THE INFLUENCE OF A MAGNETIC FIELD ON VIBRATION PARAMETERS OF A CANTILEVER BEAM FILLED WITH MR FLUID

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Abstract: The paper investigates a magnetic field acting on a three-layer sandwich beam filled with MR fluid, the field being generated by an electromagnet. The FEM approach is applied to determine the magnetic field strength and magnetic flux density in the area between the poles and in the MR fluid layer. The results are utilised to establish the relationship between the magnetic flux density and parameters of the assumed model of the MR fluid layer.

Key words: Cantilever Beam, MR Fluid, Magnetic Field

1. INTRODUCTION

Beams, plates and shell elements are widely used as structural components in vehicles, aircraft and various installations. Their operation, however, gives rise to some undesired phenomena, such as vibrations. Such vibrations can be reduced by the use of active and semiactive control methods.

Recently, semiactive methods using smart materials e.g. magnetorheological (MR) fluids have received a great deal of attention. MR fluids properties are varied under the action of a magnetic field. The stiffness and damping characteristics of the structure incorporating MR fluid are modified, too. These changes occur within a very short time and that is why MR fluids can be well applied in highly dynamic systems (Sun et al., 2003; Yalcinitias et al., 2004; Sapiński et al., 2009; Lara-Prieto et al., 2010; US Patent 5547049). Through varying the magnetic field strength, we are able to control mechanical parameters of the structure. Development of the magnetic field is crucial to functioning of the structures with MR fluid.

Magnetic field generated by an electromagnet and acting on a cantilever beam filled with MR fluid is investigated. The FEM model (Vector Fields Ltd 2007) developed in the Opera-2D environment (version 12) is used to determine the magnetic field strength and magnetic induction in the MR fluid layer. The influence of the beam's static deflection on the magnetic field distribution is investigated, too. The relationship is found between the Kelvin-Voigt model parameters of the MR fluid layer and magnetic flux density.

2. BEAM AND ELECTROMAGNET STRUCTURE

Schematic diagrams of the beam and the electromagnet are shown in Fig. 1 and 2. The beam shown schematically in Fig. 1 is made of two outer layers made of aluminium 400 mm long, 30 mm wide and 2 mm high. The space between the two layers is sealed with silicone rubber 2 mm thick and 1.5 mm wide and the beam interior is filled with MR fluid of the type 132DG,

manufactured by Lord Corporation (US Patent 5547049). The beam is placed centrally in the gap of the electromagnet and fixed on one end, so that the electromagnet can be moved smoothly.
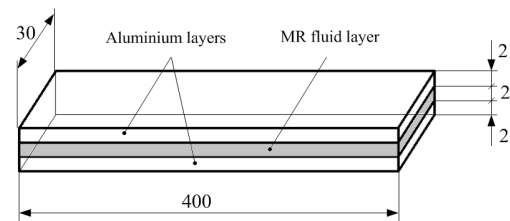

Fig. 1. Three-layer sandwich beam

The electromagnet (Fig. 2) is made of steel. The distance δ between the poles (gap) can be varied in the range 20-30 mm by moving the upper arm of the electromagnet, fixed on bolts. Each arm of the electromagnet has 370 wound turns of copper wire 1.4 mm in diameter.
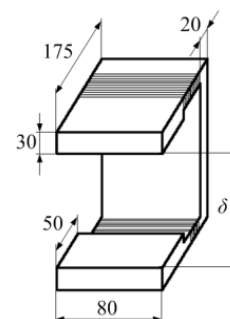

