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Dynamic Performance of a Novel Magnetorheological Pin Joint*

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Abstract

Magnetorheological fluid (MRF) has received significant attention lately and MRF based devices have been proposed for structural control applications in recent years. The unique characteristics of MR fluid lies in its abilities to reversibly, repeatedly and instantly change from a free flowing liquid to a semi-solid state when exposed to a magnetic field. The electric power required to drive the MR devices can be easily provided by a battery. Possessing such unique properties, MR fluid based devices, such as MR damper, have become promising candidates in the semi-active control for civil structure applications. However, most of the published research has focused on application of MR dampers instead of exploring other type of MR devices. In addition, MR based devices exhibit complex nonlinear hysteresis behaviour and thus making their modelling a challenging task.

In this paper, a novel MR fluid based device, namely MR pin joint, is proposed as a smart structural member in development of an intelligent civil structure that can suppress unwanted vibrations to ensure safety and serviceability of the structure. After design and fabrication, experiments have been conducted to characterise dynamic behaviours of the new device under different harmonic excitations with various input currents. Response time of the MR pin joint is compared when the MR pin joint is driven under different applied currents and moving speeds. Test data shows that the MR pin joint possesses a unique behaviour in the moment-angular velocity plot. A hyperbolic hysteresis model is proposed to model such unique behaviour. The investigation presented in the paper explores dynamic performance of MR pin joint. Finally, a parametric model is developed following the investigation on the correlation of coefficients in the proposed model with the loading conditions and applied currents.

Key words: Magnetorheological Fluid, Hyperbolic Hysteresis Model, Parameter Identification

1. Introduction

Magnetorheological fluid (MR fluid) is a type of smart fluid in which tiny Ferro-particles suspend in a carrier fluid, usually a type of oil. Normally, at zero magnetic field the iron particles, including big-size spherical shape particles and smaller-size irregular shape particles, randomly scatter in the carrier oil (silicon oil) and the additives in the MR fluids will prevent the micro-size iron particles from sedimentation. Exposure to a magnetic field transforms MR fluids to a plastic-like solid in milliseconds. Removal of the magnetic field allows the fluid to return to its original state [1-2]. The induced chain structure can be broken under flow when the stress caused by the flow exceeds the yield stress of the MR

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fluid. Due to exceptional characteristics of MRF, many explorations and investigations have been undertaken in its use on the development of vibration reduction devices, such as dampers, brakes and clutches [3-4].

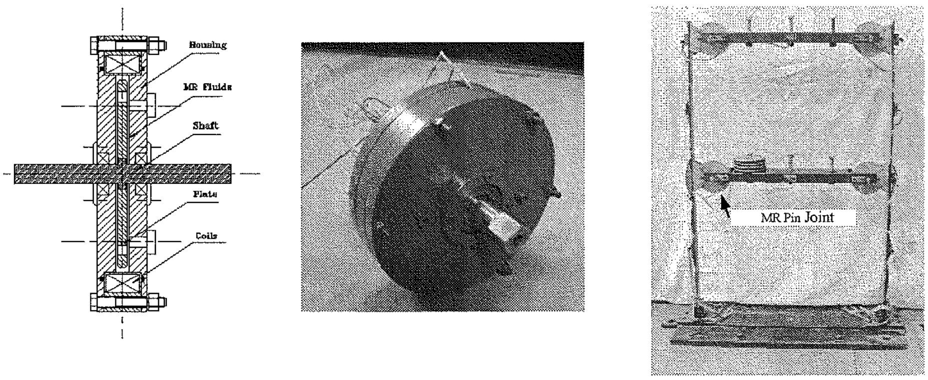
Much work on vibration control of civil engineering applications using MR devices has been undertaken recently. Xu [3] theoretically investigated two optimal displacement control strategies for semi-active control of earthquake-excited structures using ER or MR dampers. Dyke [4] studied acceleration feedback control in a three-storey building model with MR brace installed in the first floor only. The research findings have demonstrated the effectiveness of semi-active control of civil structure using MR structural members. Till now, MR fluid based smart devices for seismic protection normally refer to MR dampers. In the published research, other types of MR devices for civil engineering applications are very limited [5-7].

