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Experimental dynamic performance of an Aluminium-MRE shallow shell

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Abstract. The nonlinear dynamics of a directly forced clamped-clamped-free-free magneto-rheological elastomer (MRE) sandwich shell has been experimentally investigated. Experiments have been conducted on an aluminium shallow shell (shell A) and an MRE-aluminium sandwich shallow shell with single curvature (shell B). An electrodynamic shaker has been used to directly force shells A and B in the vicinity of their fundamental resonance frequency; a laser displacement sensor has been used to measure the vibration amplitude to construct the frequency-response curves. It was observed that for an aluminium shell (shell A), that at small forcing amplitudes, a weak softening-type nonlinear behaviour was observed, however, at higher forcing amplitudes the nonlinear dynamical behaviour shifted and a strong hardening-type response occurred. For the MRE shell (shell B), the effect of forcing amplitude showed softening at low magnetic fields and hardening for medium magnetic fields; it was also observed the mono-curved MRE sandwich shell changed dynamics to quasiperiodic displacement at some frequencies, from a periodic displacement. The presence of a magnetic field, initial curvature, and forcing amplitude has significant qualitative and quantitative effects on the nonlinear dynamical response of a mono curved MRE sandwich shell.

Keywords: shallow shell; experimentation; mechanics; nonlinear experiments; magneto-rheological elastomer

1. Introduction

Magneto-rheological elastomers (MREs) are a class of smart materials which contain iron particles suspended in a rubber matrix (Carlson and Jolly 2000, Lee *et al*. 2012, Schubert and Harrison 2015, Jung *et al*. 2016). When MREs are polarised by an external magnetic field they exhibit a controllable shear modulus and damping (Sun *et al*. 2017a, Wang *et al*. 2017). The controllable shear modulus and damping make MREs ideal as an active vibration absorber in many engineering scenarios where ambient vibrations become large and can cause fatigue or failure in components (Bocian *et al*. 2017, Gu *et al*. 2017). MREs are already being used as vibration absorbing devices in automotive suspension and in civil structures (Deng and Gong 2007, Jung *et al*. 2011, Karavasilis *et al*. 2011, York *et al*. 2011, Sun *et al*. 2017b, c). MREs are used as sandwich elements for reducing resonance and there are two main categories where MREs are present, the first are MRE sandwich beams (Korobko *et al*. 2012, Yildirim *et al*. 2015, 2016a, b) and the second are MRE sandwich plates (Zhang *et al*. 2018).

For the MRE beams, Nayak *et al*. (2013) derived the governing equation of motion using a finite element method (FEM) for the stability of a partially filled MRE sandwich beam and investigations were carried out at eight different locations for the MRE. Results showed that by increasing the magnetic field the systems stability was increased. Dyniewicz *et al*. (2015) developed a control method for use with a partially filled MRE sandwich beam for reducing resonant vibrations and experiments were also conducted showing a reduction of the vibration. Sun *et al*. (2003) investigated the reduction of the primary resonance of an MRE sandwich beam and it was shown MRE can be effectively used to suppress the primary resonance. Zhou and Wang (2005, 2006) numerically investigated the dynamic response of an MRE sandwich beam for different magnetic fields and it was shown that the resonant frequencies only slightly change.

For the MRE plates, Ying *et al*. (2014) numerically investigated the dynamic vibrations resulting from stochastic excitation of the supports for an MRE sandwich plate. It was shown that with an increasing magnetic field applied to the supports of the plate, larger vibration attenuation could be achieved. Aguib *et al*. (2014) both

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numerically and experimentally investigated the linear behaviour of an MRE sandwich plate with different iron concentrations and magnetic fields.