Fig. 2. Schematic diagram of the electromagnet

3. MODEL OF THE ELECTROMAGNET–BEAM STRUCTURE

The model of the electromagnet and the beam is developed in the Opera-2D environment. It is a 2D model contained

in the plane *x-z* (Fig 3). The symbol *I* stands for the current flowing through the electromagnet coil, z_u denotes the distance of the beam's cross section from the equilibrium position. Further, the area in which magnetic field is determined is bounded by a rectangle 220 x 180 mm. The model comprises 870389 finite elements and 174854 nodes.
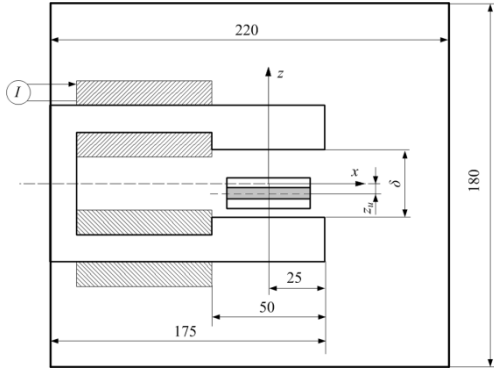

Fig. 3. Schematic diagram of the 2D beam-electromagnet model in the coordinate system *x–z*

Magnetic properties of MR fluid and of the electromagnet core are described by relevant magnetisation characteristics based on the catalogue data (Fig. 4). Relative permeability of aluminium layers is taken to be constant and equal to 1.
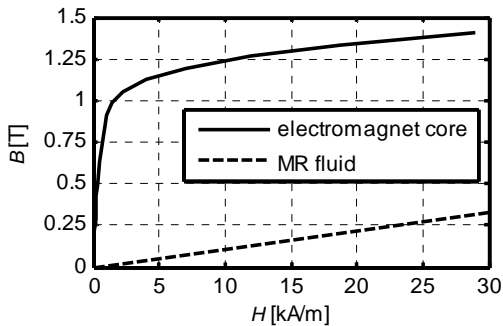

Fig. 4. Magnetisation characteristic of MR fluid and the electromagnet core

4. CALCULATION RESULTS

The calculation procedure is applied to obtain the magnetic flux density *B* and magnetic field strength inside the MR fluid layer. First the magnetic flux density is determined in the area between the electromagnet poles, without the beam present. Simulation results are then compared with measurement data. The measurements consist in varying the current *I* in the electromagnet coil from 1 to 10 A, with the step 0.5 A. In each case the magnetic flux density *B* is measured for three gaps *δ:* 20, 25, 30 mm. Registered values are then used to derive the static characteristic of the electromagnet. Fig. 5 shows the experimental data (continuous line) against the simulation results (broken line) for the air gap *δ*=20 mm (black) and *δ*=30 mm (grey). It appears that the proposed model sufficiently well emulates the behaviour of the real system. The discrepancies may be attributable to certain inadequacies of *B–H* characteristics of the electromagnet core. For example, all the details relative to connecting the electromag-

net arms are left out from the modelling procedure and a 2D model can only approximate any real system. 2D models take into account the magnetic flux distribution in two directions only, that is why the calculation results seem to be overestimated in relation to measurement data.
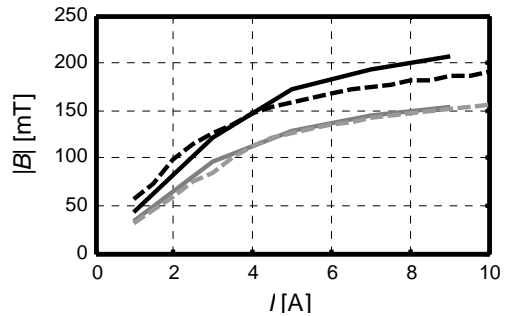

Fig. 5. Magnetic flux density *B* in the gap vs. current *I*

The experimental procedure is applied in which the MR beam is placed centrally in the gap of the electromagnet *δ*=20 mm (Fig 3). Magnetic properties of MR fluid are duly taken into account in the context of the magnetisation characteristics (Fig 4). The distribution of magnetic flux density *B* and magnetic field strength *H* in the middle of the MR fluid layer for the beam placed symmetrical z_u=0 mm (no static deflection) and for three selected currents *I* are shown in Fig. 6 and 7 (*I*=1 A – dashed line, *I*=5 A – continuous line, *I*=9 A – dotted line). It is apparent that flux density assumes higher values in the middle of the MR fluid layer (for *x* in the range from -15 to 15 mm), and decreases beyond the MR fluid. In the case of magnetic field strength, however, the situation is just the opposite.
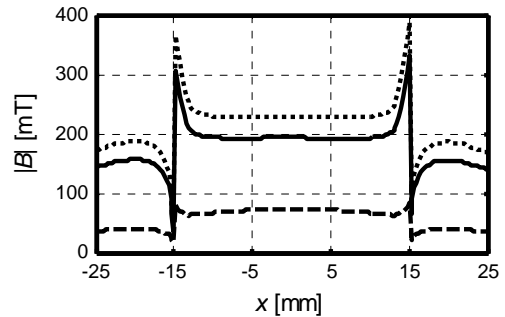

