An explicit dissipative model for isotropic hard magnetorheological elastomers — ABAQUS implementation guidelines

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Abstract

This note is an explanatory document of the ABAQUS input file used to implement the h-MRE beam bending problem, presented in the Section 7 of "Mukherjee, D., Rambausek, M., and Danas, K. (2021). An explicit dissipative model for isotropic hard magnetorheological elastomers. *Journal of the Mechanics and Physics of Solids*, 104361".

The details of the ABAQUS input file corresponding to the solution of the h-MRE boundary value problem in the Section 7 of the paper "Mukherjee, D., Rambausek, M., and Danas, K. (2021). An explicit dissipative model for isotropic hard magnetorheological elastomers. *Journal of the Mechanics and Physics of Solids*, 104361" is provided in the following text. Specifically, the provided input file solves the boundary value problem described in Fig. 1. As shown in the figure, the BVP is solved in two steps, namely, the pre-magnetization step "Step-1" and the actuation step "Step-2". The following commentary explain the ABAQUS input file employed to solve this BVP.

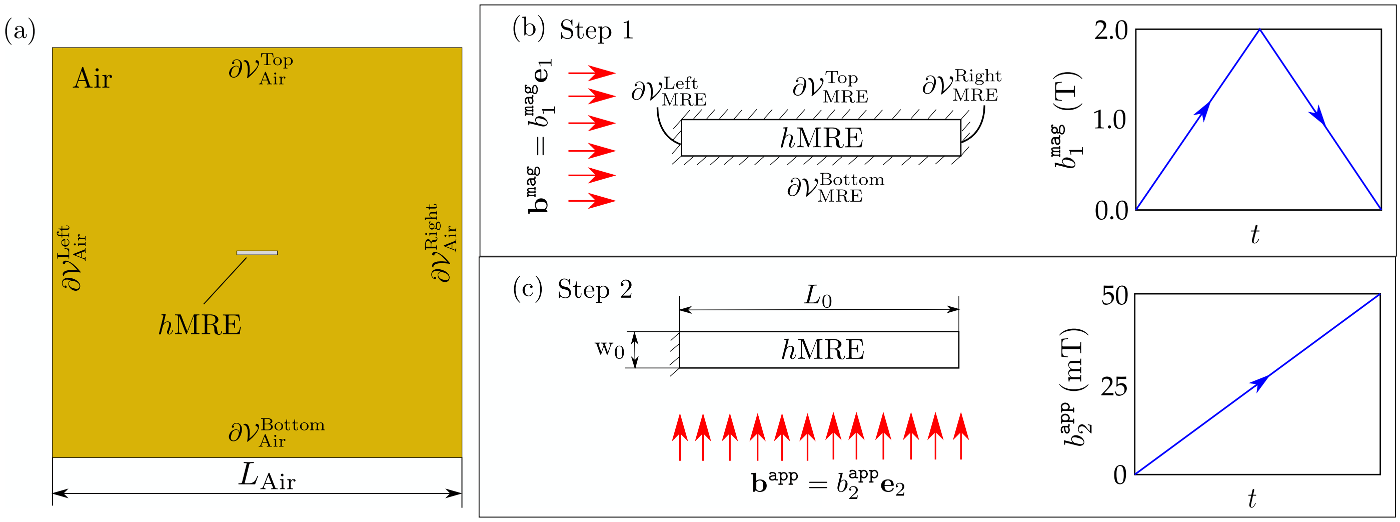

Figure 1: (a) Schematic diagram of the numerical BVP involving the h-MRE and surrounding air. The length of the square air domain L_{Air} is considered to be $L_{\text{Air}} = 10L_0$ and four boundaries of this domain are denoted by $\partial\mathcal{V}^{\text{Left}}_{\text{Air}}$, $\partial\mathcal{V}^{\text{Top}}_{\text{Air}}$, $\partial\mathcal{V}^{\text{Right}}_{\text{Air}}$ and $\partial\mathcal{V}^{\text{Bottom}}_{\text{Air}}$. (b) Step 1, indicating the applied pre-magnetizing field $\mathbf{b}^{\text{mag}}$ direction (by red arrows) and magnitude (right hand side plot). The four interfaces between air and h-MRE are denoted by $\partial\mathcal{V}^{\text{Left}}_{\text{MRE}}$, $\partial\mathcal{V}^{\text{Top}}_{\text{MRE}}$, $\partial\mathcal{V}^{\text{Right}}_{\text{MRE}}$ and $\partial\mathcal{V}^{\text{Bottom}}_{\text{MRE}}$. The hatched interfaces represent fixed displacement degrees-of-freedom, i.e. $\mathbf{u} = \mathbf{0}$. (c) Two subsequent magnetic loading paths for (c) Step 2, indicating the actuation field $\mathbf{b}^{\text{app}}$ applied along $\mathbf{e}_2$, while its magnitude is shown in the adjacent plot. The length and width of the h-MRE are indicated by L_0 and w_0, respectively, while the fixed h-MRE-air interface in this step is indicated by a hatched line.

The ABAQUS input file `input.inp` is divided in mainly three sub-parts, namely, (a) parameter definitions, (b) element definitions and their property assignments and (c) definitions of the loading steps and different boundary conditions corresponding to them.

(a) Parameter definitions:
First, we define the step size along with the minimum and maximum allowable increments under the parameter section of the input file. This part reads the following

```
*PARAMETER
```

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Preprint submitted to Elsevier *March 8, 2021*

```
** Step size specifier***************************
mag_step_size = 250.0
actu_step_size = 2.0*mag_step_size
init_step_size=10.0e-4
min_step_size=1.0e-6*init_step_size