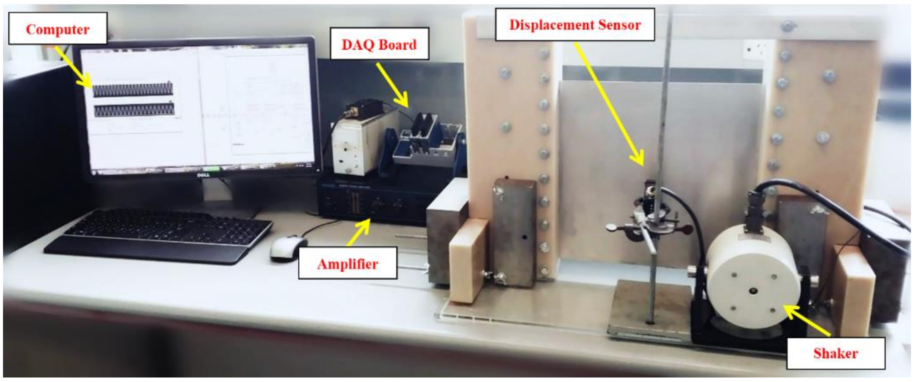
In this paper the nonlinear dynamics of an aluminium and mono curved MRE aluminium composite plate are investigated. Specifically, the geometric imperfection arises from manufacturing imperfection when a plate is rolled which makes a plate slightly curved forming a shallow shell. The effect of this slight curvature results in complex nonlinear dynamical behaviour with a shift from a softening-type response at low forcing amplitudes to a strong hardening-type response for larger forcing amplitudes when the MRE layer is in the presence of a magnetic field. To the authors best knowledge, this is the first experimental work towards the complex nonlinear softening and hardening behaviour of an MRE aluminium composite shell during resonance As we shall see, the geometric nonlinearity, initial curvature, magnetic coupling and large stretching about the mid-plane result in complex nonlinear dynamical behaviour for an MRE aluminium shell.

2. Problem statement and system description

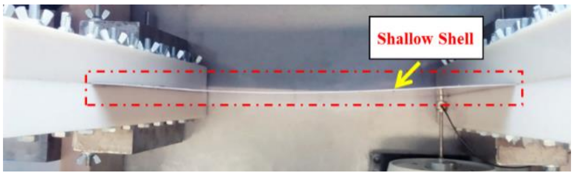
The experimental setup used is shown in Figs. 1(a)-(d) showing the overall photograph of the system, top view of the shallow shell, magnet interaction, excitation and geometry of the shell, respectively. Curvature has been introduced by means of a mechanical roller to manufacture a shell. Each shell has been excited by a force of the form $F\sin(2\pi ft)$ where F is the value of the forcing signal in N, f is the excitation frequency in Hz and t is the time in seconds (s). The shells are excited using the force sensor which is in contact with the shell (contact is on the aluminium side for the MRE shell) and held with super glue to maintain contact (i.e., no drills and rigid connections were used).

2.1 Measurement of curvature

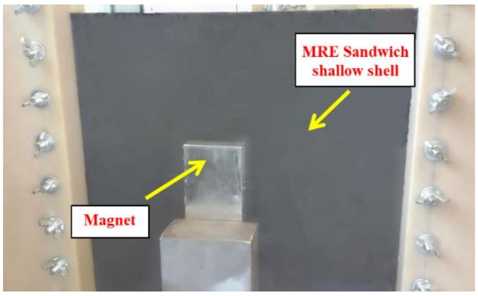
The curvatures of the shallow shells have been experimentally measured with a static reading using a laser displacement sensor. A polynomial fit has been used for the most dominant curvature, however, miscellaneous curvature



