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VIBRATION PARAMETERS OF SANDWICH BEAMS WITH TWO TYPES OF MR FLUID

SUMMARY

The study presents the results of laboratory studies on free vibrations of sandwich beams filled with magneto-rheological (MR) fluids characterised by various proportions of ferromagnetic particles by weight. Based on the obtained results, it was possible to determine the impact of the content of the particles in question on the natural frequency of free vibrations and the dimensionless damping coefficient of beam.

***Keywords**: beam, MR fluid, vibration*

PARAMETRY DRGAŃ BELKI
Z CIECZAMI MR O RÓŻNEJ ZAWARTOŚCI CZĄSTEK FERROMAGNETYCZNYCH

W pracy przedstawiono wyniki badań laboratoryjnych drgań swobodnych trójwarstwowych belek wypełnionych cieczami magnetoreologicznymi (MR) o różnej zawartości wagowej cząstek ferromagnetycznych. Na podstawie uzyskanych wyników określono wpływ zawartości tych cząstek na podstawową częstotliwość drgań własnych i bezwymiarowy współczynnik tłumienia belki.

***Słowa kluczowe**: belka, ciecz MR, drgania*

1. INTRODUCTION

MR fluids belong to a group of intelligent materials characterised by a rapid change of viscosity (within a few milliseconds). The introduction of MR fluids to such systems as beams, plates, shells, etc. enables the changing of their stiffness and damping properties under the impact of a magnetic field. This study presents the analysis of the impact of the proportions of ferromagnetic particles by weight in MR fluids on the dimensionless damping coefficient, as well as the natural frequency of free vibrations for two beams, filled with MR fluids of the 122EG and 132DG types, made by Lord Corporation (www.lord.com). The fluid contained in the beams was activated by a magnetic field generated by an electromagnet. The data required for the analysis was obtained by the registering of free vibrations of the beams along their length, in a magnetic field, characterised by variable intensity and different locations of the field.

Comparative studies of MR fluids with various proportions of ferromagnetic particles by weight, contained in the carrier fluid (made on the basis of water and hydrocarbon), in the tension loading mode have been presented herein (Mazla *et al*. 2009). The tests discussed in the study (Lara-Prieto 2010) were carried out on aluminium and PET (polyethylene terephthalate) beams. The MR fluid contained in the beams was activated by permanent magnets located in different positions along the beams' lengths. The study demonstrates the impact of the magnets' location and magnetic flux density on the damping and stiffness properties of the beams.

The authors had previously conducted research into free vibrations of cantilever sandwich beams using MR fluid in a magnetic field. The field referred to in the study (www.lord.com) was generated by a system of permanent magnets, while the field referred to in the other study (Sapiński *et al*. 2010a) was generated by an electromagnet located in different places along the beams' lengths. The results of the studies enabled the determining of the impact of magnetic field strength on the damping and frequency of free vibrations of the beams, as well as the identifying of the parameters of the adopted model.

2. BEAM STRUCTURE

The object of the study was the cantilever sandwich beams filled with MR fluid. Figure 1 presents a schematic of the beam's structure. The two external aluminium layers had the following dimensions: length l = 400 mm, width b = 30 mm and height h_1 = 2 mm (each). The space between both layers was sealed with silicone rubber: height h_2 = 2 mm and width g = 1.5 mm. The insides of both beams were filled with MR fluids manufactured by Lord Corporation, characterised by a variable content of ferromagnetic particles. The first beam contained the 122EG fluid, while the other the 132DG fluid. The weight of both beams without the fluid totalled 140 g. When filled, their weight was: 190.6 g for the beam with the 122EG fluid and 223.1 g for the beam with the 132DG fluid.

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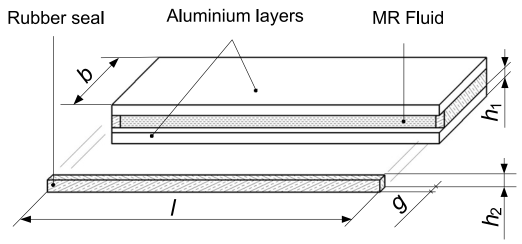

Fig. 1. Structure of the beams

Table 1 presents the basic parameters of the MR fluids used in the studies. The fundamental difference between both fluids was the proportions of ferromagnetic particles by percentage. The ferromagnetic particles were made of carbonyl iron and put into a hydrocarbon-based carrier fluid. An increase of iron particles in MR fluid translates to an increasing in its viscosity and density. Such changes influence the characteristics of magnetisation properties $B(H)$ and the yield point τ_o. The magnetisation properties of the 122EG and 132DG fluids have been presented in Figure 2. The stresses at the yield point τ_o as a function of magnetic field strength have been demonstrated in Figure 3.