In this paper, after a detailed introduction of new MR pin joint and its potential application in civil engineering, comprehensive experimental investigations are presented. To explore the characteristics and full potential of the MR pin joint, experimental research was conducted by investigating its response time and hysteretic behaviour. The MR pin joint is applied with different levels of current input to create varying applied magnetic fields, respectively, during the tests. In order to portray the behaviours of the MR pin joint, a novel mathematical model, containing a hyperbolic hysteresis element, rotational spring and rotational viscous damping, is introduced. Discussions are provided on the accuracy and effectiveness of the proposed new model.

2. MR Pin Joint and its Application in Civil Engineering

2.1 MR pin joint

MR pin joint, Figure 1a) and b), is designed as a smart structural member whose joint moment resistance can be controlled in real-time by altering the applied current. It mainly consists of five parts: a rotary thin plate inside the pin joint, a shaft connected to the plate to transfer the joint moment, two uniform housings to form the hollow cavity, MR fluids between the housing and the plate, and a circular coil producing magnetic field to magnetise MR fluids. Between the shaft and the housing, two bearings are placed to ensure the rotary motion of the device. Because of the unique features of MR fluids, MR pin joint is capable of instantly changing its moment resistance under a variable magnetic field. This device also has other advantages such as simple construction, low power requirement and fast response, thus enabling the physical parameters, such as stiffness, of a smart structure equipped with smart MR pin joints to be controllable in real-time.



a) Cross-section of MR pin   b) Second-generation MR pin   c) MR pins in a two-storey building frame

Figure 1. MR pin joint and its application to a civil structure

Detailed design parameters of the MR pin used in this paper can be found in Table 1. There are gaps of approximately 1 mm between the plate and the housings, to hold the MR fluid therein. Inside the gap is filled with MR liquid (MRF140CG) purchased from Lord

Corporation. The liquid can provide yield stresses up to 60 kPa at saturated magnetic field of B=1.0 T. Due to the high shear capacity of MR fluids, this MR pin joint can produce about 15Nm of torque with a saturated current of 2.0 A.

Table 1. Structural parameters of the MR pin joint (all in mm)

Shaft radius $\mathbf{R_1}$	12.5	Outer diameter **D**	140
Radius of rotary plate $\mathbf{R_2}$	40	Inner diameter **d**	90
Gap **h**	1	Thickness **B**	40

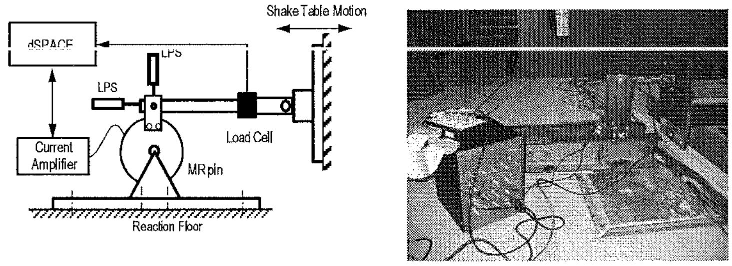
2.2 Potentials of MR pin joint in civil structures

In a civil structure, the smart pin joints can be used as controllable connectors in the column-beam connection, as shown in Figure 1c) to create a smart civil structure. By changing the electric current of the magnetic coils, the rigidity of the structural connection can be varied between fully rigid and fully pinned as well as any state in between. Thereby, the natural frequencies of civil structures can be shifted in order to avoid the resonant frequency region and therefore prevent damage to the structure. Researchers in University of Technology Sydney (UTS) have been pioneering the research on this novel structural member since 2005. Previous research by UTS researchers can be found in references [5-7]. The proposed simplified civil structure to be installed with MR pins is shown in Figure.1c). The structure consisted of two columns, two crossbeams and four joint elements. The columns were made of flat steel with a cross-section of 65 mm × 5.5 mm and a height of 1,600 mm and mounted on a steel base with a fixed connection. The distance between the two columns was 800 mm. The main body of the crossbeams consisted of a box section of 150 mm × 50 mm and a wall thickness of 3 mm. The crossbeams were located 700 mm and 1,400 mm above the steel base connection, respectively, and there was a spacing of 700 mm between the steel base connection and the lower beam, and between the two crossbeams.

