network representation is considered, yielding the relations [8]

$$V = Z_eI + T_{em}v, \tag{3}$$

$$F = T_{me}I + Z_mv. \tag{4}$$

Here, the force F and voltage V are effort variables while velocity v and current I are flow variables. Impedance parameter Z_e denotes the blocked electrical impedance obtained when the transducer is prevented to displace and Z_m denotes the mechanical impedance given by Eq. (1) or (2) depending on which transducer element is considered; T_{em} and T_{me} are transduction coefficients which describe the electromechanical transduction. Assuming an external load of mechanical impedance Z_L, Eq. (4) gives an expression for the head mass velocity,

$$v = \frac{-T_{me}I}{Z_m + Z_L}. \tag{5}$$

Substitution of this equation in Eq. (3) gives the total driving point electrical impedance

$$Z_{ee} = \frac{V}{I} = Z_e + \frac{-T_{em}T_{me}}{Z_m + Z_L}, \tag{6}$$

which is composed of a blocked component Z_e obtained when the transducer is prevented to displace and a motional component $Z_{mot} = -T_{em}T_{me}/(Z_m + Z_L)$ associated with the mechanical motion of the transducer and load.

To quantify the blocked impedance Z_e and complex transduction coefficients T_{em} and T_{me} in terms of measurable material properties, the electroacoustic equations (3)–(4) are combined with constitutive equations which describe the strain and polarization of the transducer drivers. Considering first the Terfenol-D section, the linear piezomagnetic constitutive relations along the axial rod direction have the form

$$\varepsilon = \frac{\sigma}{E_y^H} + qH, \tag{7}$$

$$B = q^* \sigma + \mu^\sigma H, \tag{8}$$

where ε is strain, σ is axial stress, H is magnetic field, B is magnetic flux density, μ^σ is permeability at constant stress, and $q = q^*$ is a symmetric magnetoelastic coupling coefficient. To convert these expressions into a form compatible with (3) and (4), the following electromechanical relations are employed:

$$H = nI, \tag{9}$$

$$\varepsilon = \frac{v}{\mathrm{j}\omega L_{e,2}}, \tag{10}$$

$$\sigma = \frac{F}{A_2}, \tag{11}$$

$$V = RI + \mathrm{j}\omega NBA_2, \tag{12}$$

where n is the turns ratio of the magnetic coil ($n = N/L_{e,2}$), $L_{e,2}$ is the length of the coil and composite rod, A_2 is the rod cross-sectional area and internal area of the coil, and R is the wire resistance. Thus, the total voltage drop is that of a dc resistance R in series with an electrical inductance. Substitution of these expressions into (7) and (8), and subsequent rearrangement yields [9]

$$V = [R + \mathrm{j}\omega\mu^\sigma(1 - k_{\text{eff}}^2)n^2 A_2 L_{e,2}]I + Nqk_m^M v, \tag{13}$$

$$F = -Nqk_m^M I + \frac{k_m^M}{\mathrm{j}\omega} v, \tag{14}$$

where k_{eff} is the effective coupling coefficient and k_m^M is the mechanical stiffness. Comparison of these equations with the general electroacoustic relations (3)–(4) gives

$$Z_{e,M} = R + \mathrm{j}\omega\mu^\sigma(1 - k_{\text{eff}}^2)n^2 A_2 L_{e,2} = R + \mathrm{j}\omega L_{\text{block}}, \tag{15}$$

where L_{block} is defined as $\mu^\sigma(1 - k_{\text{eff}}^2)n^2 A_2 L_{e,2}$. Thus, the blocked electrical impedance $Z_{e,M}$ can be represented by an ideal resistor connected in series with an inductor. Expressions (13) and (14) also provide expressions for the transduction coefficients,

$$T_{em,M} = -T_{me,M} = Nqk_m^M, \tag{16}$$

which are equal in magnitude and opposite in sign as is expected of all magnetostrictive transducers because of the spatial orthogonality between current and magnetic field [8].