max_step_size=1.0e3*init_step_size
```

Here the variables `mag_step_size` and `actu_step_size` define the magnetization (Step-1) and actuation (Step-2) step sizes, respectively. Since the material model is rate-independent, these step sizes and increments remain arbitrary and do not play crucial role in the simulation. Nonetheless, the total number of increments at each step must be $\sim 0.5-5\times 10^3$ to ensure convergence.

Next, the permeability of air (or vacuum) μ_0 is defined. Notice that the computations are done by considering the shear moduli in the MPa scale, while all the length dimensions are given in mm. Thus, the variational formulation given by equation (7.5) in the main text is divided by 10^6. Hence, μ_0 reads

```
**Permeability of air****************************
mu0=1.25664e0
```

The length of the air domain L_{Air} is then specified along with the penalty parameter ζ in order to constraint the air node motion according to the boundary deformation of h-MRE.

```
** Specify length of air domain and penalty parameter
*************************************************
L_AIR=100.0
zeta_penalty=1e-3
```

Once L_{Air} is specified, we define the b_{mag} and b_{app} to be the initial magnetization and actuation b-fields. Subsequently, the corresponding values of φ in the present scalar potential-based variational principle is also prescribed, which will be referred back in the `STEP` module.

```
**Magnetic b field loading amplitude ***********
b_mag = 2.0
phi_mag = -b_mag/mu0*L_AIR
*************************************************
**Actuating b field loading amplitude ***********
*************************************************
b_app = 0.05
phi_app = -b_app/mu0*L_AIR
```

Now, the local material properties of the h-MRE is specified, Note that, the h-MRE model is proposed in terms of the underlying matrix and particle properties along with the particle volume fraction c and the coupling coefficient $\beta(c)$, which is calculated explicitly as a function of c.

```
**Particle volume fraction***********************
volfrac=0.177
*************************************************
**Matrix Properties******************************
*************************************************
**Neo-hookean************************************
G_m=0.186
G_prime_m=500.0*G_m
*************************************************
*************************************************
**Hard-magnetic particle properties *************
chie_p=0.105
chi_p=8.0
ms_p=0.67
bc_p=0.845*mu0
*************************************************
** Coupling parameter ***************************
beta_MRE = 19.5*volfrac*volfrac-10.55*volfrac+1.72
*************************************************
```

Here c is indicated via `volfrac`, while the matrix shear ($G_{\mathtt{m}}$) and bulk ($G'_{\mathtt{m}}$) moduli are represented via `G_m` and `G_prime_m`, respectively. The hard magnetic particle properties defined via $\chi_{\mathtt{p}}^{e}$, $\chi_{\mathtt{p}}^{r}$, $m_{\mathtt{p}}^{s}$ and $b_{\mathtt{p}}^{c}$ in the main text are represented here by `chie_p, chi_p, ms_p` and `bc_p`, respectively. The coupling parameter $\beta(c)$ defined via equation (6.4) of the main text is defined in this input file via `beta_MRE`.

