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Response and control of jacket structure with magneto-rheological damper at multiple locations/combinations

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Abstract. In this paper a comprehensive study for the structural control of Jacket platform with Magneto-Rheological (MR) damper is presented. The control is implemented as a closed loop feedback of the applied voltage in the MR Damper using fuzzy logic. Nine cases of combinations with MR damper are presented to complete the work. The selection of the MR damper (RD 1005-3) is based on the operating parameters (i.e., the range of frequency and displacement). Bingham model is used to obtain the control forces. The damping co-efficient of the model is obtained using empirical relationship between the voltage in the MR damper and input velocity from the structural members. The force acting on the structure is obtained from Morison equation using P-M spectrum. The results show that the reliable control was obtained when there was a continuous connection of multiple MR dampers with the lower levels of the structure. Independent MR dampers at different levels provided control within a range, while the MR dampers placed at alternate positions gave very high control.

Keywords: response and control; Jacket platform; multiple MR dampers; wave hydrodynamics; fuzzy logic; morison equation

1. Introduction

Offshore structures are unique in form and functionality with regards to onshore structures. The fixed offshore structure in higher water depths encounters higher hydrodynamic force. The force generates higher response's leading the structure to functional failure or total collapse.

Earlier failure studies of jacket platforms have detailed the extent of risk on the structural integrity in face of environmental and accidental loads. As loads acting on the offshore structures are cyclic, they tend to vibrate the system. These vibrations may lead to resonance resulting in structural failure. To maintain the structural integrity, this resonating phenomena and significantly more critical responses due to high amplitude waves need to be curtailed.

To arrest these vibrations, various control techniques are available. The techniques are categorized as Passive, active, semi-active and hybrid techniques. These control methods are successfully implemented in various fields of engineering in mitigating the vibrations effectively.

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Each method has its advantages and disadvantages. The passive control works only under certain frequency range effectively (Suhardjo and Kareem 1997).While the active and semi-active system need higher power to control (Aly 2013) relative to the semi-active control with the MR damper. These disadvantages limit the pragmatic implementations. The above mentioned deficiencies can be taken care by semi-active control using the MR Dampers. The power requirement of the MR damper based system is extremely low and can be operated by using a battery power. While the other semi-active mechanisms, for example with Tuned Mass Damper (TMD) requires more power to regulate the mass movement.

The MR damper system consists of a tubular piston arrangement (Fig. 1). It contains grooves for the passage of fluid within the piston. The grooves are wound around by the electric coil. The piston is filled with fluid with suspended particles sensitive to the magnetic field.

The magnetism effect is generated by the flow of current in the coil surrounding the grooves. In the presence of magnetic induction, the ferrous particles acquire magnetic dipole. They realign themselves in linear chains (fibration) (Venkatesan 2011). This formation will obstruct the flow changing the apparent viscosity of the fluid, in other words change in yield stress. This non-Newtonian behavior can change the pure viscous flow to quasi-solid state (Spaggiari 2012). This property is useful for the application of the MR fluid damper in all types of control problems. The yield stress of the fluid is dependent on current supply in the coil. The current supply is based on the control demand. The principle of damping is based on the external energy being absorbed as the work done against the fluid flow. The damping mechanism is passive when there is natural viscous flow in the absence of current. In the presence of current flow the mechanism changes to semi-active.

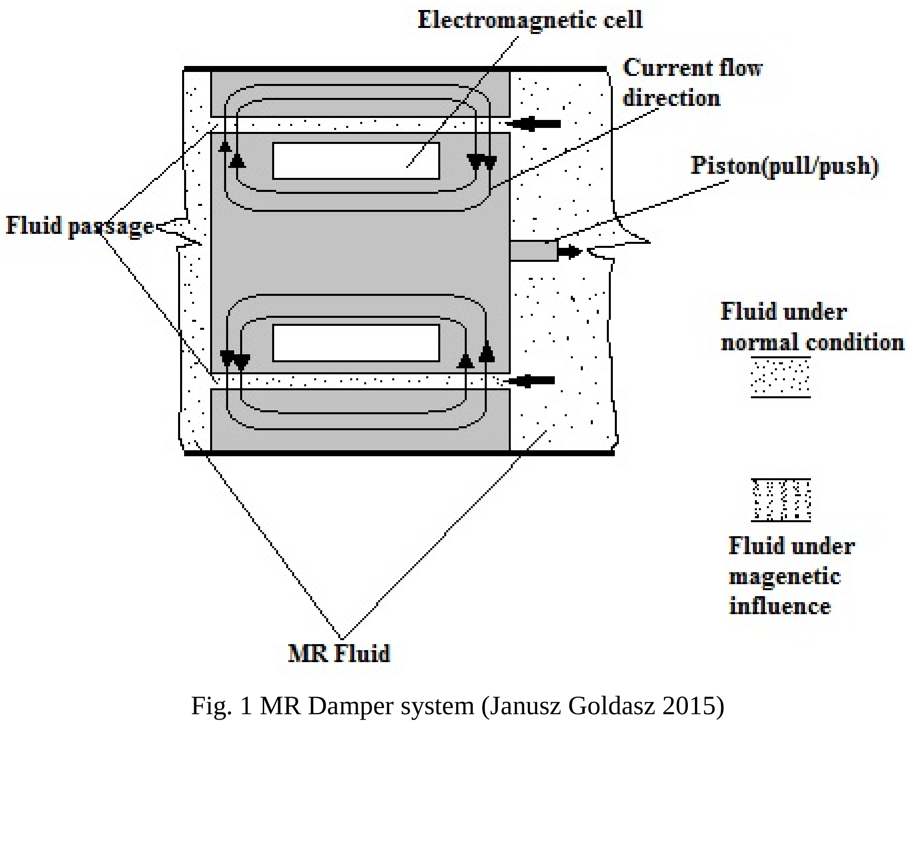


Fig. 1 MR Damper system (Janusz Goldasz 2015)

Various MR damper mathematical models are based on the rheological behavioral properties defined by the ‘viscosity’ which is a fluid property and artificially generated dynamic behavior induced by the magnetic field i.e., ‘elasticity’, ‘plasticity’ and ’hysteresis’ (Yang *et al*. 2002). Based on the different property considerations various mathematical models are defined viz., Bingham, Bouc-Wen, Li and Spencer models (Sapiński and Filuś 2003). The above stated rheological properties generate variable damping effects under the influence of magnetism. The electricity supplied at any time instant is obtained by the control algorithms.

The fluidic particles comprise non-colloidal mixture of ferromagnetic material. They are randomly dispersed in the fluid. The settling of ferromagnetic particles is avoided by using a surfactant which will make the particles to be always in suspension. Some of the commonly used are Oleic acid, tetramethylammonium hydroxide, citric acid, soy lecithin. The carrier fluids used are water, silicone oil or DTE light mineral oil (Lijesh *et al.* 2016).

The particle size is around 10 microns (Ahn *et al*. 2009). The alignment of the article is of microscopic scale. The flash point is also high.

The density of the fluid is of range 2.98 to 3.18 g/cm^3 for RD 1005-3. The viscosity of the fluid is 0.092±0.015 pa-s (Ahn *et al.* 2009).

The reaction time to the current/magnetism is milliseconds (Truong 2012, Khan *et al.* 2014). They can operate within a wide range of temperature by affecting the behavioral properties to a very little extent (Carlson and Weiss 1994). The operating temperature is -50° c to 150° c (Housner *et al.* 1997). The fluid properties are not influenced by unwanted impurities (Ghorbany and Daruish 2011). Moreover, there are non-toxic in nature (Solepatil and Awadhani 2014).

A widely explored theme with regards to usage of MR dampers in civil structures is their usage for base isolation purpose. The idea is to dampen the response of the structure foundations to seismic signals (for example earthquake response in facilities used for semiconductor fabrications). In this line of this investigation, base isolation studies with the MR dampers are presented (Khoshnoudian and Molavi-Tabrizi 2012, Ali and Ramaswamy 2009) in which the vibratory fixed offshore platform is separated from the supporting structure. It was shown that better control can be achieved in base isolation with MR damper. Among the experimental studies, new kind on impact resistant isolator was experimented with MR damper. Constant current to the MR damper was supplied, and the control was observed. Good performance of the device was evident especially at the natural frequency of the structure (Deng 2008). Another experimental frequency analysis of jacket platform was studied (Yang and Ou 2006). Several mechanical and design parameters are considered for the study of base isolation damping with MR damper. Acceleration and drift of the deck are effectively reduced for different earthquake loadings.