An analogous procedure for the PMN-PT stack is began by considering the linear piezoelectric constitutive relations, which in strain-charge form are given by

$$\varepsilon = \frac{\sigma}{E_y^E} + dE, \tag{17}$$

$$D = d^* \sigma + \epsilon^\sigma E, \tag{18}$$

where E denotes electric field, D is electric charge density, E_y^E is Young's modulus at constant field, ϵ^σ is electric permittivity at constant stress, and $d = d^*$ is a symmetric electroelastic coupling coefficient.

Relationships analogous to those derived for magnetostrictive materials have the form:

$$E = \frac{V}{t}, \tag{19}$$

$$\varepsilon = \frac{v}{\mathrm{j}\omega L_{e,1}}, \tag{20}$$

$$\sigma = \frac{F}{A_1}, \tag{21}$$

$$D = \frac{I}{\mathrm{j}\omega A_1}, \tag{22}$$

in which t and A_1 denote the thickness and cross-sectional area of each layer, respectively, and $L_{e,1}$ denotes the total stack length. Substitution of these expressions into (17) and (18), followed by suitable rearrangement yields

$$V = \frac{t}{A_1 \mathrm{j}\omega N(\epsilon^\sigma - E_y^E d^2)} I + \frac{-dE_y^E}{\mathrm{j}\omega N(\epsilon^\sigma - E_y^E d^2)} v, \tag{23}$$

$$F = \frac{-dE_y^E}{\mathrm{j}\omega N(\epsilon^\sigma - E_y^E d^2)} I + \frac{\epsilon^\sigma E_y^E A_1}{\mathrm{j}\omega N(\epsilon^\sigma - E_y^E d^2)} v. \tag{24}$$

Comparison of these relations with the general electroacoustic equations (3) and (4) indicates that the blocked electrical impedance of the PMN-PT stack is purely capacitive,

$$Z_{e,E} = \frac{t}{\mathrm{j}\omega A_1 N(\epsilon^\sigma - E_y^E d^2)} = \frac{1}{\mathrm{j}\omega C_{\text{block}}}, \tag{25}$$

where $C_{\text{block}} = A_1 N(\epsilon^\sigma - E_y^E d^2)/t$. The two coefficients that characterize the electromechanical transduction can be written from (23) and (24) as

$$T_{em,E} = T_{me,E} = \frac{-dE_y^E}{\mathrm{j}\omega N(\epsilon^\sigma - E_y^E d^2)}. \tag{26}$$

Consistent with the electrical nature of ferroelectric transduction [8], and in contrast with the Terfenol-D section, the coefficients are symmetric since they are identical in both magnitude and sign. It is noted that (14) and (24) provide expressions for the mechanical impedances which contain only linearly elastic contributions and do not account for dynamic effects such as inertia and damping. Due to this discrepancy, the more accurate forms $Z_{m,E}$ and $Z_{m,M}$ given by (1) and (2) are used instead.

Quantities of interest for design and control applications are the total electrical impedance and head mass velocity. To that end, it is first noted that since the PMN-PT and Terfenol-D sections are wired in electrical parallel, their total electrical admittances (including motional contributions) are added. Thus the transducer's total electrical impedance, incorporating electrical and mechanical effects in both active sections, is given by

$$Z_{ee,\text{total}} = \frac{Z_{ee,E} Z_{ee,M}}{Z_{ee,E} + Z_{ee,M}}, \tag{27}$$

in which $Z_{ee,M}$ is quantified by (6), (15), and (16), and $Z_{ee,E}$ by (6), (25), and (26). To quantify the head mass velocity first the current in each section is found from the definition of electrical impedance,

$$I_E = \frac{V}{Z_{ee,E}},$$

$$I_M = \frac{V}{Z_{ee,M}},$$

where the applied voltage is V for both sections. The velocity contribution from each section is then given by Eq. (5), which results in

$$v_E = \frac{-T_{me,E} I_E}{Z_{m,E} + Z_L},$$

$$v_M = \frac{-T_{me,M} I_M}{Z_{m,M} + Z_L}.$$

The final step in the velocity calculations is performed by recognizing that the mechanical series configuration allows for the superposition of the velocities from the two sections,

$$v = v_E + v_M. \tag{28}$$

This also allows for the comparison of the individual section responses by graphing just $Z_{ee,E}$ and v_E or $Z_{ee,M}$ and v_M. Each set assumes no electrical input and thus no excitation of the other section but does account for the coupling due to the attached mechanical components.