Table 1

Parameters of MR fluids used in the studies

Parameter	122EG	132DG
Solids content by weight [%]	72	80.98
Density [g/cm^3]	(2.28, 2.48)	(2.98, 3.18)
Viscosity [Pa·s]	0.042	0.092

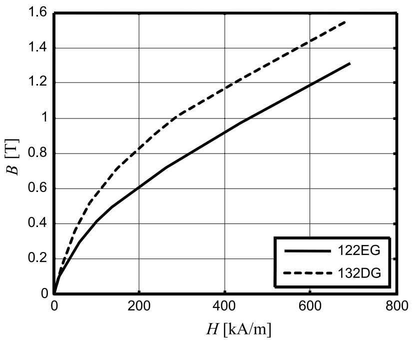

Fig. 2. MR fluid magnetic properties

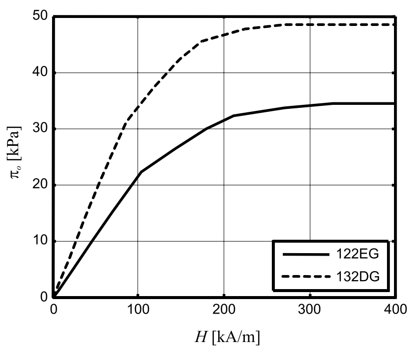

Fig. 3. Yield point of MR fluids as a function of magnetic field strength

3. EXPERIMENTAL SET-UP

The diagram of the experimental set-up used to carry out the study has been presented in Figure 4. The tests were focused on free vibrations by registration of the displacement $z(t)$ of point P on the free end of the beam. The magnetic field was generated by an electromagnet of a special design, powered by DC current I. The measurements of free vibrations were made by the changing of the current I and the location of electromagnet y_m (measured from the beam's clamped point to the centre of the electromagnet's core). The current of the intensity I was going through the coils of the electromagnet and generated a magnetic field of the intensity H in the gap of the electromagnet. The magnetic field strength H for the current level I of 1–9 A was within the range of (45–148) kA/m. The beams were tested in identical conditions, and the height of the electromagnet's gap was 20 mm. The displacement $z(t)$ of the beam's free end was measured with a laser displacement sensor. The acquisition of data was carried out by a National Instruments DAQ-Pad 3345 measuring card connected to a portable computer with DasyLab v.10 software.

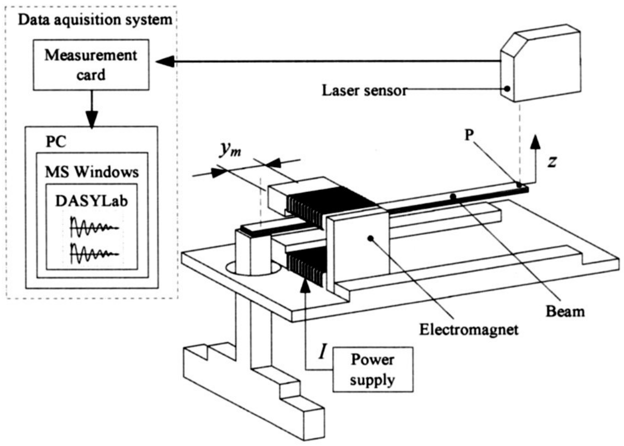

Fig. 4. Diagram of the laboratory test stand

4. EXPERIMENT

The first stage of the study consisted of the registration of the displacement of point P of the beams without the impact of the magnetic field. Figure 5 presents the displacement $z(t)$ of the beam filled with the 122EG fluid and the 132DG fluid. The differences in the characteristics for both beams are the result of the differences in the weights of the tested objects. Vibration of the beams in the magnetic field were then carried out. The tests were carried out for the following positions of the electromagnet y_m: 40, 50, 60, 70, 80, 90, 100, 110, 120, 130 and 140 mm, as well as the following magnetic field strength H: 45, 101, 127, 139 and 148 kA/m. Figure 6 presents sample displacements $z(t)$ of the beams in the magnetic field. The diagrams enabled the observation of a difference in the damping of the beams subjected to the impact of the magnetic field, depending on the content of ferromagnetic particles in the MR fluid.