Another set of investigations have focused upon the hybrid deployment of a tuned mass damper (TMD) with MR dampers. In this respect, passive TMD and with two MR dampers were successful in achieving the goals of reduced vibration (Taghikhany *et al.* 2013).

With regards to offshore structures, numerical studies of coupled tendon-riser-hull system with MR damper is studied under extreme forcing conditions (Kang *et al.* 2013). MR damper was used as a tensioner in the risers and the study investigated the feasibility of such an implementation.

The present study focuses on the deployment of MR dampers at various levels of a fixed jacket platform with focus on the control of MR dampers using fuzzy control logic. As offshore structures are subjected to forces that vary in magnitude and frequency. The damping behavior can be modeled with Fuzzy Inference System (FIS) based on the reasoning with ease and can cover wide range of frequency and magnitude. Any uncertainty and nonlinearity of the system behavior can be taken care with FIS. In this respect it is noted that multiple MR damper vibration control studies are conducted on two onshore buildings placed adjacent to each other (Uz and Hadi 2014). It was shown that although better understandable control can be achieved with relatively limited number of MR dampers, the complexity of control strategy increased as more dampers are added. Another two cases of study with three MR dampers and isolated MR damper between the 3rd storey and 12th storey buildings are studied (Chen *et al*. 2004). The results are compared without control and with rigid connections between the buildings. Results showed that significant control of the response is achieved with multiple MR dampers. Similarly, increase of displacement of the convective masses is reported with two MR dampers placed between two liquid tanks (Shrimali 2012). A decentralized mechanism of MR damper placement is shown to have a significant impact on the vibration control (Das and Som 2017). With regards to experimental test on multiple MR damper control, shaking table experiments are conducted on two adjacent buildings (Basili *et al.* 2013). Two MR dampers are placed between the buildings. Comparative results with the passive damping when the MR damper is not controlled by any logic and semi-active control results is presented. Semi-Active control indicated more significant control. Also experimental study with the single MR damper placed between the top three levels is studied with fuzzy control system (Ji 2009). The control effect is found to be stable. Another experimentation of the wind turbine placed on the footing supported by two parallel MR dampers is discussed (Caterino 2015). The control was able to reduce the stress at the base. However this resulted in increased amplitude of the hub. Multiple MR damper study with two MR dampers at lower levels (Jansen *et al*. 2000, Kori and Jangid 2009), alternative levels of the structure and at all levels are studied (Sarrafan *et al.* 2012). Considerable suppression of the vibrations was achieved using different control logics and different numerical models of MR damper. In another type of study on fatigue damage (Wandji *et al.* 2017), it is noted that different configurations of MR damper is studied by researchers for evaluating structural damage at hotspots. However, a shortcoming was that in some cases the fatigue damage increased.

The calculation of the damping force formulae contains viscous parameter which is deterministic by nature and the other term contains in-deterministic terms that are artificially generated as mentioned above. The deterministic component of the viscous force is less compared to the artificially generated damping force. Artificially generated force in the MR damper depends on the control logic. Adjustment of control logic in fuzzy inference system provides the free hand to adjust accordingly to the requirements of the objective. With regards to obtain more control of the vibrations of multiple MR dampers, micro-genetic logic is used to train the Neuro-fuzzy controller to obtain the objective of reduced vibrations (Li *et al*. 2005).

Instruments are designed to operate under specific conditions to achieve efficiency. The operating conditions of the MR damper in this selection are based on the velocity, displacement and the maximum load the damper can bear. Based on this criteria RD 1005-3 is selected. The robustness under this criteria is verified (Khalid *et al.* 2014, Dyke *et al*. 1996) for the selected damper RD 1005-3. The established relationship between current and voltage is used to evaluate the parameter dependent force of the Bingham model(Barros 2012).

Multiple MR damper works in the literate do not provide a complete investigation. The literature review with regards to control at various levels of the structure and multiple MR dampers provides only part wise results. The need to understand the control aspects under various combinations and multiple positioning of MR damper is left out. So as to supplement, present work deals with control of offshore structure comprehensively. To fill the gap in this area of research various test cases are chosen to study the control by changing positions and combination of dampers at various levels. Also the fuzzy logic control with regards to this is investigated.

The selected offshore structure is a four-level jacket platform. The structure modeling is carried out by finite element methodology (FEM) (Weaver and Johnston 1987, Hutton 2004). Fuzzy Inference System (FIS) is used for control feedback. The Bingham Magneto-Rheological (MR) damper model (Barros 2012) is used to evaluate the forces because of its simplicity and ease to analyze. Basic trial and error procedure is adopted in defining the fuzzy control logic. Eight Membership function for input and output are selected. The input and output parameters are set within the range of the damper requirements. The force acting on the structure is evaluated using the PM spectrum and Morison equation.

The organization of the paper is as follows, section 2 gives details of the platform and discusses the formation of the equation of motion using FEM modeling (using MATLAB). Force evaluation is also shown in this section. Section 3 details the criteria of selection of MR damper. Section 4 shows the evaluation of MR damper force by Bingham model. Fuzzy control algorithms and flow chart of the model are mentioned in section 5. Control strategies are mentioned in section 6. In section 7 results and discussion are presented. Section 8 presents the final conclusions.

2. Jacket structure modeling

The structure in Fig. 2 represents a two-dimensional structure of a Jacket platform. The height of the structure is 143.67 m. Mean Sea Level (MSL) is 120 m. Further details of the structure are given Table 1.

The structure considered is comparable to real life structure. As the depths of jacket platform may be upto 250 m and in the Gulf of Mexico, 300 m depth jacket platform exists. The top side weight range from few hundred tons to thousands of tons.

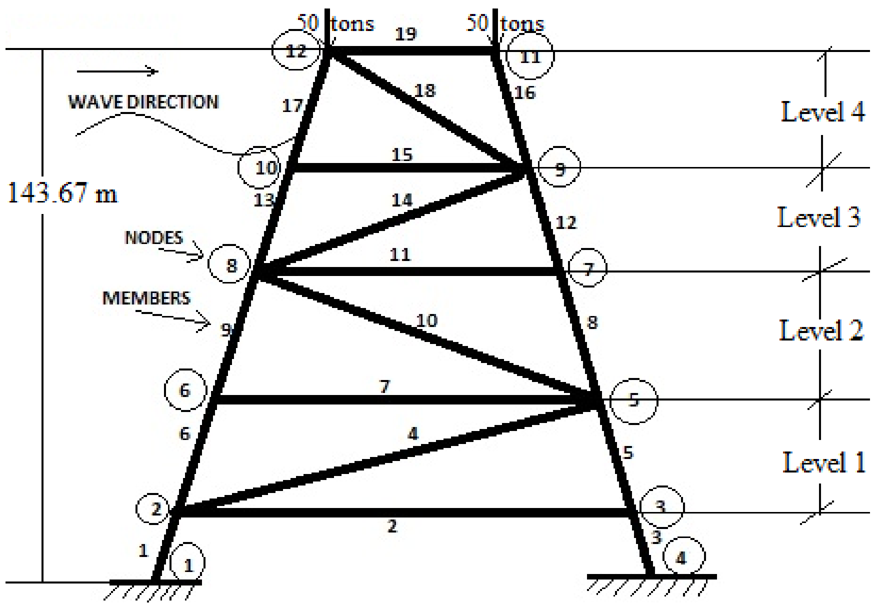


Fig. 2 Jacket Platform

Table 1 Details of the structure

Element No	Outer diameter(m)	Thickness (mm)	Length (m)	Angle of Orientation (°)
1	0.5	7	25.00	86.00
2	0.4	7	21.51	180.00
3	0.5	7	25.00	94.00
4	0.4	7	36.86	56.89
5	0.5	7	30.00	94.00
6	0.5	7	30.00	86.00
7	0.4	7	17.32	180.00
8	0.5	7	30.00	94.00
9	0.5	7	30.00	86.00
10	0.4	7	33.58	116.97
11	0.5	7	13.14	180.00
12	0.5	7	30.00	94.00
13	0.6	7	30.00	86.00
14	0.5	7	31.90	69.73
15	0.5	7	8.96	180.00
16	0.6	7	20.00	94.00
17	0.6	7	20.00	86.00
18	0.5	7	21.34	110.75
19	0.5	7	6.20	180.00

Structural member sizes depend on diameter (d) to thickness (t) ratio (API/RP 2A WSD). They govern the local buckling criteria. If local buckling occurs, one cannot do a dynamic analysis. However in this case it is assumed that local buckling do not occur or protected by the bracing to prevent local buckling.