3. Experiments

The electrostrictive component of the transducer consists of an EDO Ceramic model EP200-62 EC-98 stack with composition lead magnesium niobate–lead titanate in a 65–35 ratio. This material exhibits high electrostriction and high linearity. The stack is composed of 62 individual layers for a total length of 35.2 mm and a diameter of 16 mm. A composite Terfenol-D rod 50.8 mm in length by 6.35 mm in diameter was fabricated by embedding ball-milled Terfenol-D particles 106–300 μm in diameter in a low viscosity epoxy vinyl ester resin. The epoxy, catalyst, and promoter were mixed first and the desired amount of Terfenol-D powder was added to the mixture. A volume fraction of 50% was used as it provides a compromise between high magnetostriction and ease of fabrication. No degassing of the slurry was done as this was found to carry little or no benefit while greatly complicating the preparation of the composite. To achieve high magnetostriction, the particles were magnetized during cure with an external magnetic field applied along the rod axis. A mold enclosed within a hollow Nd-Fe-B cylindrical magnet was used for this purpose. The chains of particles created by the field give an anisotropic (1–3) structure, as opposed to the isotropic (0–3) structure obtained when the particles are randomly aligned. To ensure homogeneity of the magnetic field throughout the specimen, and thus even particle distribution, a semi-continuous magnetic circuit was designed to balance the magnetic field. This was achieved by using steel end caps smaller than the magnet, thus creating a gap which increases the magnetic reluctance in the exact amount. The end caps are tapered to aid the magnetic flow while the gap between the steel parts and magnet prevents the ends of the mold from becoming magnetized in excess, thus pulling the particles toward the ends. The material was cured at 70 °C and atmospheric pressure for about 6 h to ensure complete reaction of the epoxy and catalyst, and subsequently machined to final dimensions. Further details on the mold construction and composite preparation can be found in Ref. [10].

Quasistatic strain and magnetization measurements as a function of magnetic field were performed on the Terfenol-D composite rod and PMN-PT stack to determine the linear strain coefficients (q and d) and constant-stress permeability and permittivity (μ^σ and ϵ^σ) [9]. These values are shown in Table 1. Static magnetic fields ranging between 27 kA/m and 40 kA/m were determined as optimal for centering the operation of the composite on the steepest region of the strain versus field curve for a 4 MPa load. For these measurements, the composite was tested in a materials characterization system consisting of a water-cooled transducer and axial loading fixture [10].

Dynamic electrical impedance measurements represented as Nyquist plots were obtained for each transducer section separately and for the complete transducer through white noise excitation over a frequency range from dc up to 20 kHz. Measurements on the complete transducer were conducted with each section driven independently and with both sections wired in parallel. Activation of the Terfenol-D composite is provided by a solenoid coil composed of 850 turns of 20 AWG magnet wire with a resistance of 2.3 Ω and

Table 1
Measured material and design parameters of the hybrid transducer

50% Terfenol-D composite	PMN-PT
$c_2 = 5.11 \times 10^{-8}$ m/N	$c_1 = 7.78 \times 10^{-8}$ m/N
$q = 2.71 \times 10^{-9}$ m/A	$d = 3.08 \times 10^{-10}$ m/V
$r_2 = 250$ N s/m	$r_1 = 200$ N s/m
$\mu^{\sigma} = 8.36 \times 10^{-6}$ H/m	$\epsilon^{\sigma} = 3.25 \times 10^{-8}$ F/m
$k_2 = 0.08$	$k_1 = 0.279$
$n = 2090$ turns/m	$N = 62$ layers
Dia. = 6.4 mm	Dia. = 16 mm
$L_{e,2} = 50.8$ mm	$L_{e,1} = 35.2$ mm
Prestress 4.0 MPa	Prestress 13.8 MPa
Head mass $m_1 = 308$ g, Dia. 76.2 mm, Thick. 26.2 mm	
Center mass $m_2 = 670$ g, Dia. 76.2 mm, Thick. 15.2 mm	
Tail mass $m_3 = 777$ g, Dia. 76.2 mm, Thick. 18.8 mm	

a field rating of 19.2 kA m^{-1}/A; magnetic induction data is obtained from an innermost single layer, 52-turn pickup coil.