For the air domain $\mathcal{V}_{\rm Air}$, we set $G_a = 0$ MPa, while all the aforementioned properties remain inconsequential, and hence, set to zero, except the coercive field $b^c_{\rm a}$, which is set to a very large value in order to ensure purely energetic, linear $\mathbf{b} = \mu_0\mathbf{h}$ constitutive response.

```
**AIR**Properties********************************
*************************************************
G_a=0.0
G_prime_a=500.0*G_a
*************************************************
chie_a=0.0
chi_a=0.0
ms_a=0.0
bc_a=2000.0
beta_a=0.0
```

(b) Element definitions:
We employ user-defined elements supplied via the `UEL` subroutine of ABAQUS. We use four-node quadrilateral, linear elements for the bulk h-MRE and air modeling. These elements are defined via the following line.

```
*USER ELEMENT, NODES=4, TYPE=U1, IPROPERTIES=1, PROPERTIES=10, COORDINATES=2, VARIABLES=16, UNSYMM
1,2,11
```

The displacement degrees-of-freedom are defined via `1,2`, while the scalar potential degree-of-freedom is defined via `11`. We employ a four-point Gauss integration scheme in the UEL, where in each Gauss point we store 4 internal variables. Thus we set `VARIABLES=16`, which are stored in the `SVARS` array. The number of properties are 10, while one integer flag is supplied to flag for reduced integration of the volumetric mechanical energy density term.

Similarly, we define the penalty elements to apply a linear constraint on the motion of the air nodes. These elements are defined as two-node elements containing one air node and its nearest air/h-MRE interface node.

```
*USER ELEMENT, NODES=2, TYPE=U2, IPROPERTIES=1, PROPERTIES=10, COORDINATES=2, VARIABLES=1, UNSYMM
1,2
```

Next, we include the mesh files for the user element `U1`, the dummy element of type `CPS4` for visualization and the penalty elements of type `U2` from the three following files, respectively.

```
****************************************************************
*INCLUDE, INPUT=mesh.inp
*INCLUDE, INPUT=mesh_dummy.inp
*INCLUDE, INPUT=mesh_penalty.inp
****************************************************************
```

Next, the 10 UEL properties corresponding to the h-MRE and the air elements (`ELSET=MRE` $\equiv \mathbf{X} \in \mathcal{V}_{\rm MRE}$ and `ELSET=AIR` $\equiv \mathbf{X} \in \mathcal{V}_{\rm Air}$). The last property is the integer flag set to 1 in order to activate the reduced integration.

```
****************************************************************
*UEL PROPERTY, ELSET=MRE
<G_m>,<G_prime_m>,<chie_p>,<chi_p>,<ms_p>,<bc_p>,<volfrac>,<beta_MRE>,
<zeta_penalty>,<L_AIR>,1
1
*UEL PROPERTY, ELSET=AIR
<G_a>,<G_prime_a>,<chie_a>,<chi_a>,<ms_a>,<bc_a>,<volfrac>,<beta_a>,
<zeta_penalty>,<L_AIR>,1
1
****************************************************************
*UEL PROPERTY, ELSET=penalty
<G_a>,<G_prime_a>,<chie_a>,<chi_a>,<ms_a>,<bc_a>,<volfrac>,<beta_a>,
<zeta_penalty>,<L_AIR>,1
1
****************************************************************
```