3. Experimental Setup for Characterisation Test

An experimental setup to study behaviours of the MR pin joint was developed using the 10-tonne capacity, 3m x 3m MTS uni-axial shake table at the Structures Laboratory of the University of Technology Sydney, as shown in Figure 2. It was designed to obtain the moment vs. angular velocity relationship of the MR pin at different levels of magnetic field intensities and loading frequencies. In the setup, MR pin joint is firmly mounted to a stand on the floor outside the shake table. Two steel plates fixed on the housing of the pin were firmly attached to the shake table by a steel rod. A load cell, with the capacity of 300N, attached to the steel rod, was used to measure the force applied to the MR pin. A custom-designed current amplifier was used to supply currents to the magnetic coil in the MR pin, hence providing magnetic fields with desired intensities. Two linear position sensors were used to measure the horizontal and vertical displacements of the tip of the steel rod. Data from load cell and linear position sensor were recorded by the data acquisition system of the shake table control and acquisition system. In order to fully capture the desired dynamics of the MR pin joint, the sampling rate was set at 2,048 Hz. The dSPACE control kit, DS1104 and ControlDesk, were used to generate and monitor control signal to provide desired input to the amplifier.

During the test, shake table was moving horizontally with standard harmonic motions. Shake table movement drives the steel rod to drag/push the MR pin to swing through the steel plates amounted on the MR pin. It should be noted that the swinging movement of the MR pin is not a standard sinusoid rotation due to the rotary motion of the steel plates. Proper steps were taken to convert the force data into the torque data of the device. The two bearings placed in the connections of shake table and steel rod, as well as of steel rod and steel plates, ensure the smooth transition from horizontal movement of the shake table to the rotation of the experimental specimen.



a) Sketch map of experimental setup b) Experimental setup

Figure 2. Experimental setup for MR pin modelling test

4. Response Time of MR Pin Joint

Response time is an important measure to identify the dynamic performance of a device. The response time of a rotor system supported upon a disk-like MR fluid damper is measured by Zhu [8]. Koo et al [9] experimentally investigated the response time of a MR damper (commercial damper from Load Corporation) under various operating currents and piston velocities. Laun et al [10] studied the response time of a high-torque MR fluid limited slip differential clutch. It is quite natural to pay attention on the response time of the MR device when the current steps up from zero to a certain value. However, little research has been dedicated to the response time of MR device when the applied current falls from a certain value to zero current.

To experimentally investigate the response time, both rising and falling changes, of the MR pin joint, a series of tests were conducted using the UTS shake table facility. The shake table operated, by generating triangular waves, to ensure a steady velocity during the test. In the meantime, step currents were applied to the specimen with the aim to quantify the response time of the device. Specifically, the shake table ran at the velocities of 5 mm/s, 10 mm/s, 20 mm/s and 30 mm/s, respectively. Different currents, i.e. 0.5 A, 1.0 A, 1.5 A and 2.0 A, were applied to the MR pin. Those conditions were to investigate the impact of shear velocity and applied current levels on the response time. To maintain the accuracy of the data, each test was repeated three times.

In this research, the response time of the MR pin joint is defined as the time period from the instance when the dSPACE sends "step-up" or "step-down" signals to the instance when the moment output of the device reaches 63.2% of the steady state. Figure 3 illustrates the example on how to calculate the response time when the shake table moves at a velocity of 6 mm/s.

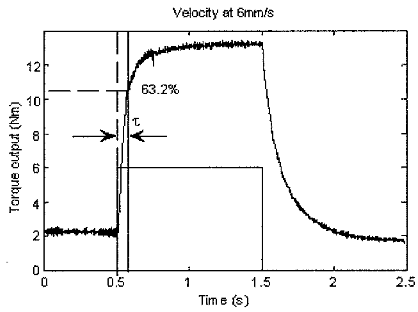
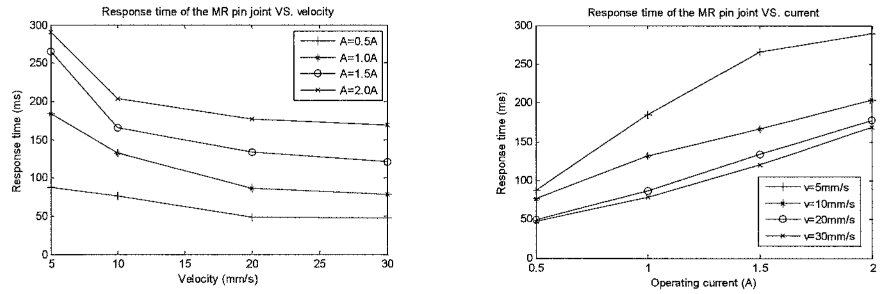