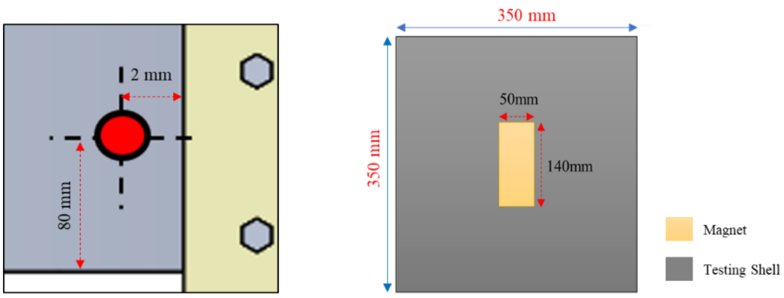
(a) Photograph of experimental setup



(b) Top view of the shallow shell

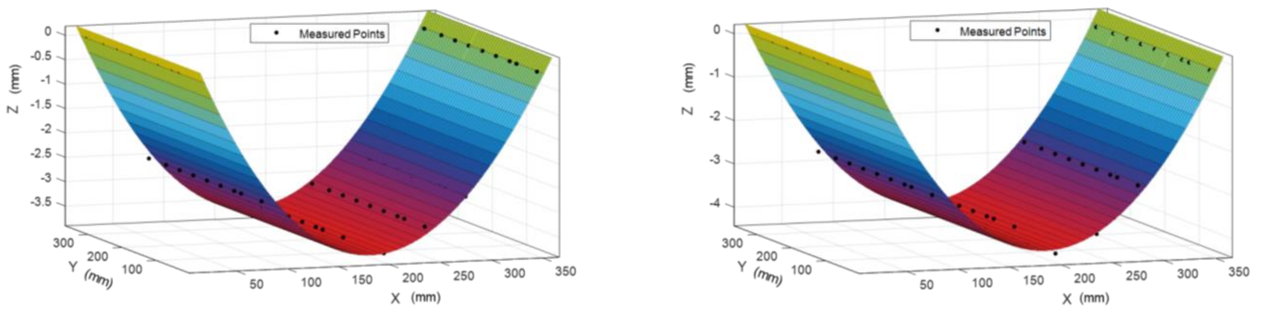


(c) Magnetic interaction of shallow shell



(d) Excitation point of the shaker in the bottom right corner of the shell (left) and geometry of the experiment (right)

Fig. 1 Experimental setup



(a) Aluminium shallow shell (shell A)

(b) Mono-curved MRE shallow shell (shell B)

Fig. 2 Measured geometric imperfections

Table 1 Coefficients of the polynomial fitted functions

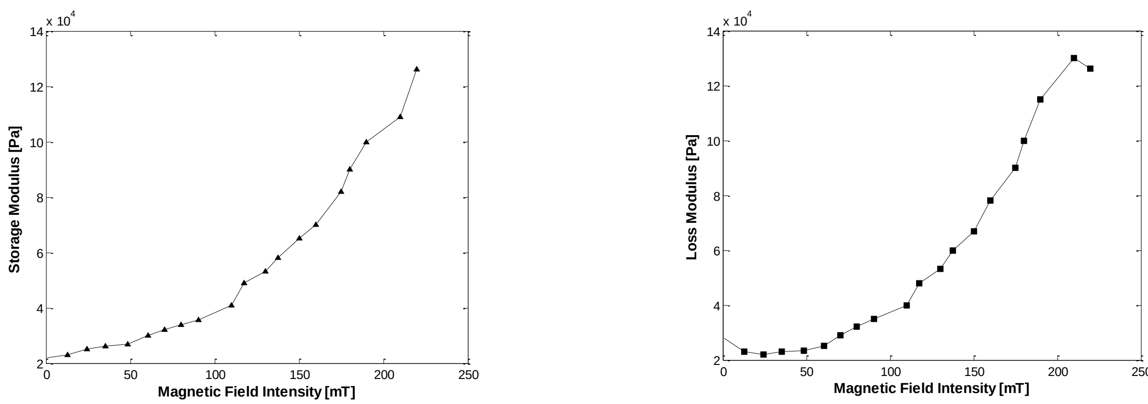
Coefficients	Aluminium shallow shell (shell A)	MRE mono-curved shallow shell (shell B)
a_1	0.8911	0.9447
a_2	-0.05206	-0.05465
a_3	-1.738e-17	-2.408e-17
a_4	0.0001555	0.0001496
a_5	1.703e-19	2.736e-19
a_6	-4.435e-08	-7.257e-09
a_7	-3.626e-22	-6.462e-22

points are also present due to manufacturing inconsistencies, imperfections and clamping the shells into the supporting fixture and that is why these curves are not classical half waves. Initial curvatures play a large part in engineering due to manufacturing or machining inaccuracies and this behaviour leads to complex dynamical behaviour which is the focus of this investigation. The experimentally measured shell profiles for the mono-curved aluminium shell and mono-curved MRE sandwich shell are shown in Figs. 2(a) and (b), respectively. The polynomial fitted contours for the shell profiles have been determined using MATLAB software and for shells A and B, the following fit has been performed and the results are shown in Table 1. The origin for the fitting was taken at the clamped ends