(c) Step definitions:
The loading steps indicated by "Step-1" and "Step-2" in Fig. 1 is actually implemented in four steps of ABAQUS/Standard. The first two steps are, respectively, the loading and unloading of the pre-magnetization step. Thus, the amplitudes `Amp-1` are defined and `Amp-2` are defined for that. After the pre-magnetization ends, the boundary constraints from

the h-MRE must be removed. In order to facilitate the smooth removal of these boundary constraints to the stress-free boundaries $\partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Top}}, \partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Right}}$ and $\partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Bottom}}$, we introduce an intermediate `Step-3`, whose amplitude is defined via `Amp-3`. Finally, the actuation loading amplitude is defined via `Amp-4`, which linearly increases from 0 to 1 during the timespan of `actu_step_time`.

```
**Specify loading amplitude ************************************
****************************************************************
*Amplitude, name=Amp-1
0.0,0.0,<mag_step_size>,1.0
*Amplitude, name=Amp-2
0.0,1.0,<mag_step_size>,0.0
*Amplitude, name=Amp-3
0.0,0.0,10.0,1.0
*Amplitude, name=Amp-4
0.0,0.0,<actu_step_size>,1.0
```

The first step is the loading step along the direction $\mathbf{e}_1$ (see Fig. 1). Thus, we set $\varphi = 0$ at $\partial\mathcal{V}_{\mathrm{Air}}^{\mathrm{Left}}$ (`LB_AIR`), while $\varphi = -b_{\mathrm{mag}}/\mu_0 L_{\mathrm{Air}}$ at $\partial\mathcal{V}_{\mathrm{Air}}^{\mathrm{Left}}$ (`RB_AIR`). Moreover, the displacements are blocked at the boundaries $\partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Left}} \cup \partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Top}} \cup \partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Right}} \cup \partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Bottom}}$, which are indicated in this input file `LB, TB, RB, LB`. Similarly, the four air boundaries are also blocked, so that $u_1 = u_2 = 0$ on $\partial\mathcal{V}_{\mathrm{Air}}^{\mathrm{Left}} \cup \partial\mathcal{V}_{\mathrm{Air}}^{\mathrm{Top}} \cup \partial\mathcal{V}_{\mathrm{Air}}^{\mathrm{Right}} \cup \partial\mathcal{V}_{\mathrm{Air}}^{\mathrm{Bottom}}$, which are indicated in this file via `LB_AIR, TB_AIR, RB_AIR, LB_AIR`.

```
**Loading-steps************************************************
**Step-1--Pre magnetization loading 0--2 T ********************
***************************************************************
*STEP, name=STEP-1, nlgeom=YES, inc=200000, extrapolation=linear
*COUPLED TEMPERATURE-DISPLACEMENT, STEADY STATE
<init_step_size>, <mag_step_size>, <min_step_size>, <max_step_size>
*CONTROLS, PARAMETERS=TIME INCREMENTATION
24,30,31,70,70
*BOUNDARY, amplitude=Amp-1, op=NEW
LB,1,2,0.0
BB,1,2,0.0
RB,1,2,0.0
TB,1,2,0,0
LB_AIR,1,2,0.0
BB_AIR,1,2,0.0
RB_AIR,1,2,0.0
TB_AIR,1,2,0.0
RB_AIR,11,11,<phi_mag>
LB_AIR,11,11,0.0
*Output, field, number interval=50, time marks=no
*Node Output, Nset=ALL
U,RF,COORD,NT,RFL
*Element Output, POSITION=CENTROIDAL, elset=Dummy
UVARM, EVOL
*END STEP
```