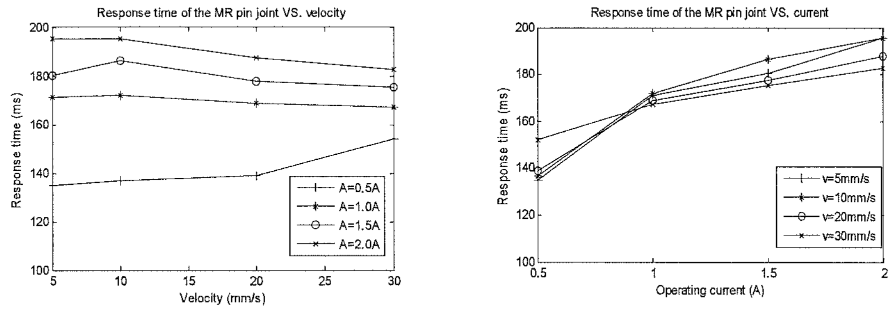
Figure 3. Definition of response time

Figure 4 shows the response time of the MR pin joint when it is applied with "step-up" current and Figure 5 shows the response time of the MR pin joint when it is applied with "step-down" current. Experimental results indicate that in the occasion of low velocity, representing low shear strain in MR fluid, the response time of the MR pin joint for "step-up" current is slightly longer that the cases when the velocities are higher. For example, when the applied current is 0.5 A, the response time along the velocity axis are 87 ms, 76 ms, 49 ms and 47 ms. It gradually come to the steady state when the velocities increase. On the other hand, the response time increases when the constant current levels go up when the device undergoes same moving velocity, as shown in Figure 4 b).



a) Response time VS Velocity b) Response time VS Current

Figure 4. Response time when the current steps up



c) Response time VS Velocity d) Response time VS Current

Figure 5. Response time when the current steps down

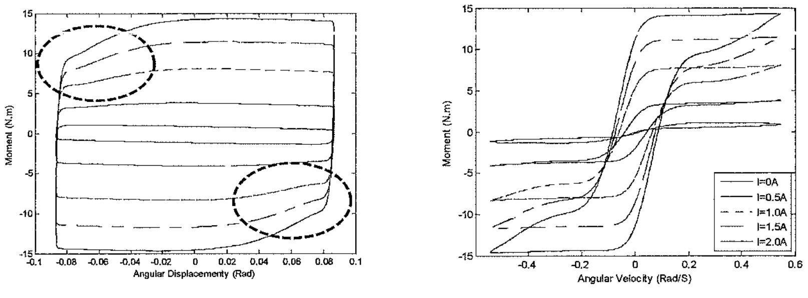
Comparatively, unlike the response time data of MR pin joint when experiencing the "step-up" current, the response time for "step-down" currents are much closer to each other under different moving velocities, as shown in Figure 5. The response time under "step-down" currents in various shear conditions varies from 135 ms to 195 ms; however, the response time under "step-up" currents in various shear conditions varies from 47 ms to 289 ms.

5. Behaviours of MR Pin Joint

Since the dominant frequencies of the earthquakes are generally below 5 Hz, the frequency range of the input sinusoidal waveform was set around 0.1-2Hz in the dynamic tests. A series of harmonic excitations at frequencies of 0.1, 0.5, 1.0 and 2.0 Hz, were simulated by the shake table to evaluate the nonlinear hysteretic behaviour of the MR pin joint. The amplitudes of the excitation were 35.20, 28.20, 17.65 and 7.06 mm, respectively, representing the maximum rotational angle of 2, 5, 8 and 10 degrees. During the tests, the MR pin joint was energised with various currents at 0, 0.5 1.0, 1.5 and 2.0A, respectively. To obtain stable test results, the measurements were taken after the MR pin joint had undergone several hundred cycles of testing.