Transducer parameters that were varied include mechanical preload, ac field and dc field. Measured quantities include head mass acceleration, which allows determination of velocity by integration, applied voltage, and current. The measurements were conducted with the transducer suspended by a string to prevent the surrounding structures from affecting its response. Procedures for identification of material properties from dynamic measurements described in Refs. [1,9] were used to determine coupling coefficient, mechanical stiffness, and internal damping of each driver element (see Table 1).

4. Results and discussion

Focusing on measurements conducted on the assembled transducer, the head mass velocity was first determined with only the Terfenol-D composite powered by a 5 kA/m ac field at varying dc fields of 8 to 48 kA/m, and the PMN-PT stack left as an open circuit. The response increases significantly up to a bias field of 32 kA/m and shows a minimal increase at higher dc fields, while there is a slight increase in the resonance frequency due to a dc magnetic field-induced stiffening of the composite [10]. With both sections powered, the overall response continues to increase over this range of bias fields while both resonance frequencies decrease slightly. The PMN-PT stack exhibits a larger response than the composite for the same applied ac voltage.

The unloaded head velocity measurements and model simulations shown in Fig. 2(a) were obtained with the electrostrictive section powered and the magnetic drive coil left as an open circuit. The measurements show a decrease in the resonance frequency of the Terfenol-D composite of 200 Hz relative to that of the monolithic material tested by Downey and Dapino [1], which is due to the lower stiffness of the composite. The resonance peak of the PMN-PT stack is located at roughly the same frequency as in the previous transducer [1], and has a magnitude 25-dB higher than that of the composite. The spurious dynamics appearing in the range from 1500 Hz to 2200 Hz are attributed to the preload washers in the magnetostrictive section [9], and are thus coupled to the vibratory response of the Terfenol-D rod.

With only the composite powered, Fig. 2(b), the resonance frequency of the composite shows a slight decrease consistent with the ac magnetic field-induced softening of Terfenol-D [9]. The magnitude of head velocity response at the composite's resonance frequency is 16-dB higher due to the magnetic field activation. The frequency components associated with the preload washers increase in magnitude as well, except for the notch near 2200 Hz. The resonance frequency of the PMN-PT stack increases relative to that of the previous case due to the reduced effective piezoelectric compliance in open circuit. For this reason, the model calculation based on a nominal PMN-PT modulus underestimates the resonance frequency. It is emphasized that while the PMN-PT stack is in open circuit, its electromechanical transduction is in quadrature with the