The `Step-2` is associated with the same boundary conditions, while the loading amplitude is now changes to `Amp-2`, which is reducing the applied field linearly from 2 T to 0 T.

```
****************************************************************
**Step-2--Pre magnetization unloading 2--0 T *******************
****************************************************************
*STEP, name=STEP-2, nlgeom=YES, inc=200000, extrapolation=linear
*COUPLED TEMPERATURE-DISPLACEMENT, STEADY STATE
<init_step_size>, <mag_step_size>, <min_step_size>, <max_step_size>
*CONTROLS, PARAMETERS=TIME INCREMENTATION
24,30,31,70,70
*BOUNDARY, amplitude=Amp-2, op=NEW
LB,1,2,0.0
BB,1,2,0.0
RB,1,2,0.0
```

```
TB,1,2,0.0
LB_AIR,1,2,0.0
BB_AIR,1,2,0.0
RB_AIR,1,2,0.0
TB_AIR,1,2,0.0
RB_AIR,11,11,<phi_mag>
LB_AIR,11,11,0.0
*Output, field, number interval=50, time marks=no
*Node Output, Nset=ALL
U,RF,COORD,NT,RFL
*Element Output, POSITION=CENTROIDAL, elset=Dummy
UVARM, EVOL
*END STEP
```

Next, we introduce an intermediate step so that the stress-free boundaries $\partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Top}} \cup \partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Right}} \cup \partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Bottom}}$ of the h-MREs are obtained smoothly from their displacement-free conditions in the last step. Note that $\partial\mathcal{V}_{\mathrm{MRE}}^{\mathrm{Left}}$ is still kept fixed in this step along with all the air boundaries. The scalar potentials at all the boundaries are kept 0.

```
*****************************************************************
**Step-3--Intermediate small step to facilitate change in BCs*****
*****************************************************************
*STEP, name=STEP-3, nlgeom=YES, inc=200000, extrapolation=linear
*COUPLED TEMPERATURE-DISPLACEMENT, STEADY STATE
<init_step_size>, 10.0, <min_step_size>, <max_step_size>
*CONTROLS, PARAMETERS=TIME INCREMENTATION
24,30,31,70,70
*BOUNDARY, amplitude=Amp-3, op=NEW
LB,1,2,0.0
LB_AIR,1,2,0.0
BB_AIR,1,2,0.0
RB_AIR,1,2,0.0
TB_AIR,1,2,0.0
BB_AIR,11,11,0.0
TB_AIR,11,11,0.0
RB_AIR,11,11,0.0
LB_AIR,11,11,0.0
*Output, field, number interval=2, time marks=no
*Node Output, Nset=ALL
U,RF,COORD,NT,RFL
*Element Output, POSITION=CENTROIDAL, elset=Dummy
UVARM, EVOL
*END STEP
```

Finally, `Step-4` corresponds to the actuation step, where $\mathbf{b}$ is applied along $\mathbf{e}_2$, while only the left boundary of the h-MRE kept fixed. The actuation amplitude is employed here as `Amp-4` as defined beforehand.

```
*****************************************************************
**Step-4--Actuation step loading -- 0--50 mT ********************
*****************************************************************
*STEP, name=STEP-4, nlgeom=YES, inc=200000, extrapolation=linear
*COUPLED TEMPERATURE-DISPLACEMENT, STEADY STATE
<init_step_size>,<actu_step_size>, <min_step_size>, <max_step_size>
*CONTROLS, PARAMETERS=TIME INCREMENTATION
24,30,31,70,70
*BOUNDARY, amplitude=Amp-4, op=NEW
LB,1,2,0.0
LB_AIR,1,2,0.0
BB_AIR,1,2,0.0
RB_AIR,1,2,0.0
TB_AIR,1,2,0.0
BB_AIR,11,11,0.0
TB_AIR,11,11,<phi_app>
*Output, field, number interval=100, time marks=no
```

```
*Node Output, Nset=ALL
U,RF,COORD,NT,RFL
*Element Output, POSITION=CENTROIDAL, elset=Dummy
UVARM, EVOL
*END STEP
```

The user-element file `hMRE_FH_QAD4RI.f` and the mesh files `mesh.inp`, `mesh_dummy.inp` and `mesh_penalty.inp`. are provided along with this input file. To run the ABAQUS/Standard code type in the terminal

```
abaqus job=<jobname> input=input.inp user=hMRE_FH_QAD4RI.f cpus=<no_cpus> interactive
```

If you find this code useful please cite "Mukherjee, D., Rambausek, M., and Danas, K. (2021). An explicit dissipative model for isotropic hard magnetorheological elastomers. *Journal of the Mechanics and Physics of Solids*, 104361".