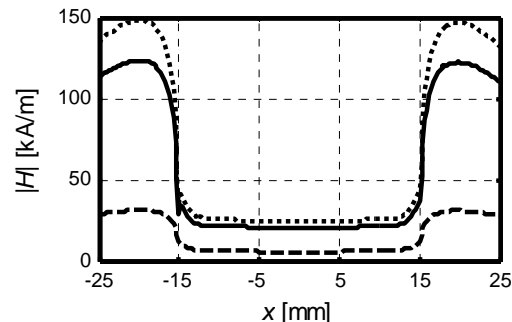**Fig. 6.** Distribution of magnetic flux density *B* along the *x*–axis; z_u=0 mm

Fig. 7. Magnetic field strength *H* along the *x*–axis; z_u=0 mm

The further step of the calculation procedure is applied to investigate the flux density distribution in the middle of the MR fluid

layer in the case when the beam's cross-section is displaced by z_u=2 and 5 mm, the electromagnet gap being δ=20 mm. Vertical displacement of the beam's cross-section is associated with static deflection or the beam' movements during vibration. Results are shown in Fig. 8 and 9, line designations as in Fig. 6. Apparently the flux density distributions for the two values of z_u are nearly identical and follow the same pattern. Higher values of B are registered in the middle of the MR layer (for x ranging from -15 to 15 mm) than beyond the beam. Flux density distributions for two beam positions: z_u=0 mm and z_u=5 mm are compared in Fig. 10.
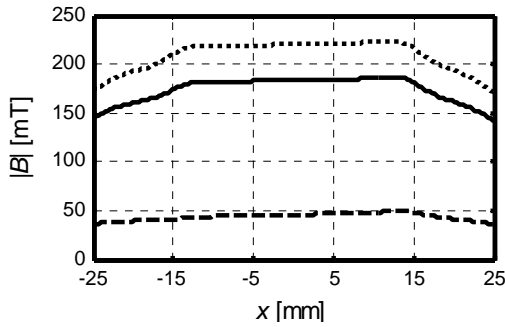
The flux density distribution shown in Fig. 10 reveals major differences on the beam edges only, for x=−15 mm and x=15 mm. In quantitative terms, the flux density in the MR fluid layer and outside the beam is quite similar.

Further, the distribution of magnetic flux density B in MR fluid is obtained in the function of current I. Results are summarised in Fig. 11, for the applied current levels I: 1, 3, 5, 7, 9 A, revealing the pattern of flux density variations in the middle part of the MR fluid layer with current I. MR fluid contains a ferromagnetic material, that is why an increase of the external magnetic field strength H at the certain point reaches the state of saturation.

The works (Sapiński et al., 2010; Snamina et al., 2010) focus on the developed FEM model of a cantilever sandwich beam (Fig. 2) and identification of its parameters. The MR layer is modelled in terms of the Kelvin-Voigt rheological model, comprising a spring and a viscous damper connected in parallel. Its schematic diagram is shown in Fig. 12. The spring stiffness is expressed by the parameter k_p, whilst c_p is the damping coefficient.

Parameters k_p and c_p are identified by comparing the computed first natural frequency f_o and the modal damping coefficient ζ with experimental data. The relationship between those parameters and magnetic flux density B in the middle section of the MR layer is shown in Fig. 13 and 14, revealing a similar variability pattern of these two parameters. In qualitative terms, that agrees well with research data provided in the work (Sun et al., 2003). The authors relied on the loss coefficient G'' when defining the energy dispersion level whilst the coefficient G' applies to energy conservation.