The response of the structure in surge direction was obtained by modeling the structure in Finite Element Method (FEM) (Hutton 2004) and the solution to the model equation was obtained by the Newmarks-Beta method.

The structure consists of 19 elements and each element consists of 6 DoF (Figs. 3 and 4). Elemental matrix is formulated for each element. Then they are globally assembled at each node with respective degrees of freedom. Finally, the reduced matrix in the surge directions is assembled.

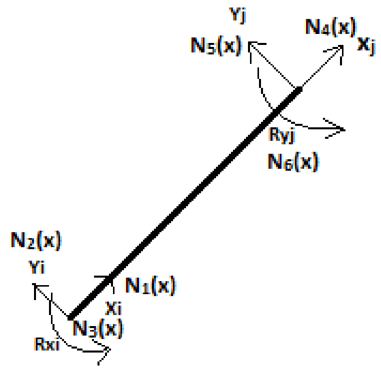


Fig. 3 Beam element in local coordinates

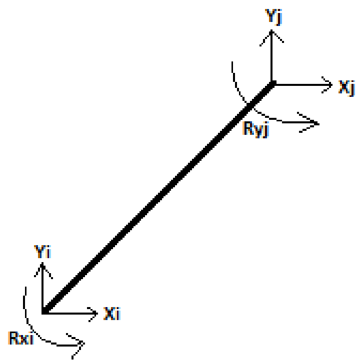


Fig. 4 Beam element in global coordinates

Where N_i (i=1,2,3...) is the shape factor and X_i, Y_i and R_{xi} are the degrees of freedom (two translational and one rotation at the ith node and similarly at the Jth node).

A P-M spectrum (Pierson and Muskowitz 1964) with significant wave height (h_s) of 14 m is considered to obtain the loading and is given in Fig. 5. The sea state considered is very high with sea state code of eight according to world metrological organization sea state code. Peak time period is taken as 8 *sec*. Spectral density function $S(\omega)$ for a fully developed sea is given in Eq. (1).

$$S(\omega) = 0.0081\frac{g^2}{\omega^5}e^{-0.0032(g/h_s\omega^2)^2} \tag{1}$$

An comparison is presented with the Gulf of Mexico hurricane with a return period of 100 years who's significant wave height is 12.8 mts and time period is 17 secs (Wilson 1956).

The shallow depth velocities and accelerations (Mani 2012, Chandrasekaran 2015)are used to evaluate the PM spectrum force (Eq. (2)) acting on the structure.

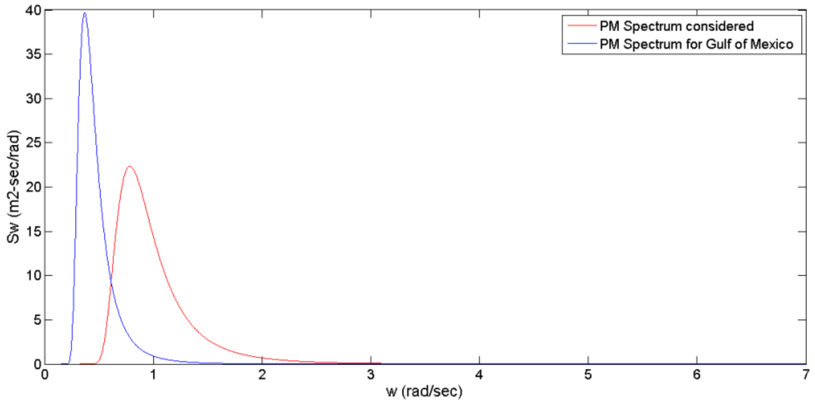


Fig. 5 PM Spectrum

$$F = (0.5 * \rho * C_d * A * \dot{u} * |\dot{u}|) + (\rho * C_m * V * \ddot{u}) \tag{2}$$

Where F is the nodal force on the member, C_d is the drag co-efficient, C_m in the inertial co-efficient, ρ is the density of the sea water, A is the cross sectional area of the member, $\dot{u}$ is the velocity of the water particle, $\ddot{u}$ is the acceleration of the water particle and V is the volume of the element member.

The Modal force $F_{Mg}(t)$ acting at each node is given by Eq. (3)

$$F_{Mg}(t) = \Phi^T F_{Ng}(t) \tag{3}$$

The final modal form of the equation (Eq. (4)) is represented as below by the term obtained by the Eq. (4).

$$\Phi^T [M_g]_{surge} \Phi \ddot{x}(t) + \Phi^T [C_g]_{surge} \Phi \dot{x}(t) + \Phi^T [K_g]_{surge} \Phi x(t) = F_{Mg}(t) \tag{4}$$

Where F_{Mg} is the global force matrix in the x-direction, Φ is the Eigen vector of the 1st natural frequency, M, and K are the mass stiffness matrices, C is the Rayleigh-Ritz matric obtained using mass and stiffness matrices.

The solution to the equation of motion can be obtained by Newmark-Beta method by average acceleration method where γ=1/2 and β=1/4. Following equations are used to obtain velocities (Eq. (5)) and displacements (Eq. (6)) at particular time instance.

$$\dot{x}_{i+1} = \dot{x}_i + \left[(1-\gamma)\Delta t\right]\ddot{x}_i + \gamma \Delta t \ddot{x}_{i+1} \tag{5}$$

$$x_{i+1} = x_i + \Delta t x_i + \gamma \Delta t \ddot{x}_{i+1} + \left[(0.5-\beta)\Delta t^2\right]x_i + \left[\beta \Delta t^2\right]\ddot{x}_{i+1} \tag{6}$$

γ and β defines the variation of acceleration over a time step. The stability criteria is given by the following Eq. (7)

Table 2 Operating limits of the MR Damper RD 1005-3 (Khalid *et al*. 2014)

Variable	**Variation range**
Displacement	-0.03 m to 0.03 m
frequency	0.5(Hz) to 5 (Hz)
Supplied Voltage	0 (V) to 5 (V)

$$\frac{\Delta t}{T_n} < \frac{1}{\Pi\sqrt{2}} \times \frac{1}{\sqrt{\gamma - 2\beta}} \tag{7}$$

where

$T_n = \dfrac{2\Pi}{\omega_n}$, $\omega_n = \sqrt{\dfrac{k}{m}}$

T_n is the natural time period, ω_n is the natural frequency of the structure, K is the stiffness and m is the mass.

3. Selection of MR damper

The MR damper selection is based on the conditions of operation (Displacement and frequency). The maximum relative displacement and frequency of the structure is found by running the numerical model without damping. In the absence of the damper, maximum relative displacement was found out to be 2.77 cm at 3rd level and the 1st natural frequency is 1.6 Hz. RD 1005-3 damper model can accommodate displacement of 6 cm within the frequency range of 0.5 Hz to 5 Hz. Based on comparison of parameters the damper found out to fit the requirements is RD 1005-3. Following are the details of the RD 1005-3 (Table 2).

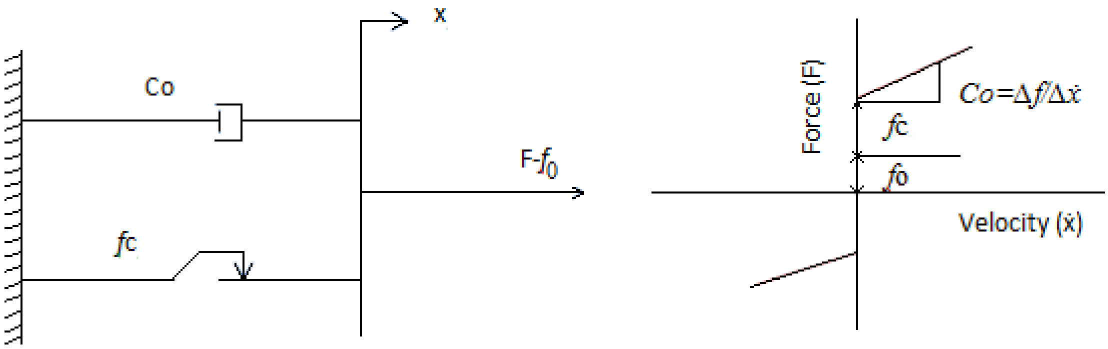
4. Bingham model

Mathematically MR damper is modeled using Bingham model (Khalid *et al.* 2014), which only considers viscosity and plastic rheological properties. The Bingham model can be represented as in Fig. 6. The Bingham damper model was validated with the maximum damping force of 4448 *N* and with the maximum voltage output of 5 *Volts* is used in the study.