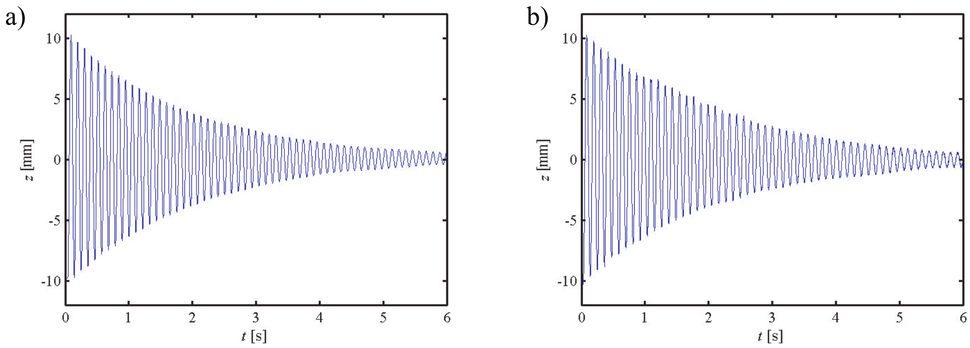

Fig. 5. Displacement of the beam's free end; H = 0 kA/m: a) 122EG fluid; b) 132DG fluid

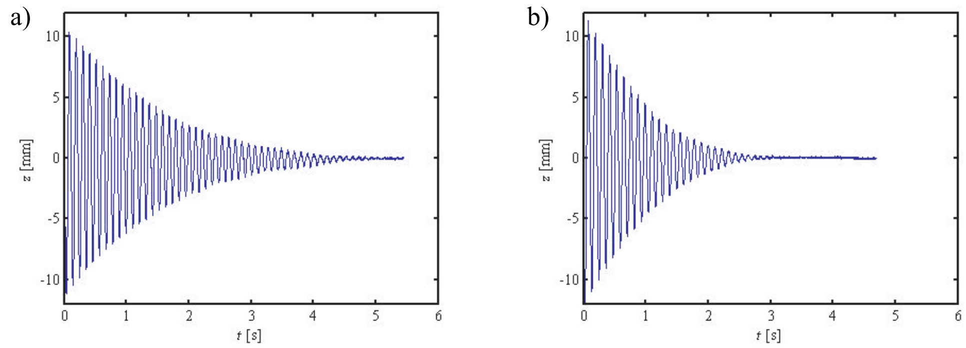

Fig. 6. Displacement of the beam's free end; H = 127 kA/m, y_m = 90 mm: a) 122EG fluid; b) 132DG fluid

5. DISCUSSION

The displacement $z(t)$ for various positions y_m of the electromagnet and the magnetic field strength H for the beams filled with the 122EG and 132DG fluids enabled the calculation of the vibration parameters of the beams. The frequency of free vibrations f_0 and the dimensionless damping coefficient ζ were determined for the first mode of free vibrations.

The characteristics presented in Figure 5 indicate a significant impact of both the magnetic field and the content of the MR fluid's ferromagnetic particles on the beams' vibrations. The dimensionless damping coefficient was used to describe vibration damping. In order to do so, the values of each successive amplitude Z_i and the times of their occurrences t_i were read from the diagrams. An amplitude range of 0.5–10 mm was adopted for the purposes of data analysis. The changes in the value of the dimensionless damping coefficient ζ as a function of the amplitude Z was estimated on the basis of the following relationship:

$$\zeta(Z)\bigg|_{Z=\frac{1}{2}(Z_i+Z_{i+1})} = \frac{1}{2\pi}\ln\frac{Z_i}{Z_{i+1}} \tag{1}$$

A equivalent dimensionless damping coefficient ζ_z was then determined, which characterised the vibration of the beam in certain conditions (the magnetic field strength H and location of its impact y_m):

$$\zeta_z = \frac{1}{2\pi(n-1)}\ln\frac{Z_1}{Z_n} \tag{2}$$

where n is the number of cycles.