5.1 Hysteresis loop of MR pin joint

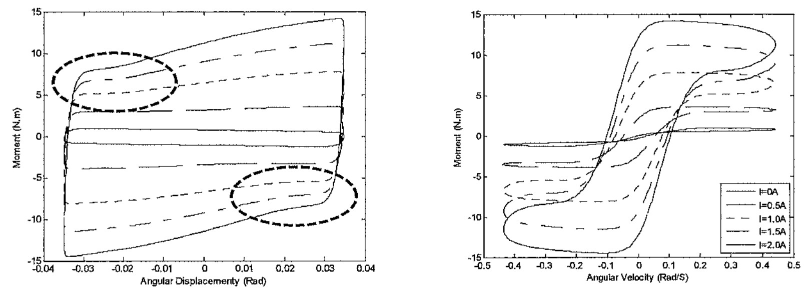
The responses of MR pin joint under a 1.0Hz sinusoid excitation with amplitude of 17.65mm is shown in Figure 7 and the responses of MR pin joint under a 2.0Hz sinusoid excitation with amplitude of 7.06mm is shown in Figure 8. All the figures are plotted at five different current levels, 0A, 0.5A, 1.0A, 1.5A and 2.0A, illustrated with different line styles. The moment-angular displacement loops are shown in Figure 7 a) and Figure 8 a) and the moment-angular velocity loops are shown in Figure 7 b) and Figure 8 b), respectively.



a) Moment vs. Angular displacement b) Moment vs. Angular Velocity

Figure 7. Experimental data for 1.0 Hz excitation with an amplitude of 17.65mm

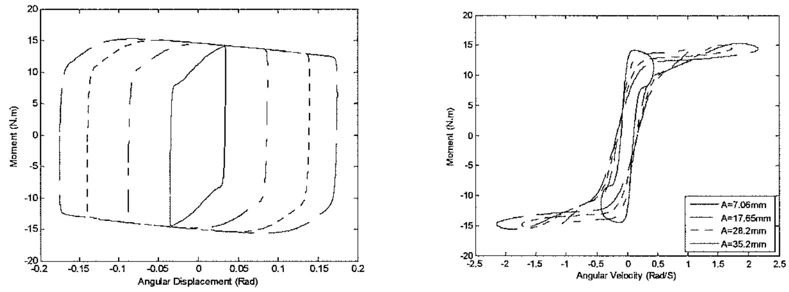
Experimental data on the outputs of moment resistance of the MR pin joint show a readily-observed increase in moment with elevated magnetic field. At the current level of 0A, the moment-angular displacement loop is approximately elliptical, representing a typical viscous behaviour of the device. Increasing the magnetic field leads to the expansion of the hysteresis loop and the increase of the slope of the hysteresis loop in roll-off region (low velocity area). Specially, when increasing the applied currents, the moment-angular displacement loop shows abnormity at high magnetic field when the angular displacement is negative and the angular acceleration is positive (or when the angular displacement is positive and the angular acceleration is negative). Note that the moment-angular displacement loops move in a clockwise direction and the moment-angular velocity loops moves in a counter-clockwise direction. For the case when I=2.0A in Figure 7a), the moment output rapidly climbs to 7~8 Nm and steadily increases to the saturation output when the angular displacement moves away from the negative displacement toward positive displacement. The abnormity in the moment-angular displacement loop is also reflected in the moment-angular velocity loop in Figures 7 b) and 8 b) as the fatty branches of the loop.



a) Moment vs. Angular displacement b) Moment vs. Angular Velocity

Figure 8. Experimental data for 2.0 Hz excitation with amplitude of 7.06mm

The measured moment at 1 Hz (Figure 7a)) reaches the saturation level when the angular displacement approaches zero. However, at 2 Hz (in Figure 8a)) the moment produced by the MR pin joint is still ascending after the angular displacement passes zero, even when I=2.0A. To find out the reason behind this behaviour, a comparative study is conducted for 2.0Hz excitation with various amplitudes: 7.06mm, 17.65mm, 28.2mm and 35.2mm, at the current level of 2.0A as shown in Figure 9. It can be observed from Figure 9 a) that the moment output of the MR pin joint under the 2.0Hz excitation with amplitude of 7.06 mm just reaches its maximum value when the angular displacement reaches positive maximum. When the excitation amplitude is greater than 7.06 mm, the measured moment initially increases at the same rate as that of amplitude 7.06 mm case and then steadily declines when the angular displacement increases. The obtuse turn indicates moment outputs are influenced by angular velocity. Reference [7] suggested that the absolute maximum/minimum value of the moment output is mostly related to the applied current and angular velocity has little effect on the peak moment output. However, the angular velocity of MR pin joint has distinct impact on the shape of the hysteresis loop, as shown in Figure 9 b).