$$f(x,y) = a_1 + a_2x + a_3y + a_4x^2 + a_5xy + a_6x^3 + a_7x^2y \tag{1}$$

2.2 MRE fabrication and testing

An MRE layer has been fabricated using 80% iron particles with 5 μm mean particle size iron particles (Carbonyl iron, C3518, Sigma-Aldrich Pty Ltd.), 10% silicone rubber (Selleys Pty. Ltd) and 10% silicone oil (percentages are mass ratio); the iron particles are suspended in the rubber matrix, the mixture for the composite shell wasn't polarised by an external magnetic field during the curing process. The MRE layer has been bonded to an aluminium plate with length (L), width (B) and thickness (h) having dimensions of 350 mm, 350 mm and 0.6 mm, respectively, and this was allowed to cure for five days. The aluminium shell has mechanical properties with Young's modulus (E) and density with properties of 69.5 GPa and 2700 kg/m^3, respectively. The MRE-layer was bonded to an aluminium shell by allowing the MRE to cure for one week; after the MRE bonded to the aluminium shell, the overall thickness (hMRE) was 0.8 mm and the MRE sandwich shell was rolled. In addition, the properties of the MRE have been tested using a parallel plate rheometer (MCR 301, Anton Paar Companies, Germany) under a magnetic sweep and a constant angular velocity of 5 rad/s and the storage modulus (E') and loss modulus (E'') are



(a) Storage modulus

(b) Loss modulus

Fig. 3 Rheological properties of the MRE sample

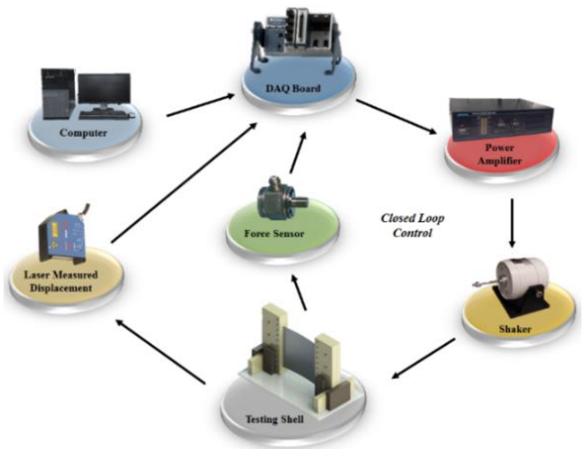


Fig. 4 Flowchart of the experimental setup

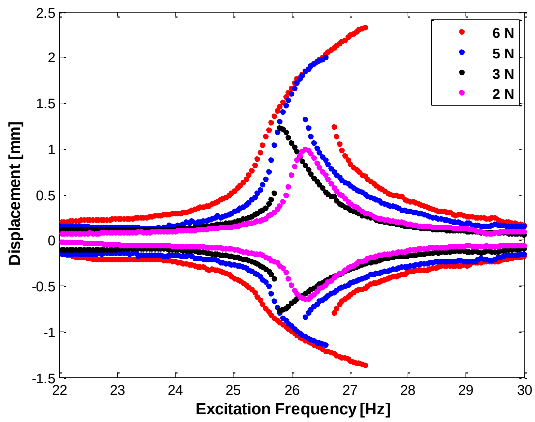


Fig. 5 Frequency-response curves for the mono-curved aluminium shallow shell for different forcing amplitudes (shell A)

shown in Figs. 3(a) and (b), respectively. With an increased magnetic field these two properties increased. The relation between the damping factor and the complex moduli is given by

$$\zeta = \tan^{-1}(E''/E') \qquad (2)$$

3. Experiment procedure and measurement recording system

A system flowchart of the experimental setup showing system interaction is given in Fig. 4. The shallow shells were directly forced using an electrodynamic shaker (Sinocera Piezotronics modal shaker JZK-5) with a force sensor (CLD Y303) attached to the shaker. When the shell resonated the corresponding displacement at the centre of the shell was measured using a laser displacement sensor (Microepsilon opto NCDT1700ILD1700-20) and all measurements were recorded using a data acquisition board (DAQ National instruments compact DAQ-9174 – NI9263 AO module and NI9201 AI module) which was also responsible for maintaining closed loop control to maintain constant sinusoidal forcing. The excitation point was selected near a clamped end to maintain contact and provide constant sinusoidal loading during the shells resonance. Moreover, sufficient settling time (five seconds) was allowed for a steady-state measurement to be recorded at a 5kHz sampling rate. The MRE was stimulated using a permanent magnet and the magnetic field was increased by changing the location between the permanent magnet and the MRE-layer. The distances used were 130 mm, 70 mm and 25 mm which resulted in the magnetic fields 5 mT, 10 mT and 45 mT, respectively, at a static distance apart (this refers to the distance of the MRE side to the magnet when the system is not excited i.e. the system is at the initial zero position).