No changes in the frequency of damped vibrations f_t as a function of the amplitude Z were observed in the tested range of amplitudes. An average frequency of damped vibrations f_t was determined for each measurement according to the formula (3), and then the natural frequency of free vibrations without damping f_0 was calculated using (4).

$$f_t = \frac{n}{t_n - t_1} \tag{3}$$

$$f_0 = \frac{f_t}{\sqrt{1-\zeta_z^2}} \tag{4}$$

Table 2 presents the calculated values of the natural frequency of free vibrations f_0 and the equivalent dimensionless damping coefficient ζ_z for the beams without the impact of the magnetic field.

Table 2

Parameters of vibrations for the tested beams;
H = 0 kA/m

Parameter	122EG	132DG
f_0 [Hz]	9.31	8.92
ζ_z [–]	0.0084	0.0090

The characteristics of the dimensionless damping coefficient as a function of the amplitude $\zeta(Z)$ were determined on the basis of the analysis of the free vibrations of the beams in the magnetic field and using the formula (1).

The obtained results were interpolated with a linear function. The criterion for the selection of the linear function coefficients was the minimum mean square error. Figure 7 presents selected results for the dimensionless damping coefficient ζ determined through the experiment and approximated with a linear function. The diagrams demonstrate the nature of the changes ζ and justify the selection of a linear function to make an interpolation.

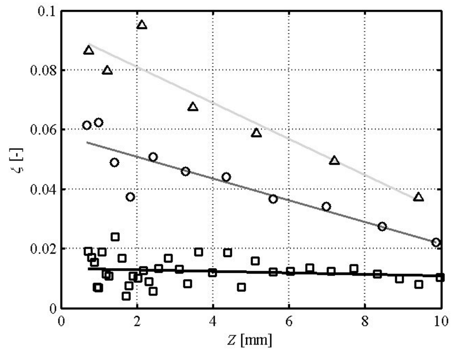

Fig. 7. Interpolation of the dimensionless damping coefficient ζ as a function of the vibration amplitude Z

Figures 8, 9 and 10 present the relationship between the dimensionless damping coefficient ζ as a function of the vibration amplitude Z for the beams with the 122EG and 132DG fluids. The results show the influence of the location y_m of the magnetic field and its strength H in the gap of the electromagnet on the damping of a cantilever sandwich beam. The electromagnet was located with a distance of 40, 90 and 140 mm from the beam's clamped point, while the magnetic field strength H was: 45, 127 and 148 kA/m. If H = 45 kA/m, the dimensionless damping coefficient demonstrates hardly any changes. In this case, the object demonstrates the properties of a linear object with viscous damping, where ζ(Z) = const. Decrease in the vibration amplitude of the beam usually translates into an increase in the dimensionless damping coefficient. The closer the magnetic field is to the free end of the beam and the higher the strength H of the field, the greater the changes. The 132DG fluid with a higher content of ferromagnetic particles demonstrates a greater increase in the dimensionless damping coefficient ζ.

Having determined the dimensionless damping coefficient as a function of the amplitude ζ(Z), the parameter describing the vibrations of the beams were calculated. The first parameter was the equivalent dimensionless damping coefficient ζ_z, while the other parameter was the natural frequency of free vibrations f_0. Figure 11 demonstrates the relationship between the equivalent dimensionless damping coefficient ζ_z as a function of the magnetic field strength H and the location y_m of the electromagnet. The increase in both H and y_m results in the increasing of the dimensionless damping coefficient: for the 122EG fluid, by 270%, and for the 132DG fluid, by 752%, respectively.