The maximum force coming from the MR damper depends on the difference of the force between the nodes of connection (i.e., the Relative force between the nodes of MR damper connection). But the amount of force it damps is based on the control algorithms defined by the fuzzy inference system (FIS).

The governing equation of the MR damper force is given as follows (Eq. (8)) (Barros 2012)

$$F(t) = C_o \dot{x} + f_c \,\mathrm{sgn}(\dot{x}) + f_o \tag{8}$$



(a) Pictorial (b) Resolution of forces

Fig. 6 Bingham Model(Yang *et al.* 2002)

Where F(t) is the MR damper force, C_o is the damping coefficient, f_c is the frictional force, f_o is the force offset with the presence of an accumulator (40 Newton's for RD 1005-3), $\dot{x}$ is the relative velocity of the nodes connected to the damper.

The above coefficient is evaluated at each time step given by the following relationships (Barros 2012)(Eq. (9)).

$$f_c(I) = -910.09I^3 + 986.49I^2 + 663.56I + 52.19$$
$$C_o(I) = 48.74I^4 - 106.39I^3 + 66I^2 + 1.43I + 0.53 \tag{9}$$

where I is the current passed to generate the magnetic effect by which the magnetic particles react to generate the damping force.

The relationship between the voltage (V) and current (I) is given by the relation (Eq. (10))

$$I = 0.446V - 0.237 \tag{10}$$

The supply of voltage should be such that the current generated by the above Eq. (10) returns a positive value of current (I) and the same setting need to be made in the fuzzy logic. The minimum voltage should be set in defuzzification by adjusting the membership functions in such a manner that it gives voltage which on substituting in the Eq. (10) gives a positive value of current (I).

5. Fuzzy Inference logic

The flow chart (Fig. 7) represents the sequential steps followed in achieving the control objective.

The force evaluation (Eq. (8)) in the Bingham model is dependent on only one parameter i.e., velocity. Therefore the only velocity is chosen as an input parameter in the fuzzy logic control system. Fuzzified value of the input parameter at each time step is used to infer the deffuzified output parameter i.e., voltage.

A proportional criterion is chosen to evaluate the rules. Eight membership functions are taken for fuzzification and defuzzification. Centroid method is selected to obtain fuzzified and crisp values. The Fig. 8 below with eight membership functions is for the fuzzification of velocity and Fig. 9 defuzzification of voltage. The membership functions are equally divided between the limits.

The flowchart (Fig. 10) represents the evaluation of the controlled response. The dynamic analysis is carried out in FEM. Velocity response is fed to the FIS to obtain the voltage at that instance which generate the damping force in the controller. The obtained damping force is deducted at the nodes connected to the MR damper at the next time level.