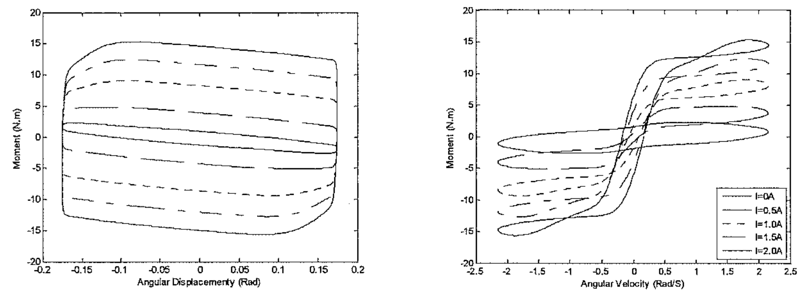


a) Moment vs. Angular displacement b) Moment vs. Angular Velocity

Figure 9. Experimental data for 2.0 Hz excitation with various amplitudes (I=2.0A)

5.2 "Crossover" behaviour of MR pin joint

Another interesting behaviour of moment-angular velocity loop is "crossover" which can be seen in Figure 10 b). When the angular velocity approaches its maximum value, either positive or negative, the moment output first gradually reaches the peak and then slowly drops down before the maximum angular velocity occurs, thus causing a crossover area in the two branches in the hysteresis loop, shown in Figure 10 b) when the amplitude of the movement is 28.2mm and 35.2mm, respectively. Generally, "crossover" behaviours appear at the two branches of the hysteresis loop when loading amplitude is large and the applied current also maintains a high level. The reason for this interesting phenomenon is that the moment output reaches the peak value after the angular displacement deviates from the maximum/minimum displacement and then gradually descends monotonically. Reflection of the change of moment output in moment-angular velocity loop is the "crossover" behaviour. Similar "crossover" features in the hysteresis loop were also reported in reference [11-13].



a) Moment vs. Angular displacement b) Moment vs. Angular Velocity

Figure 10. Experimental data for 2.0 Hz excitation with amplitude of 35.2mm

6. Rotational Hyperbolic Hysteresis Model

With emerging research on MR fluid based devices, there are continued interests in developing an efficient mathematical model to describe their dynamics. This work is interesting and yet challenging because of the nonlinearity and hysteresis that MR devices possess. Much effort has been devoted to develop comprehensive models that are able to describe the hysteretic behaviours of MR devices, including Bingham model [14], Chebyshev polynomials model [15], Bi-viscous model [16] and Bouc-Wen model [17]. In general, the most comprehensive models, such as Bouc-Wen model, are complex in form and difficult to be used in structural control applications. Hence, trade-off has to be made between the simplicity and accuracy of the model. It is, therefore, necessary to develop a simple and yet accurate model for MR device.

Despite the efforts in developing mathematical models for MR dampers, little consideration has been given to investigate the oscillatory behaviour of a rotational controllable device, such as MR pin in such research.

A computationally-efficient hyperbolic hysteresis model is proposed to portray the behaviour of the MR pin joint (Figure 11). The model consists of rotational spring k, viscous damping c and a hyperbolic hysteretic element [18] and can be formulated as:

$$T = c\dot{\theta} + k\theta + \alpha z + T_0 \quad (1)$$

$$z = \tanh(\beta\dot{\theta} + \delta sign(\theta)) \quad (2)$$

where T is the joint moment resistance from MR pin, θ and $\dot{\theta}$ are rotational angle and rotational velocity, respectively. c and k are viscous and stiffness coefficients; α is the scale factor of the hysteresis; z is the hysteresis variable, determined by variables β and δ; T_0 is the MR pin moment offset.

Coefficients α, β and δ are the most important parameters determining the features of the hysteresis loop. The scale factor α is responsible for the amplitude of the hysteresis loop along the y-axis. β defines the slope of the loop when it crosses zero velocity. δ defines the width of the loop in the middle without changing the sharpness of the two ends of the loop. Hence, α, β and δ are the major contributors to the features of the hysteresis loop. Viscous coefficient c is another coefficient representing the slope of the hysteresis loop. Stiffness coefficient k contributes to the opening of the hysteresis loop. Increasing k will enhance the opening of hysteresis loop not only near zero velocity but also at the two ends of the loop. T_0 corresponds to the y-axis offset of the moment-angular velocity hysteresis.