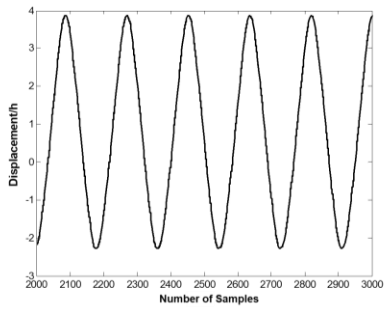
4. Experimental results

Experiments have been performed for both forward and reverse frequency sweeps and the resulting frequency-response curves are a combination of both. This was done to capture the highly nonlinear dynamical behaviour of these systems. The dimensional frequency-response curves have been plotted for the aluminium shell and for various magnetic fields for the mono-curved MRE sandwich shallow shell. For some of the test frequencies, the experimental time traces, phase-plane diagrams, probability density functions (PDF) and fast Fourier transforms (FFT) have been plotted to show the complex nonlinear dynamics that can arise for geometric imperfect plates.

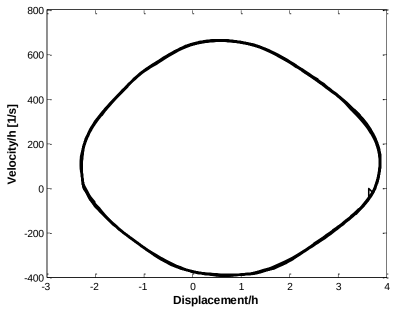
4.1 Experimental results for mono-curved shallow shells

The frequency-response curves for a mono-curved aluminium shallow shell (Shell A) under various forcing amplitudes are shown in Fig. 5. The experimentally obtained fundamental out-of-surface resonance was 26.23 Hz (at F = 2N). With a 3 N forcing amplitude the dynamical behaviour of the system changes (compared to the case with 2 N forcing) and a softening-type nonlinear response was observed; i.e., the frequency-response curve leans towards the left with 2% nonlinear behaviour. With larger forcing amplitudes (i.e., F = 5 or 6 N), a strong hardening-type nonlinear behaviour was observed with the frequency-response curves leaning towards the right; 4% nonlinear behaviour was observed for F = 6 N with a maximum amplitude of 2.33 mm. For this point in the space-parameter the time trace (number of samples), phase-plane diagram, PDF and FFT are shown in Figs. 6(a)-(d), respectively, illustrating an un-symmetric periodic displacement due to the initial geometric imperfection. This nonlinear behaviour is due to the fighting between softening and hardening behaviours from the shell geometry where at higher forcing amplitudes the hardening behaviour is dominant.

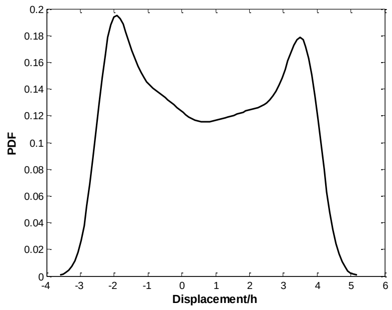
The frequency-response curves for a mono-curved MRE sandwich shell (shell B) in the absence of an external magnetic field is shown in Fig. 7. The linear fundamental resonance frequency was experimentally obtained as 19.68 Hz. A strong softening-type nonlinear behaviour was observed for the MRE sandwich shell in the absence of a magnetic field from a 2N forcing amplitude onwards; discontinuous points were observed which theoretically correspond to limit point bifurcations. Multiple internal



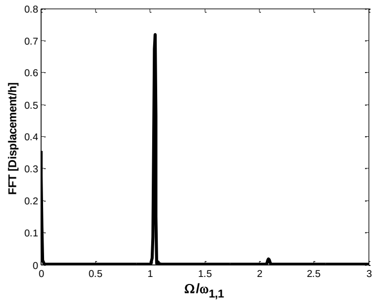
(a) Time-trace



(b) Phase-plane diagram



(c) PDF



(d) FFT

Fig. 6 Displacement characteristics for the system in Fig. 5 at f = 27.36 and F = 6 N

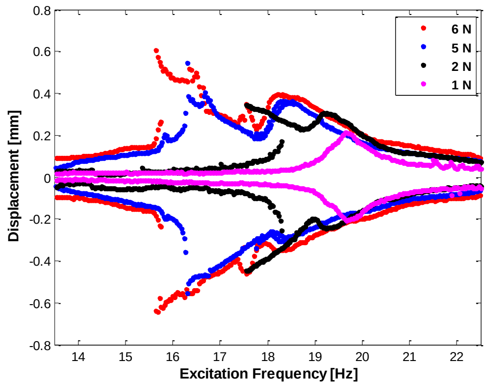
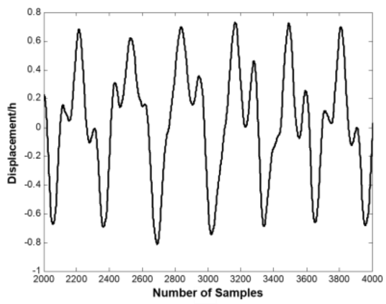