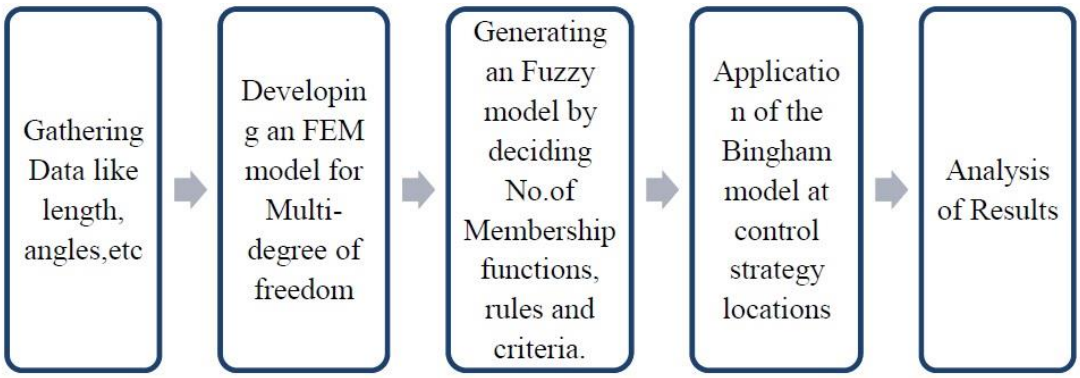


Fig. 7 Flow chart of Methodology

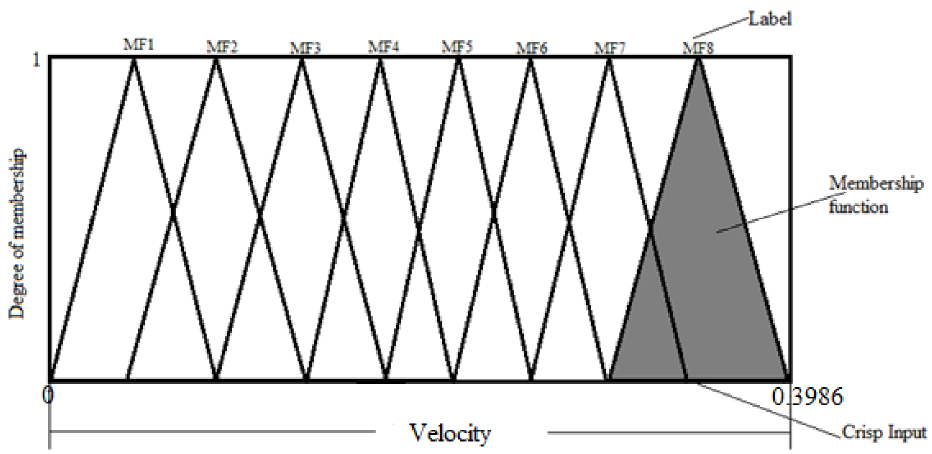


Fig. 8 Membership function for fuzzification of velocity

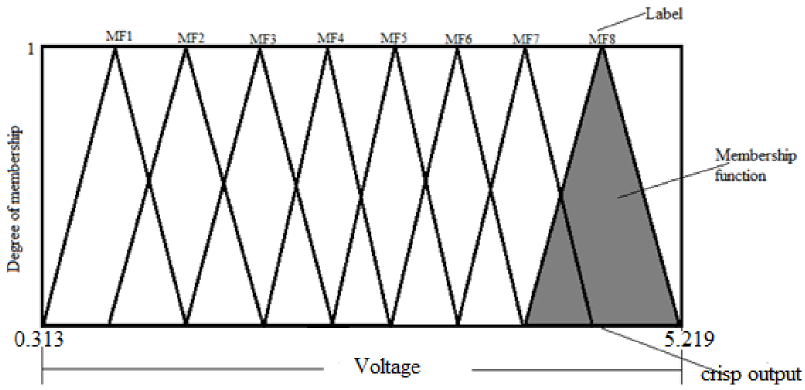


Fig. 9 Membership function for de-fuzzification of voltage

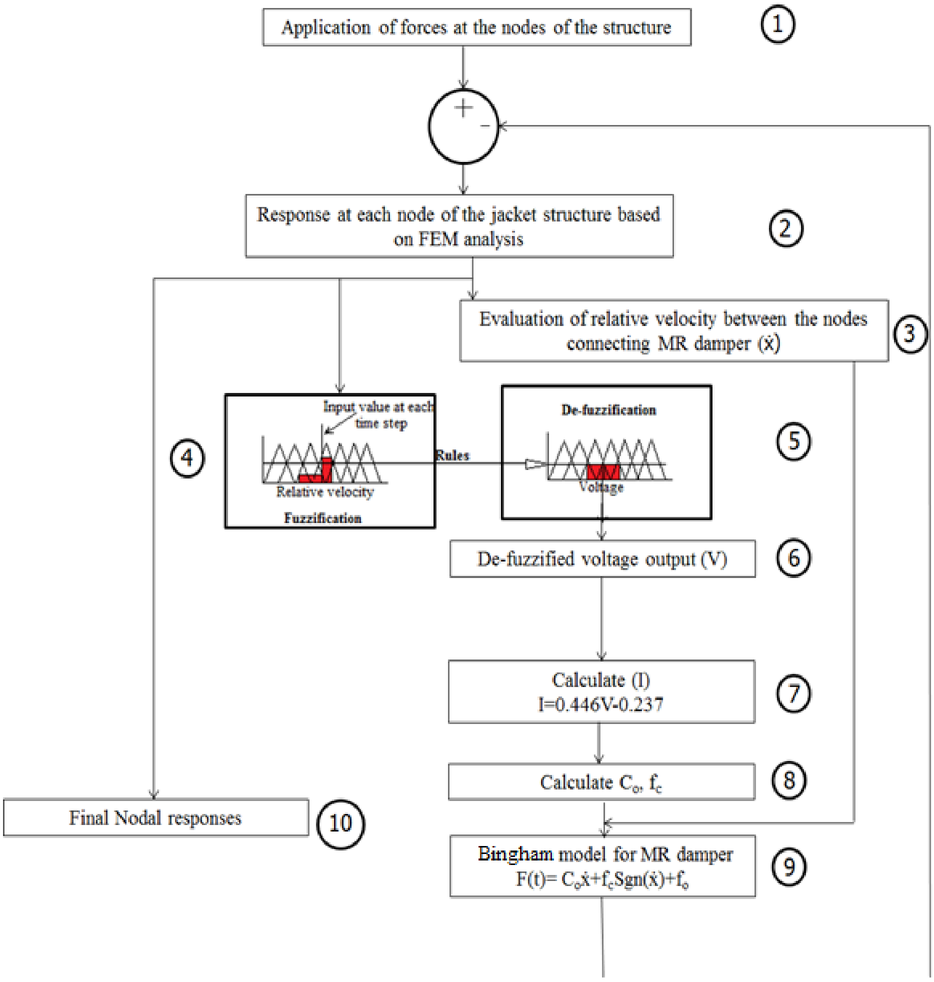


Fig. 10 Flow chart of control

6. Control stratergies

The members are replaced by the member including the MR damper as shown in Fig. 11.

The MR damper is placed at various levels of jacket structure. The reason for selection of the member in inclined position (Fig. 12) provides the relative displacement between the nodes due to differential height of the nodes.

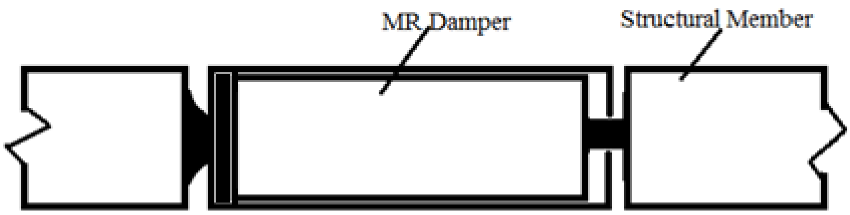


Fig. 10 MR Damper arrangement in structural member

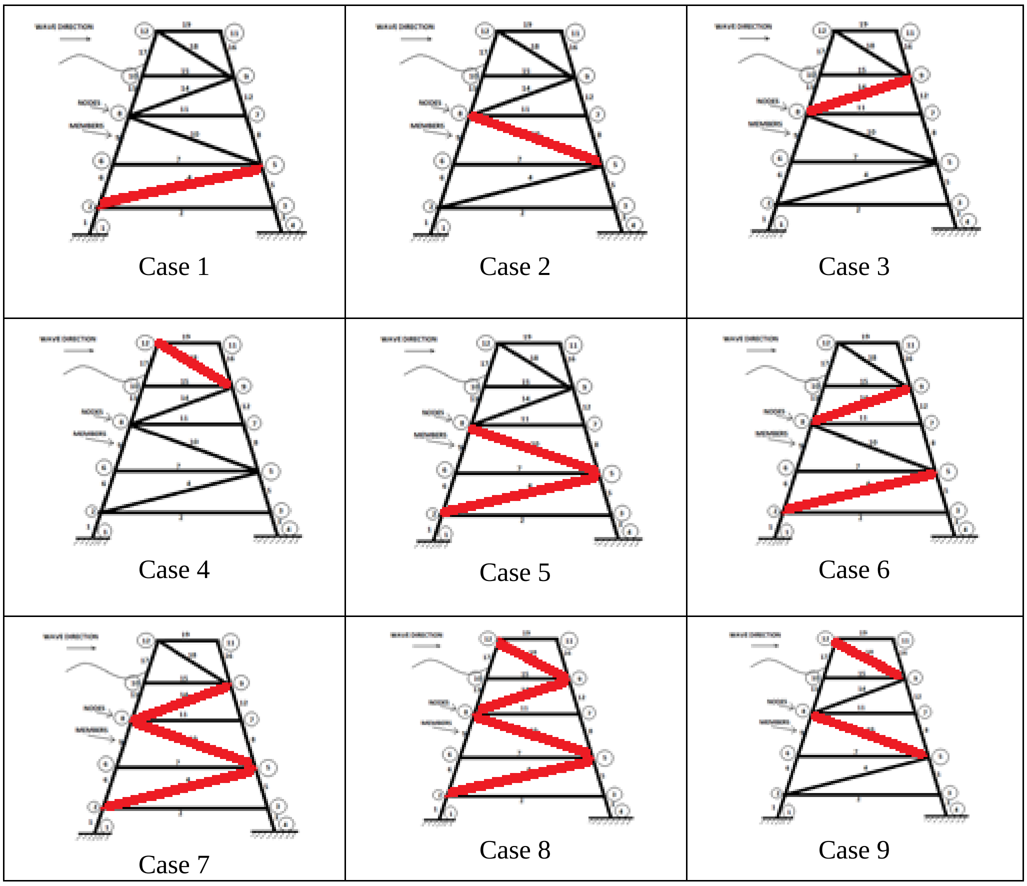


Fig. 12 Damper positions

The Fig. 12 shows the case study is carried out with different MR damper positions. Cases 1-4 represent the damper being placed at different levels independently. The other cases show that the damper is placed at various levels simultaneously. The response of the structure for various cases is studied by observing the displacement of the Node 12 at the top end of the structure. The response results are presented with Root Mean Square (RMS) values.

7. Results and discussions

The following Fig. 13 shows the forces on each of the nodes. The forces on nodes 1 and 2 are zero as they lie at the sea floor and due to the boundary condition; they are neglected in the figure.

The load acting on the MR damper is the difference of force between the nodes joining the member. The force experienced by the MR damper at any level can be obtained by the difference of forces at the nodes connected by the MR damper. For example Fig. 14 shows the force experienced by the MR damper at the 1st level.

Same rules and membership functions for all the MR damper cases are considered for this comparative study.

The results are evaluated using the root mean squared values(RMS) of the 12 th node displacement response which is given by the equation $J = \frac{\tilde{X}_c(t)}{\tilde{X}_u(t)}$ Where c is the controlled values and u represent the uncontrolled values of the node displacement

Where $\tilde{X}$ is given by

$\tilde{X} = \sqrt{T^{-1}\sum\left(\delta_t x^2{}_k(t)\right)}$ δ_t is the sampling time and T is the total excitation time.