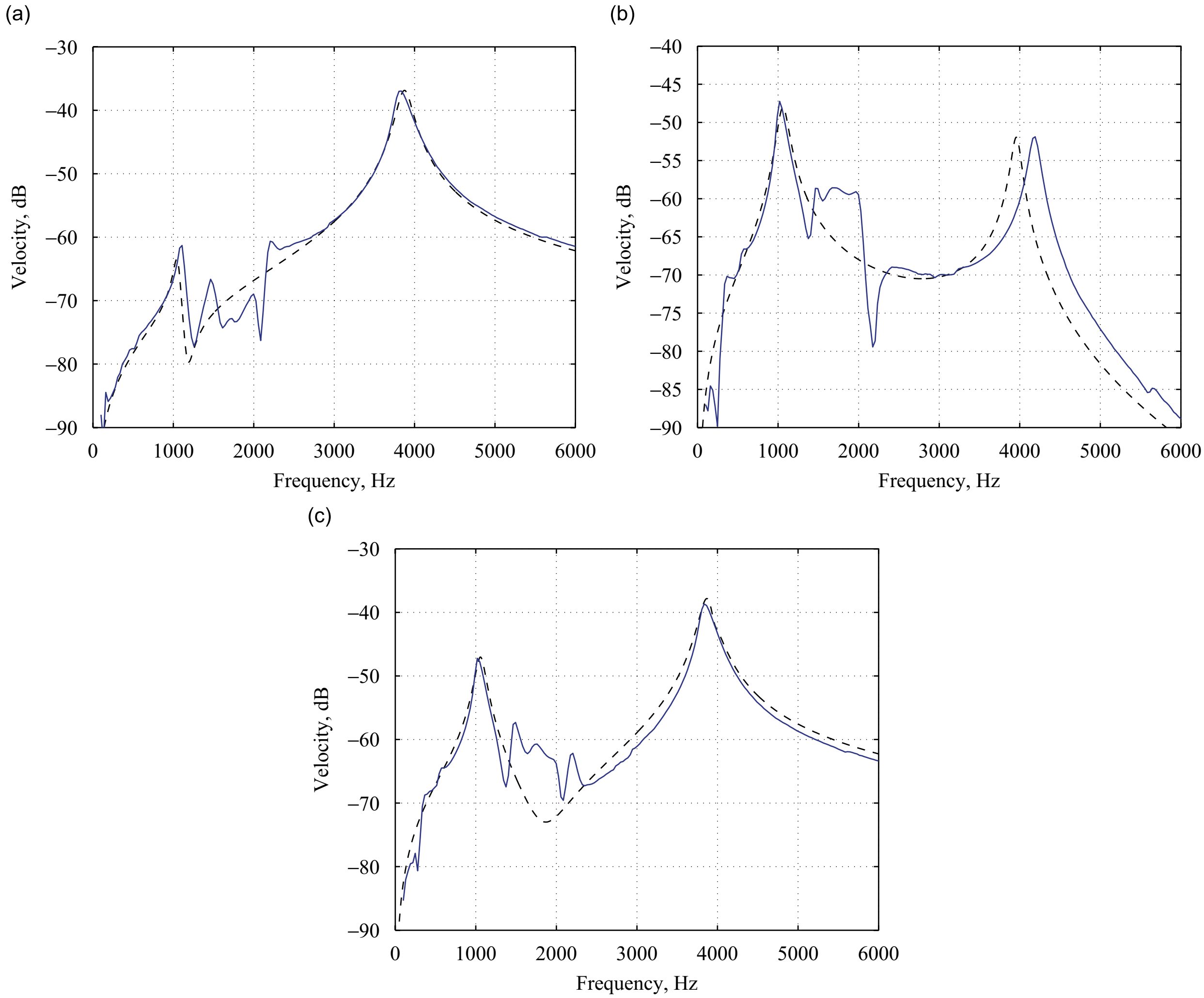

Fig. 2. Comparison of head velocity measurements and model simulations for: (a) only PMN-PT powered; (b) only Terfenol-D powered; (c) both powered. —— Data; - - - model.

magnetomechanical transduction of the Terfenol-D composite thus ensuring a significant frequency response in the region between the resonance peaks.

The head mass velocity response with both sections wired in parallel and driven with the same 4.2 V rms white noise excitation is shown in Fig. 2(c). The two resonance peaks overlap to successfully extend the transducer response over the range from 500 Hz to 6 kHz. The model accurately quantifies the response near the resonance frequencies. The spurious dynamics due to the magnetostrictive preload mechanism is mitigated by the simultaneous activation of the two sections. The overall variation of the velocity response over the frequency range considered is approximately 5-dB greater than that of the previous hybrid device [1]. This behavior is expected since in the tested transducer the Terfenol-D composite generates less mechanical output than the monolithic material does. The increased damping of the composite associated with the soft matrix proves insufficient at compensating for this reduced response and extending the overall system bandwidth. Although this behavior would be considered too limiting, Tonpilz transducers are often arrayed such that the overall frequency bandwidth and power emission are significantly enhanced relative to the individual transducers. Further, underwater loading is expected to flatten the overall transducer response thus increasing the effective frequency bandwidth [1]. Overall, the hybrid device employing Terfenol-D composite and PMN-PT provides a feasible alternative to its monolithic counterpart.

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