Fig. 7 Frequency-response curves for the MRE sandwich shell (shell B) in the absence of an external magnetic field

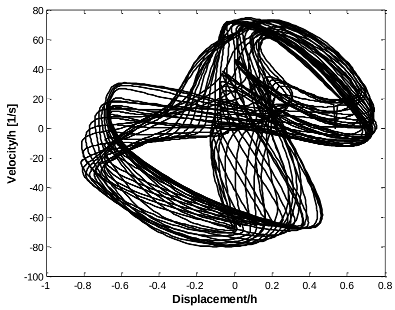
resonances also occurred when F ≥ 2 N; three internal resonances occurred when F = 6 N until reaching a maximum displacement amplitude of 0.6316 mm at f = 15.62 Hz, then the system response bifurcated to a near zero response. For this point in the space parameter the time trace, phase-plane diagram, PDF and FFT are shown in Figs. 8(a)-(d), respectively, illustrating an asymmetric quasiperiodic displacement due to the initial curvature and the elastomer. Moreover, comparing Figs. 6 and 8 the presence of an MRE-layer in combination with initial curvature resulted in a shift from periodic to quasiperiodic behaviour due to the effects of the elastomer storing deformation energy and geometric nonlinearity arising from large stretching across the mid-plane.

For the mono-curved MRE sandwich shell (shell B), the change in the fundamental out-of-surface resonant frequency versus magnetic field is shown in Fig. 9; with increasing magnetic field the fundamental natural frequency of shell B decreased. A comparison of the frequency-response curves for shell B in the absence or presence of a magnetic field is shown in Fig. 10 for a 3 N forcing amplitude (the linear resonances were observed by exciting the system with a small forcing amplitude to experimentally determine the resonance). When in the absence or presence of a weak external magnetic field a strong softening-type nonlinear response was observed; however, with a 10 mT external magnetic field applied to the MRE-layer the mono-curved shallow shells curvature slightly reduced and a hardening-type nonlinear response was observed having the largest vibration amplitude. Furthermore, with a medium external magnetic field, a linear response was observed having the smallest out-of-surface vibration amplitude due to high damping of the elastomer. The experimentally obtained natural frequencies corresponding to 5, 10 and 45 mT were 19.56, 18 and 17.5 Hz, respectively, and this was measured at a small forcing amplitude to find the resonance frequency. Moreover, a comparison of the frequency-response curves for shell B in the presence of an external magnetic field with a 1 N forcing amplitude is shown in Fig. 11 for different magnetic fields. It was observed that in the presence of a weak magnetic field, nonlinear responses were observed; however, this was not the case for a medium external magnetic field or in the absence of an external magnetic field.

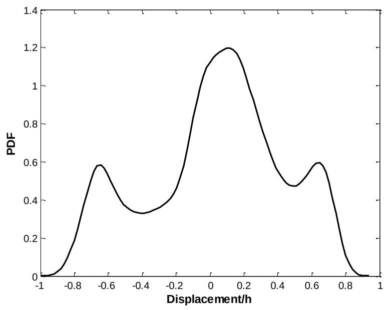
For the mono-curved aluminium shell, it was observed for certain forcing amplitudes that the frequency-response exhibited softening behaviour and at higher forcing amplitudes the systems response displayed a strong-hardening behaviour. The effect of the initial curvature also resulted in an asymmetric periodic displacement about the initial equilibrium position. For the mono-curved MRE sandwich shallow shell, a strong softening-type nonlinear



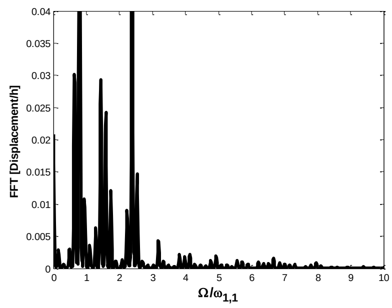
(a) Time-trace



(b) Phase-plane diagram



(c) PDF



(d) FFT

Fig. 8 Displacement characteristics for the system in Fig. 7 at f = 15.62 and F = 6 N