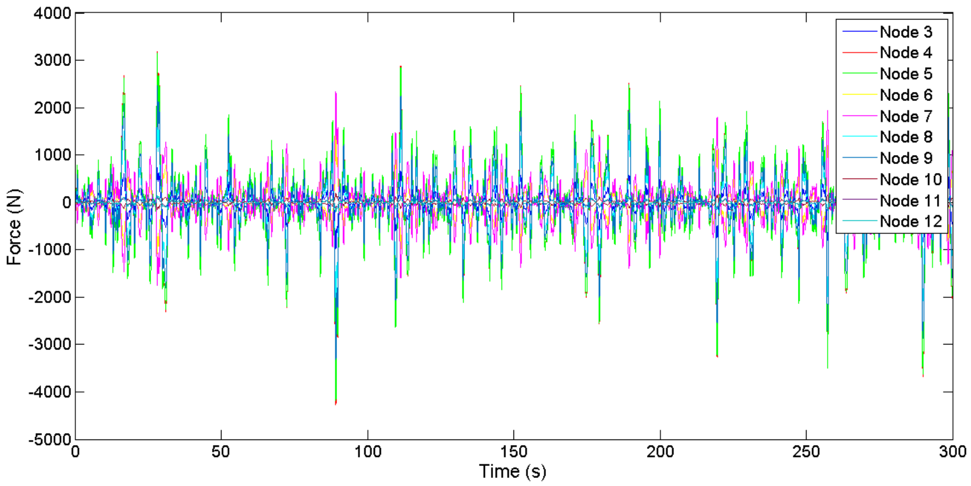


Fig. 13 Force at different nodes

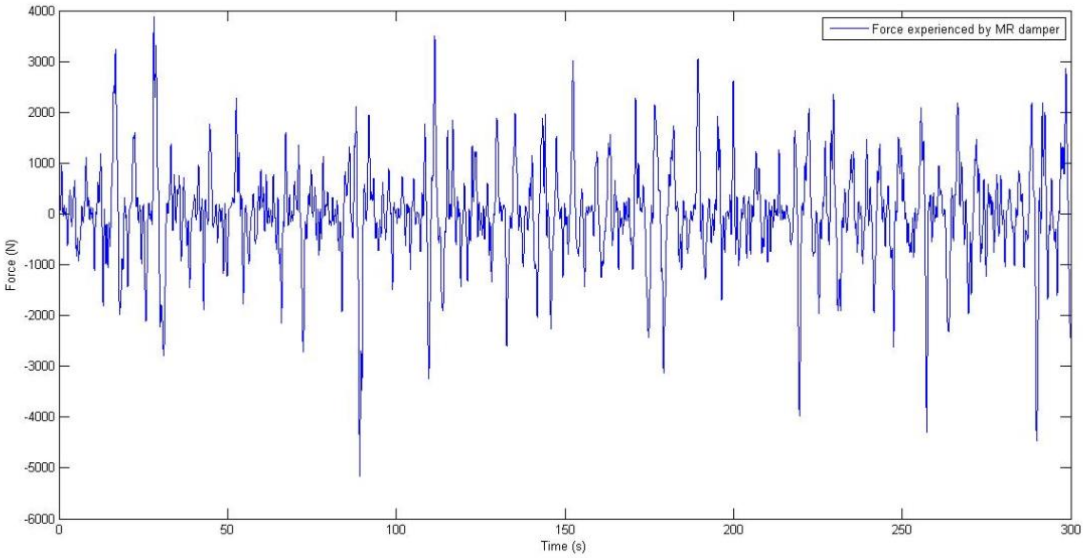


Fig. 14 Force acting on the MR damper at the 1^{st} level

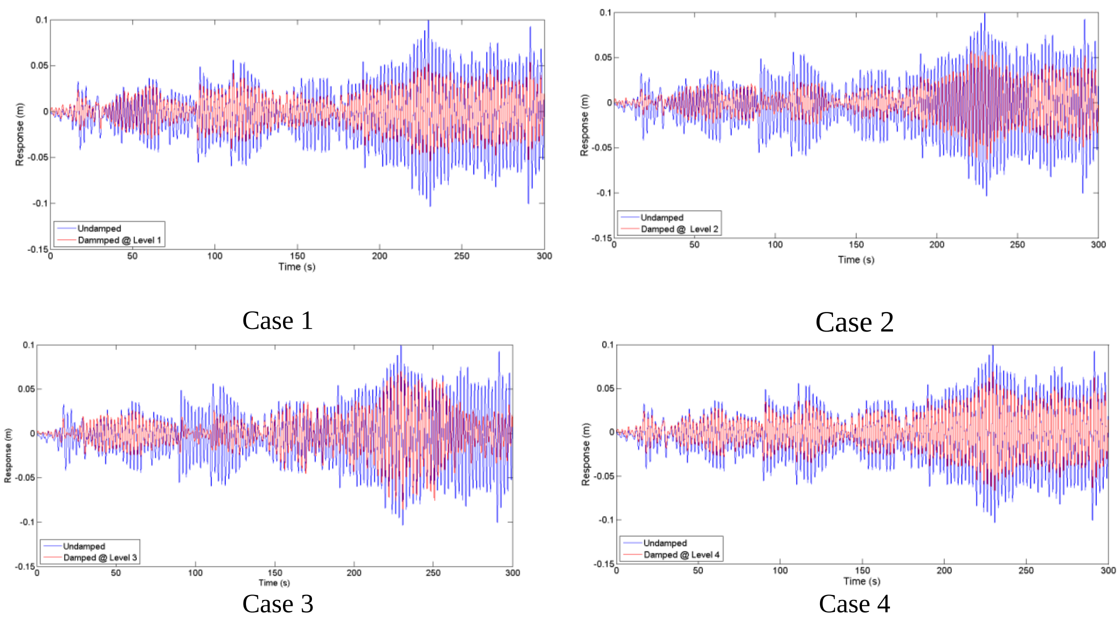


Fig. 15 MR damper placed at independent levels (cases – 1,2,3 &4)

Table 3 Control values of the damper from cases 1 to 4

Damper Level	% Control
1st level (Case 1)	42.17
2nd level (Case 2)	44.28
3rd level (Case 3)	36.45
4th level (Case 4)	34.34

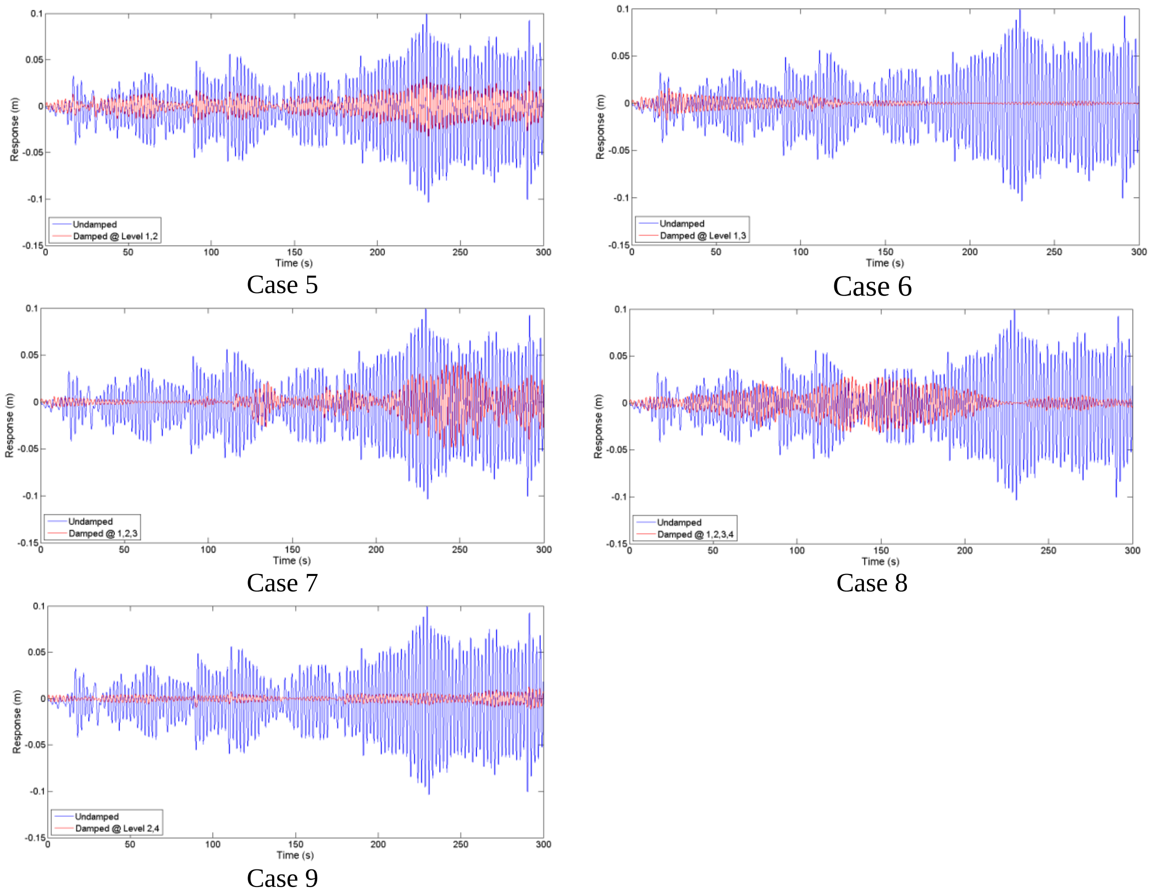


Fig. 16 MR damper placed at combination levels (cases 5,6,7,8 & 9)

Following are the response and control achieved by placing the damper at various positions. Fig. 15 represents the damper placements for the independent levels. The table 3 below represents the percentage control achieved for various cases of independent levels. More control is achieved when the damper is placed at 2nd level (case2) with control of 44.28% and less control is achieved when the damper is placed at 4th level (case4) with control of 34.34%.