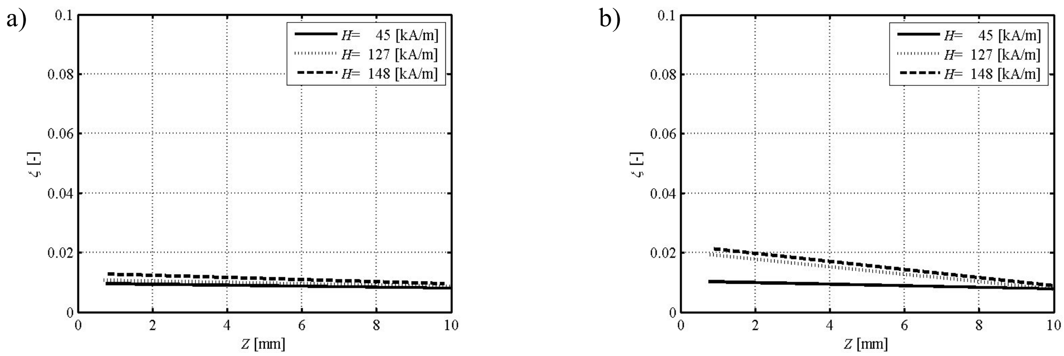

Fig. 8. Dimensionless damping coefficient ζ as a function of the vibration amplitude Z for the beam filled with: a) 122EG fluid; b) 132DG fluid; y_m = 40 mm

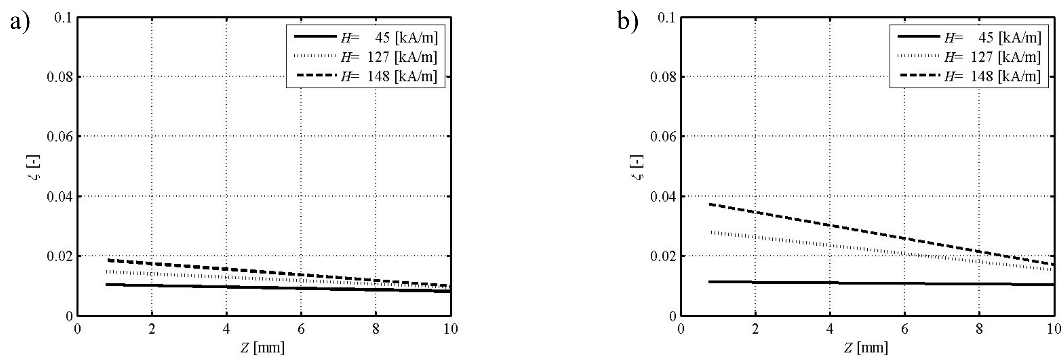

Fig. 9. Dimensionless damping coefficient ζ as a function of the vibration amplitude Z for the beam filled with: a) 122EG fluid; b) 132DG fluid; y_m = 90 mm

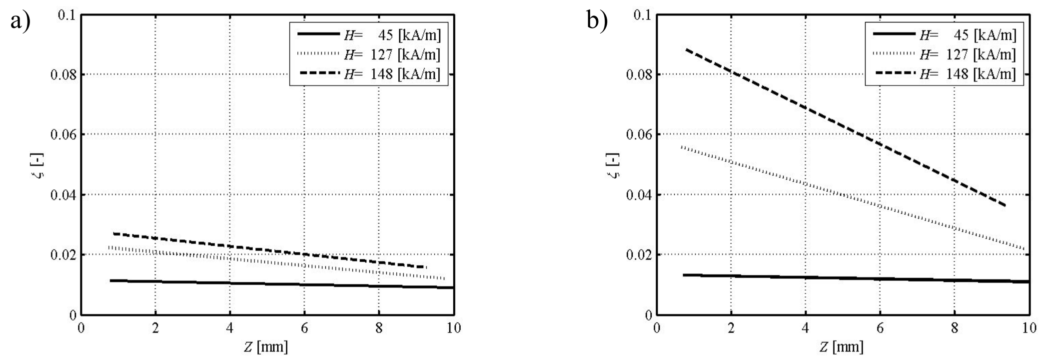

Fig. 10. Dimensionless damping coefficient ζ as a function of the vibration amplitude Z for the beam filled with: a) 122EG fluid; b) 132DG fluid; y_m = 140 mm

The changes are greater in the case of the 132DG fluid, which is characterised by a higher content of iron particles.

Another one of the analysed parameters was the basic frequency of free vibrations. Figure 12 presents the relationship between the frequency of free vibration f_0 and the intensity of the magnetic field H and its location y_m. The existence of a limiting location of the electromagnet y_m = 80 mm was also observed. When y_m < 80 mm, the MR sandwich beam demonstrates a stiffening phenomenon. The frequency of free vibrations is increased by a mere 1% for the 132DG fluid and 2.4 % for the 122EG fluid in relation to the f_0 coefficient without the magnetic field (H = 0 kA/m). An increase in the distance between the electromagnet and the beam's clamped point. translates into an increase in the impact of the non-homogenous of the magnetic field that affects the vibrating MR sandwich beam. The dominant influence of the non-homogenous of the magnetic field is observed at y_m > 80 mm. In this area, the coefficient that describes the storage of energy is lower than the coefficient that describes the dissipation of energy (Mazla *et al*. 2009). This results in a relatively fast increase in the damping of the beam filled with the MR fluid (Fig. 11). It was observed that the frequency of free vibrations f_0 was reduced for the 122EG fluid by –1.3%, and for the 132DG fluid by –9%, respectively.