Fig. 8. Flux density distribution B along the x–axis; z_u=2 mm
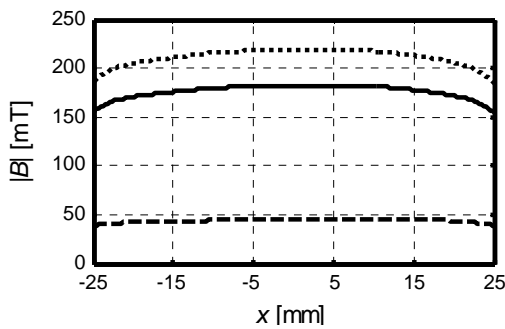

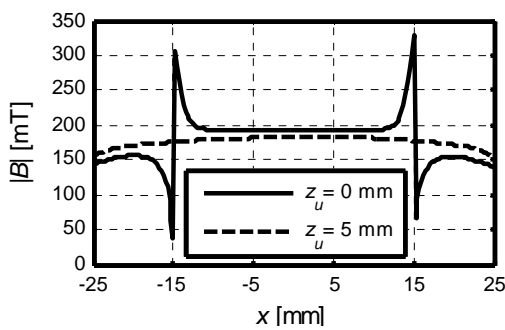**Fig. 9.** Flux density distribution B along the x–axis; z_u=5 mm

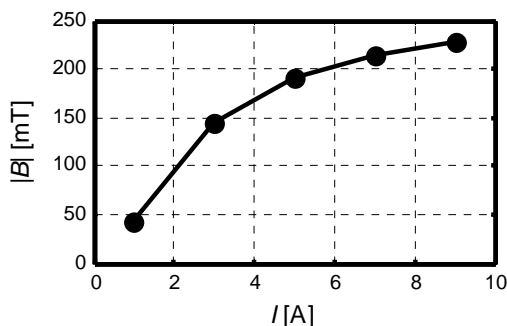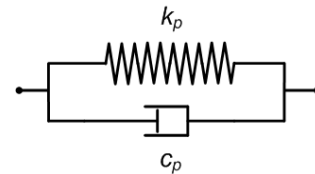**Fig. 10.** Flux density distribution B along the x–axis; I= 5 A

Fig. 11. Flux density B in the middle of MR layer vs. current I

Fig. 12. Kelvin-Voigt rheological model
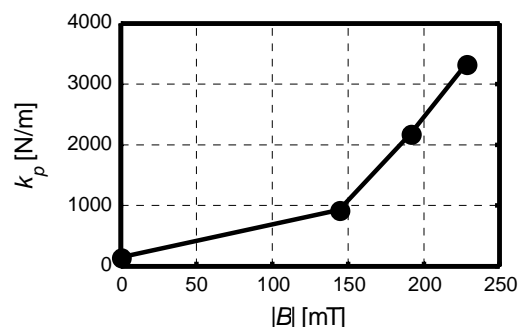

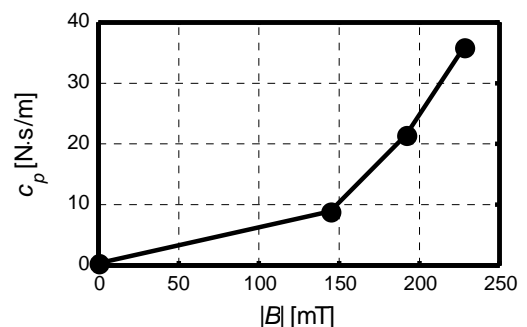**Fig. 13.** Stiffness k_p of the MR fluid model vs. magnetic flux density B

Fig. 14. Damping c_p of the MR fluid model vs. magnetic flux density B

Simulation results illustrate the influence of magnetic field on vibration parameters of the beam. Investigated parameters describing the beam vibration are: the first natural frequency f_o and the modal damping coefficient ζ. The values of f_o and ζ are obtained by investigating the beam's free vibration in the test rig designed specifically for the purpose of the research program (Sapiński et al., 2010).