The Figs. 16 and table 4 shows cases 5 to 9 in which one can observe more response control is achieved for the dampers placed at alternated positions (case 6 & 9). Hence it shows that multiple uses of the MR dampers at various positions would be the present uncertain performance of the response control. Uncertainty refers that lesser number of dampers may provide better control than the higher number of dampers.

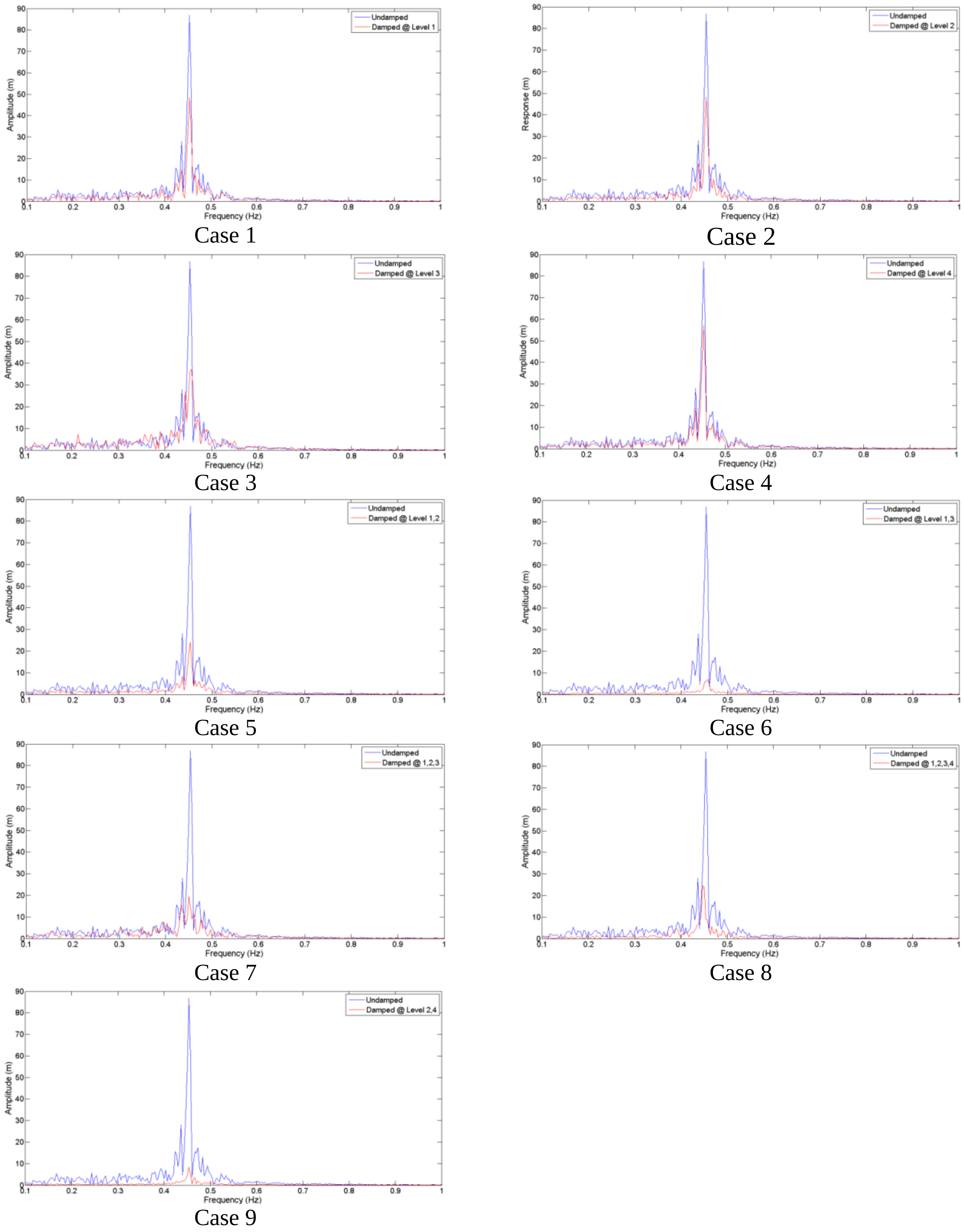


Fig. 17 Spectrum plots for all the cases

Table 4 Control values of the damper from cases 5 to 9

Damper Level	% Control
1, 2 level (case 5)	70.18
1, 2, 3 level (case 7)	64.16
1, 2, 3, 4 level (case 8)	68.67
1, 3 level (case 6)	89.76
2, 4 level (case 9)	90.06

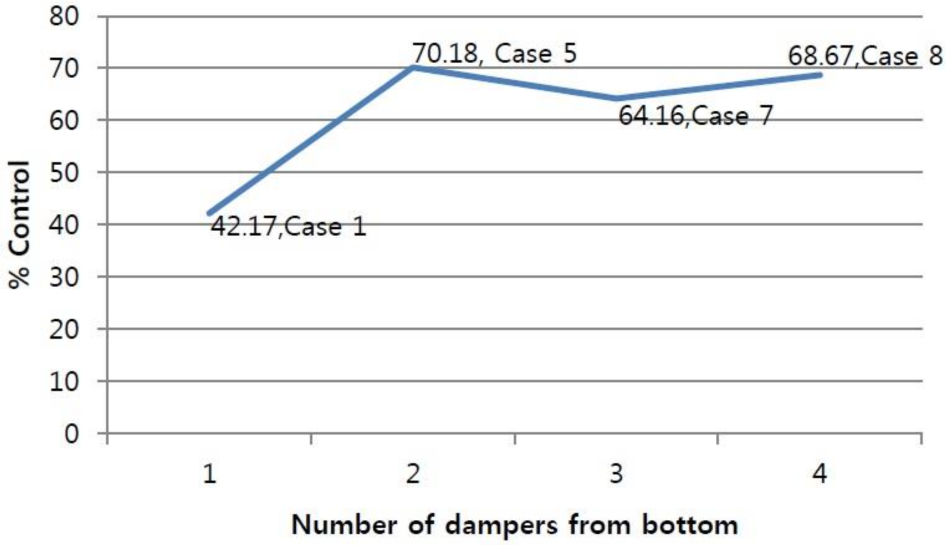


Fig. 18 Response control for cases 1,5,7,8

Following are the frequency spectrum plots for all the nine case (Fig. 17). The dominating forcingfrequency is 0.785 rad/sec (refer Fig. 5), while the structural response (displacement) dominating frequency is 0.453 rad/sec. From the response spectrum plots of the structure, it is observed that the control with MR damper with fuzzy algorithms show a robust control over wide range of fr-equencies (0.1 rad/sec to 0.6 rad/sec). Also the Choosen input parameter and fuzzy rules achievesthe objectives of control.

With the increment of a number of dampers from the bottom level to top level (cases 1,5,7,8), a considerable response reduction is observed. With dampers being placed on the all the floors give a response control of 68.67%. Higher control was achieved with the damper places at the two bottom levels with control of 70.18%. The Fig. 18 below shows the response reduction with an increment of the MR dampers from the lower levels.

8. Conclusions

The above study presents a response to the control of the structure with multiple MR Damper combinations. A four-floor structure was modeled with FEM and control current supply was obtained using the Fuzzy inference system with input velocity and output as a voltage. Control forces were evaluated with the Bingham model. Following observations were obtained from the study.

- The first natural frequency of the jacket structure is 1. 6 Hz and this satisfies the criteria for choosing the MR damper RD 1005-3, for which the operating range is 0.5 Hz to 5 Hz.
- MR damper requires very little power consumption. This can be operated with a battery. The voltage needed range from 0.313 to 5.219 volts which is obtained in the defuzzification diagram.
- The FIS is robust and effectively applicable in damping the systems. Here in this case to understand the behavior under multiple cases of study same rules are applied to all the MR dampers. The rules (input-output logic) for some cases is found to be very effective.
- When the damper is placed at the independent levels (cases 1, 2, 3 & 4) higher control is achieved when the damper is at 2nd level.
  - When the damper being incremented to the higher levels (ref to Fig.18) maximum control of 70.18 % was achieved with damper being placed at the bottom two levels.
- When the dampers are placed at the alternated levels higher controls are achieved (case 6 - 89.76 % and case 9 - 90.06%).
- Not necessary that more dampers may provide better control. Referring to the Fig. 17 the damper at bottom two levels and dampers at alternate levels provide better control than the dampers at other levels.
- In case 6 and case 9 higher response control is achieved. This is due to the structure going out of phase with excitation force.
- Reliable control was obtained when there was a continuous connection of multiple MR dampers with the lower levels of the structure.