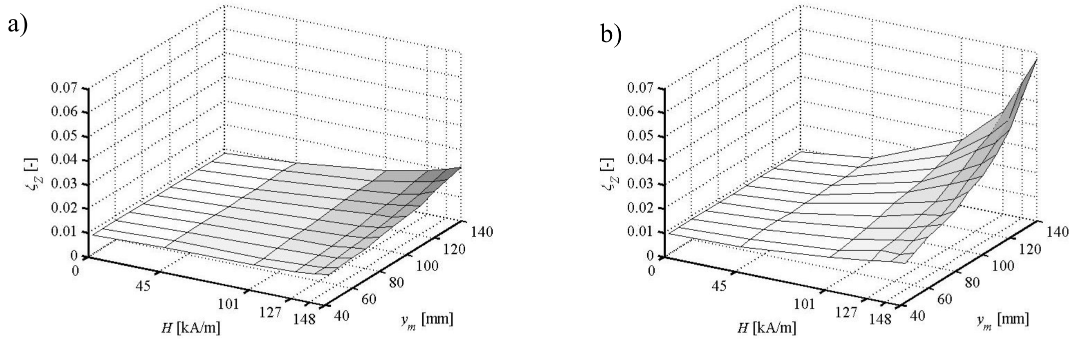

Fig. 11. Relationship between the dimensionless damping coefficient ζ_z and the magnetic field strength H and the location of the electromagnet y_m: a) 122EG fluid; b) 132DG fluid

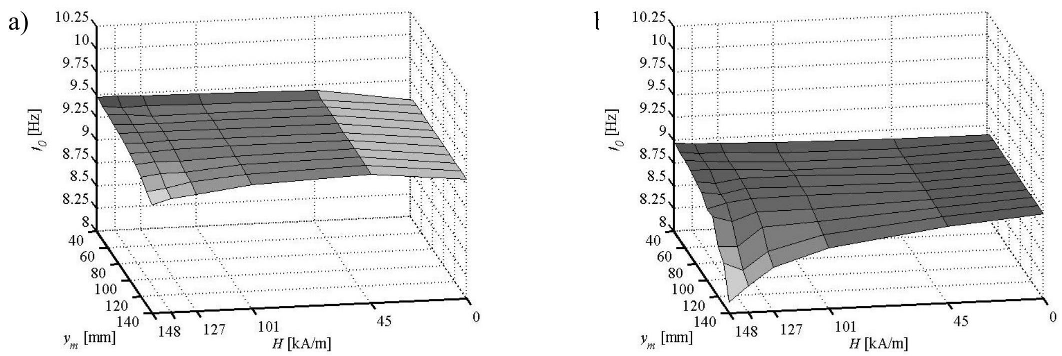

Fig. 12. Relationship between the frequency of free vibration f_0 and the magnetic field strength H and the location of the electromagnet y_m: a) 122EG fluid; b) 132DG fluid

6. SUMMARY

The study presents a comparison between the characteristics of damping and stiffness for two beams with MR fluids characterised by different content of ferromagnetic particles by weight. It was possible to determine the impact of the content of the particles in question on the basic frequency of free vibrations and the dimensionless damping coefficient of beam. It was determined that:

- the beams filled with the fluid characterised by a higher proportion of ferromagnetic particles demonstrate higher changes in the dimensionless damping coefficient and the natural frequency,
- an increase in the intensity of the magnetic field results in an increase in the dimensionless damping coefficient,
- the change in the location of the magnetic field towards the direction of the free ends of the beams results in an increase in the damping effect,
- various locations of the magnetic field along the beams' length results in the changing of the basic frequency of free vibrations.

Further stages of the tests will focus on forced vibrations and frequency characteristics of the beams.

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