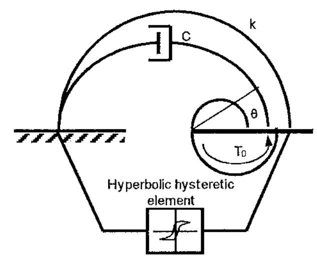
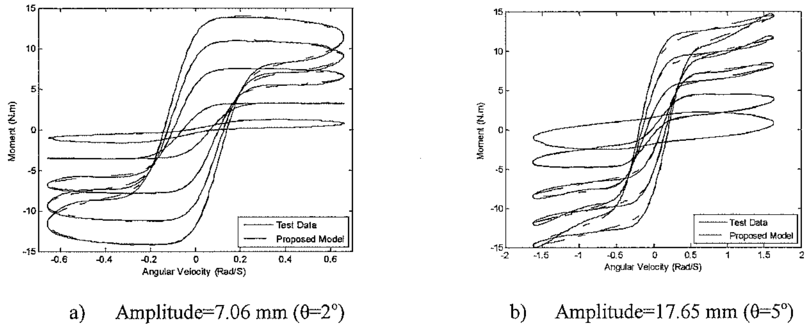


Figure 11. Rotational hyperbolic hysteresis model

In this model, a simple hyperbolic tangent function is used to describe the hysteresis loop of moment-angular velocity response of the MR pin joint. This model is able to keep simplicity and hence enhances computational efficiency. To identify the model parameters, a least-square method is deployed to find the best-fit parameters.

7. Discussions

Figure 12 provides a comparison between the experimental data and the estimation from the proposed model when loading frequency is 3.0Hz. Figure 12 a) represents the case when the displacement amplitude of the loading is small (i.e. 7.06 mm) while Figure 12 b) represents the case when there was a large displacement, i.e. 17.65 mm. As seen from the results, the proposed model is able to provide excellent match with experimental data.



a) Amplitude=7.06 mm (θ=2°) b) Amplitude=17.65 mm (θ=5°)

Figure 12. Comparison between the experimental data and the results from the analytical model under different loading conditions (f=3.0Hz)

To validate the effectiveness of the proposed model in describing the "crossover" behaviour of the MR pin joint, comparisons between test data and the predicted responses is presented in Figure 13. A "crossover" appears in two branches of the hysteresis loop. In the area of low velocities, both roll-off and crossover behaviours appear. The predicted behaviour of the MR pin by the proposed model is well-aligned with that exhibited in the experiment. It is able to capture the roll-off and cross-over in desirable manner.

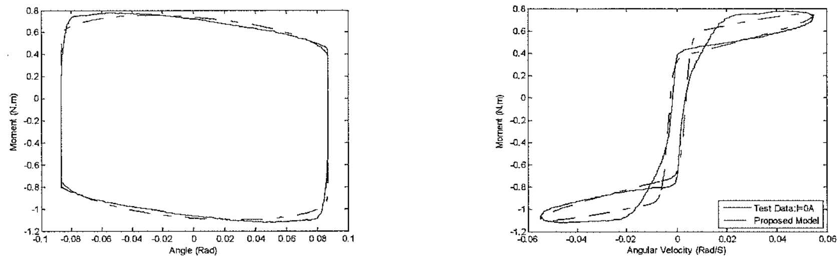


Figure 13. Comparison between test data and proposed hyperbolic hysteresis model (Amplitude=28.20 mm)

8. Conclusions

In this paper, a new smart structural member, namely a MR pin joint, has been proposed and experimental investigations were carried out to examine and characterise the dynamic behaviours of the MR pin joint, such as response time and its performance under various sinusoidal excitations and operating current levels. It was found that the response time of the MR pin joint under "step-up" and "step-down" currents show slight differences. Results also showed that MR pin, exhibited unique characteristics, for example, the "crossover" behaviour. A computationally-efficient hyperbolic hysteresis model was proposed to predict the nonlinear hysteretic behaviours of the MR pin joint. In this model, a hyperbolic tangent function is used to portray the complex behaviour of the MR pin joint. Comparison of experimental results and predictions obtained from the new model indicated that the proposed model is a good candidate in presenting the complex behaviour of the MR pin joint.

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