References:

Ahn, K.K., Truong, D.Q. and Islam, M.A. (2009), "Modeling of a magneto-rheological (MR) fluid damper using a self tuning fuzzy mechanism", *J. Mech. Sci. Technol.*, **23**(5), 1485-1499. doi: 10.1007/s12206-009-0359-7.

Ali, S.F. and Ramaswamy, A. (2009), "Hybrid structural control using magnetorheological dampers for base isolated structures", *Smart Mater. Struct.*, **18**(5), 055011 (16 pp.). doi: 10.1088/0964-1726/18/5/055011.

Aly, A.M. (2013), "Vibration control of buildings using magnetorheological damper: A new control algorithm", *J. Eng.*, 1-10. doi: 10.1155/2013/596078.

Barros, R. C. (2012) 'Experimental Behaviour and Numerical Analysis of MR Dampers dampers', *15 Wcee*.

Basili, M., De Angelis, M. and Fraraccio, G. (2013), "Shaking table experimentation on adjacent structures controlled by passive and semi-active MR dampers", *J. Sound Vib.*, **332**(13), 3113-3133. doi: 10.1016/j.jsv.2012.12.040.

Carlson, J.D. and Weiss, K.D. (1994), "A growing attraction to magnetic fluids", *Machine Des.*, **8**, 61-66.

Caterino, N. (2015), "Semi-active control of a wind turbine via magnetorheological dampers", *J. Sound Vib.*, **345**, 1-17. doi: 10.1016/j.jsv.2015.01.022.

Chandrasekaran, S. (2015), *Dynamic Analysis and Design of Offshore Structures, Ocean Eng ineering & Oceanography., Springer*. India.

Chen, J. *et al.* (2004), "Seismic response control of a complex structure using semi-active friction dampers", *Struct. Mater.*, **5391**(852), 177-188. doi: 10.1117/12.540901.

Das, D. and Som, A. (2017), "Decentralized sliding mode control of offshore jacket platforms subjected to earthquake ground excitations", *Proceedings of the 16th World Conference on Earthquake Engineering*.

Santiago.
Deng, Z. (2008), “Omae2008-57106 experimental research on the vibration reduction and impact”, 1-7.
Dyke, S.J., Sain, M.K., Spencer Jr. B.F. and Carlson, S.J. (1996), “Modeling and control of magnetorheological dampers for seismic response reduction-1996.pdf”, *Smart Mater. Struct.*, 5, 565-575.
Ghorbany, D. and Daruish (2011) *MR damper hysteresis characterization for the semi-active suspension system*, 65.
Housner, G.W. *et al.* (1997), “Structural control: Past, present, and future”, *J. Eng. Mech.*, **123**(9), 897-971. doi: 10.1061/(ASCE)0733-9399(1997)123:9(897).
Hutton, D.V. (2004), *Fundamentals of finite element analysis*, New York: Mc-Graw-Hill,Inc.
Jansen, L.M. and Dyke, S.J. (2000), “Semiactive control strategies for MR dampers: comparative study”, *J. Intel.Mat. Syst. Str.*, **126**(8), 795-803.
Janusz Goldasz, B.S. (2015), *Insight into magnetorheological shock absorbers download: Insight Into Magnetorheological Shock Absorbers*.
Ji, C. (2009), “OMAE2009-79847”, in.
Kang, H.S. *et al.* (2013), “Semi-active magneto-rheological damper to reduce the dynamic response of top-tension risers”, *Proceedings of the International Offshore and Polar Engineering Conference*.
Khalid, M. *et al.* (2014), “Nonlinear identification of a magneto-rheological damper based on dynamic neural networks”, *Comput.-Aided Civil Infrastruct. Eng.*, **29**(3), 221-233. doi: 10.1111/mice.12005.
Khan, S. A., Suresh, A. and SeethaRamaiah, N. (2014) “Principles, Characteristics and Applications of Magneto Rheological Fluid Damper in Flow and Shear Mode”, *Procedia Materials Science*. Elsevier B.V., 6(Icmpc), pp. 1547–1556. doi: 10.1016/j.mspro.2014.07.136.
Khoshnoudian, F. and Molavi-Tabrizi, A. (2012), “Responses of isolated building with MR dampers and fuzzy logic”, *Int. J. Civil Eng.*, **10**(3), 222-231.
Kori, J.G. and Jangid, R.S. (2009), “Semi-active MR dampers for seismic control of structures”, *Bull. New Zealand Soc. Earthq. Eng.*, **42**(3), 157-166.
Li, H., Chang, Z. and Li, J. (2005), “Semi-active control for eccentric structures with MR”, in *ICIC 2005*, 139-148.
Lijesh, K.P., Muzakkir, S.M. and Hirani, H. (2016), “Rheological measurement of redispersibility and settling to analyze the effect of surfactants on MR particles”, *Tribology - Materials, Surfaces and Interfaces*, **10**(1), 53-62. doi: 10.1080/17515831.2015.1132133.
Mani, J. (2012), *Coastal Hydrodynamics*, PHI Learning Private Limited.
Pierson, W. and Muskowitz, L. (1964), “A proposed spectral form for fully developed wind seas based on the similarity theory of S.A. Kitaigorodskii”, *J. Geophys.*, 69, 5181-5190.
Sapiński, B. and Filuś, J. (2003), “Analysis of parametric models of MR linear damper”, *J. Theor. Appl. Mech.*, **41**(2), 215-240, http://www.warminski.pollub.plwww.ptmts.org.pl/2003-2-sapinski-f.pdf.
Sarrafan, A. *et al.* (2012), “Neuro-fuzzy control strategy for an offshore steel jacket platform subjected to wave-induced forces using magnetorheological dampers”, *J. Mech. Sci. Technol.*, 26(4), 1179-1196. doi: 10.1007/s12206-012-0212-2.
Shrimali, M.K. (2012), “Seismic response of connected liquid tanks with MR dampers”, *Proceedings of the 15th World Conference on Earthquake Engineering (15WCEE)*, (i).
Solepatil, S.B. and Awadhani, L.V. (2014), “Transmissibility analysis of magneto - rheological damper”, **3**(5), 46-50.
Spaggiari, A. (2012), “Properties and applications of magnetorheological fluids”, *Frattura ed Integrita Strutturale*, **23**, 57-61. doi: 10.3221/IGF-ESIS.23.06.
Suhardjo, J. and Kareem, A. (1997), “Structural control of offshore platforms”, **1**, 880653-29, https://www.onepetro.org/download/conference-paper/ISOPE-I-97-062?id=conference-paper%2FISOPE-I-97-062.
Taghikhany, T. *et al.* (2013), “The effect of semi-active controller in Sirri jacket seismic vibration control under Kobe earthquake”, *J. Mar. Sci. Eng.*, **3**(2), 77-84, http://ijmase.srbiau.ac.ir/?_action=articleInfo&article=1695%5CnL1.
Uz, M.E. and Hadi, M.N.S. (2014), “Optimal design of semi active control for adjacent buildings connected

by MR damper based on integrated fuzzy logic and multi-objective genetic algorithm", *Eng. Struct.*, **69**, 135-148. doi: 10.1016/j.engstruct.2014.03.006.

Venkatesan, A. (2011), "A new model parameter identification technique for magnetorheological dampers", **5**(12), 1111-1116.

Wandji, N., Natarajan, W. and Anand (2017), "Application of magneto-rheological dampers to alleviate fatigue damage of jacket substructrues for 20 MW wind turbines", *Proceedings of the Wind Energy Science Conference*, Lyngby,Denmark.

Weaver, J.W. and Johnston, P.R. (1987), *Structural Dynamics by Finite Elements*, Prentice Hall Inc., Englewood Cliffs,NJ, USA.

Wilson, W. B. (1955), "CHAPTER 4 Hurricane wave statistics", *Coast. Eng.*, 68-95.

Yang, G. *et al.* (2002), "Large-scale MR fluid dampers: Modeling and dynamic performance considerations", *Eng. Struct.*, **24**(3), 309-323. doi: 10.1016/S0141-0296(01)00097-9.

Yang, Y. and Ou, J. (2006), "Experimental research on isolation structure model of jacket offshore platform with MR damper", *J. Vib. Shock*.

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