The influence the electromagnet configuration y_m and magnetic flux density B on the first natural frequency fundamental free vibration frequency f_o is illustrated in Fig. 15. Magnetic flux density B in the MR layer is varied by changing the current level I in the electromagnet coils. It appears that as the electromagnet moves farther from the fixed end of the beam (y_m increased to 80 mm) and magnetic flux density B increases, the first natural frequency of the beam will increase, too and the beam stiffening effect is observed in the range y_m<80 mm. Moving the electromagnet any further y_m>80 mm enhances the non-uniformity of magnetic field acting upon the vibrating beam. As the result, the first natural frequency f_o will decrease. The value of the first natural frequency with no magnetic field is 8.92 Hz.
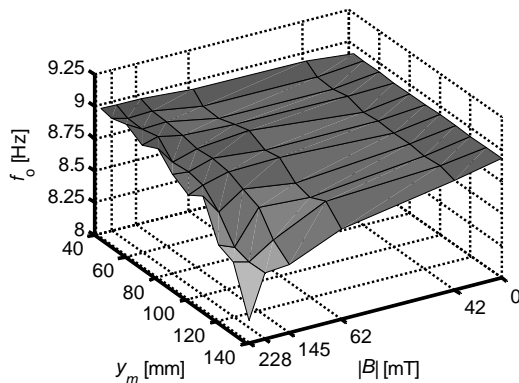

Fig. 15. Free vibration frequency f_o of the beam vs. the electromagnet position y_m and flux density B; δ=20 mm

The influence of the electromagnet position y_m and magnetic flux density B on the modal damping coefficient ζ is shown in Fig. 16. In qualitative terms, the distribution of the damping coefficient is similar to that of the natural frequency. As the electromagnet is moved farther from the fixed end of the beam (y_m increased to 80 mm) and magnetic flux density B increases, the value of the dimensionless damping ratio will increase, too, and the damping performance of the sandwich MR beam increases relatively fast. The value of the modal damping coefficient in the absence of magnetic field is 0.009.
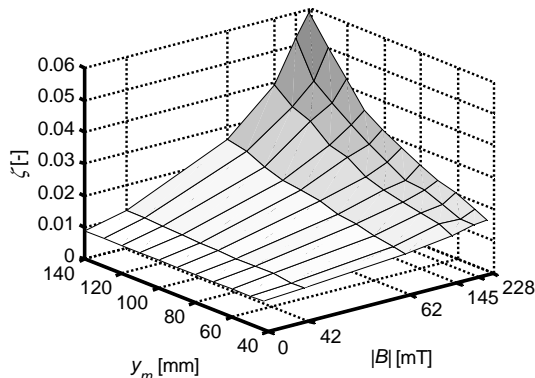

Fig. 16. Modal damping coefficient ζ vs. the electromagnet position y_m and flux density B; δ=20 mm

5. CONCLUSIONS

Underlying the 2D model of the beam-electromagnet system is the FEM approach supported by the Opera-2d software. The electromagnet is used as a source of magnetic field to interact with the MR fluid layer embedded in the sandwich beam. The model enables us to find the magnetic field distribution in the gap of the electromagnet- when empty and with the beam placed there. The study also investigates the influence of the MR fluid layer position with respect to the electromagnet poles. The change in the MR fluid layer position is due to either static deflection or beam vibrations.

Calculated parameters of magnetic field are used to establish the relationship between magnetic flux density and parameters of the adopted Kelvin-Voigt rheological model, emulating the properties of the MR fluid layer (Sapiński et al., 2010; Snamina et al., 2010). In qualitative terms, the results obtained by the authors agree well with research data reported in literature (Sun et al., 2003).

Finally, the study investigates the influence of the magnetic flux density in the middle part of the MR fluid layer on the value of the modal damping coefficient and the first natural frequency.

Research work is now underway to develop a 3D model of the beam-electromagnet system, using the Comsol Multiphysics software.

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