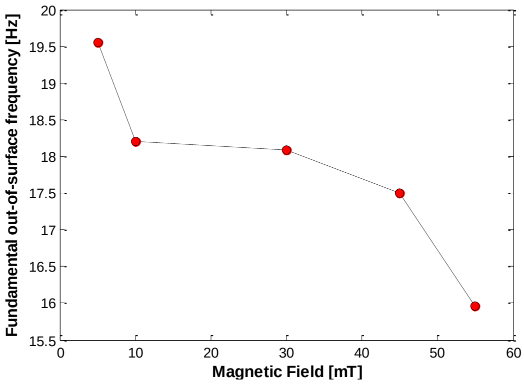


Fig. 9 Change in natural frequency against the applied magnetic field for a mono-curved MRE sandwich shallow shell (shell B)

response was observed for all forcing amplitudes in the absence of an external magnetic field, however, an interesting feature was that a quasiperiodic displacement was observed due to the initial curvature of the shell and the effect of the elastomer storing deformation energy. With an increasing magnetic field, the mono-curved MRE sandwich shell had a reduction in the out-of-surface resonance frequency. It was also observed there were multiple internal resonances accompanied by irregularities in the resonance amplitude. Furthermore, with a magnetic field applied, it was observed when the mono-curved MRE sandwich shell was in the presence of a 10 mT magnetic field, the system behaviour shifted and the system displayed a strong hardening-type behaviour. When the magnetic field strength was large enough a linear response was observed. The effects of initial curvature of the shell, the excitation, and

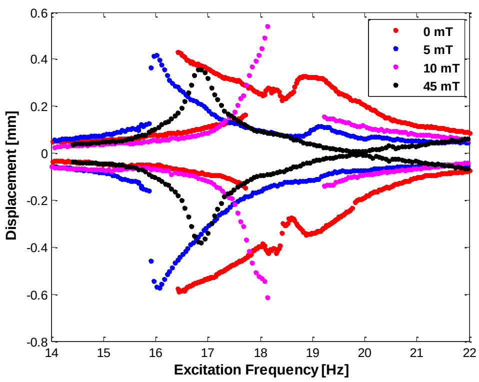


Fig. 10 Frequency-response curves for the mono-curved MRE sandwich shallow shell (shell B) in the absence or presence of an external magnetic field and a forcing (F) of 3 N

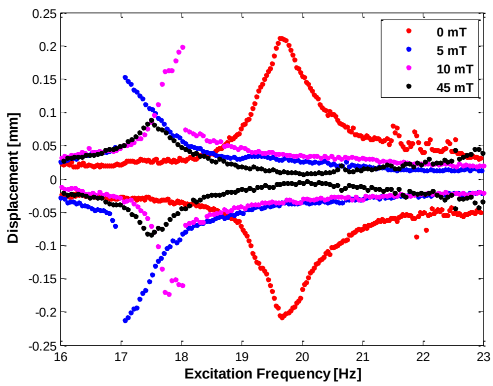


Fig. 11 Frequency-response curves for the mono-curved MRE sandwich shallow shell (shell B) in the absence or presence of an external magnetic field and a forcing (F) of 1 N

the magnetic coupling had significant qualitative and quantitative effects on the nonlinear dynamical response of an MRE sandwich shallow shells, the displacement changed from periodic to quasiperiodic and in some cases the nonlinear dynamical responses shifted from softening to hardening as a result of the presence of the MRE layer and the externally applied magnetic field. The magnetic field changed the initial curvature of the mono-curved MRE sandwich shell and changed the mechanical properties of the MRE layer and in turn this changed the dynamical response of the shell.

5. Conclusions

In this work, the nonlinear dynamic behaviour of an aluminium shell and an aluminium-MRE shell have been experimentally obtained. An electrodynamic shaker was used to excite each system and it was found that for low forcing amplitudes softening behaviour was observed for the aluminium shell and this turned into hardening behaviour as forcing amplitude increased. Moreover, the aluminium-MRE shell displayed a wide variety of nonlinear attributes when in the absence or presence of a magnetic field, this behaviour included softening, internal resonances and quasi-periodic displacement. This work has demonstrated that simple geometric imperfections can substantially influence the nonlinear dynamic response of a shell and furthermore, composite MRE shells can display significantly different behaviour compared to the purely aluminium shell which is due to the elastomer properties.

Acknowledgments

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