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Experimental and Numerical Vibration Response Comparison of Mono and Hybrid Structural System for Tall Wind Mill

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Abstract: India is one of the leading countries in wind power generation and has produced 4 GW wind power with second largest wind power generation in Asia. The wind turbines are supported by mono type or lattice type structural system towers and subjected to heavy mass of blade and rotor at top. At given location more power can be extracted by increasing hub height of wind mill. But by increasing height of structure owing to very tall slender structure, tower may experience vibrations by operation of wind turbine, so detailed dynamic analysis considering excitation frequencies are required. To overcome slenderness effects of such long slender wind mill an alternative hybrid supporting system which is combination of mono and lattice structural system is proposed in present investigation. This paper summarizes results obtained from 1:40 scaled model of prototype structure developed in laboratory supported on two types of supporting systems such as monotype and hybrid type. Both systems are excited by operating frequencies of wind mill turbine and responses are quantified in terms of displacement in time domain. The obtained experimental results of both systems are authenticated using FE simulation. The dynamic response of both systems is compared in form of displacement, stresses and shear at base. From obtained experimental and its simulation results, it can be concluded that owing to more stiffness hybrid structural system proves less sensitive to dynamic forces and can be used for tall wind mill structure to yield more power for tall wind mill structures

Index Terms: Wind turbine, Hybrid system, Dynamic analysis, Vibration Response.

I. INTRODUCTION

The use of wind power for generation of electrical energy has rapidly spread as one of the clean and naturally available sources of energy. India has produced record break 4 GW electricity from wind mill in 2017 [1] India is the second largest country in wind power generation in Asia with total installed 4148 MW wind power capacity. In the year 2017 India has generated 53,726 GWH wind power which is 4.35 percent of total power generation, and at 4^{th} rank in world. To promote the wind power generation in India government targeted to provide 175 GW capacity by end of year 2022.

Gujarat is first state of India is to install wind mill earlier in year 1986. Gujarat has 1600 km long coastal area which can be effectively used to harvest wind energy. In the states like Gujarat recently wind mill towers up to 80 m are erected. The wind potential of Gujarat state was estimated, and it shows that in shores near gulf of Khambhat has very high wind power potential. From the study it was outcome that wind velocity at 110 m height is more than 10 m/sec which is only 8 m/s at 80 m height. [2]. If the wind speed is lesser than wind turbines with lager rotors are required and cost of such turbines are more for lower wind speeds. In Gujarat the higher and steady winds with a speed of 10 m/s are available between months of April to august, whilst wind speeds are lower as 7 m/s in month of October and November.

From the above discussion it can be noticed that by elevating hub height more wind power can be extracted at given location and winds are also steadier at higher elevation, so power can be extracted for longer time durations. The conventional wind mill structures are either monopole or lattice structures. Lattice structures are made up with different shaped structural steel elements either riveted or welded to each other and can be used for smaller hub heights. While mono type structures are tubular structures made up of structural steel. The diameter of this tubular structures varies according to elevation with higher diameter at base which is reduced along height. At the top of wind mill heavy mass of nacelle is equipped. Very high mass of rotor is also procured at eccentric distance at top of tower. This blade of the rotor will revolve in vertical plane at varying frequencies, and this revolving frequency of blade depends on wind speed at given location. As velocity of wind changes in time domain the rotating frequency of blade also changes in time domain. Due to rotation of blades of rotor, forces and stresses are provoked in supporting structure of wind mill towers.

In the conventional monopole wind mill structures are made with circular shaped varying diameter cross section carrying more slenderness ratio. The lattice structural systems are suitable only for lesser heights. The mono structural system resists external loads acting on it by bending stiffness and lattice structural system transfers load by axial stiffness. The axial stiffness is more compared to bending stiffens for same material and can be used to resist heavy loads. For elevated hub heights both systems are proven to be incapable to resist loads generated due to vibration of rotors. To increase hub height of wind, and to avoid slenderness effect of wind mill a combination of mono and lattice structural system known as hybrid structural system is proposed in present investigation.

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In hybrid structural system circular shaped mono towers are provided at higher elevation of tower. In the lower elevations of tower more forces are to be resisted so axial stiffness is provided in form of lattice structure. By using hybrid structure, we can gain advantage of axial stiffness in lowered elevations where forces are more and mono structure in form of bending stiffness in higher elevations where forces are less. In order to evaluate vibration response of both systems scaled down models are prepared in laboratory and vibration response is evaluated experimentally. The experimental vibration response of hybrid system is compared with conventional mono system. The numerical simulation of both structural systems is carried out in FE software and experimental results of dynamic analysis are validated using FE simulation for both structural systems.

II. LITRATURE REVIEW

Different methods can be used to evaluate dynamic properties of wind turbine one method is to use numerical methods and validate the results using experimental works. The vibration characteristics of wind model by rigid blade model was first investigated by numerical model and effect of gravitational force on excitation of blades are studied and results of analytical model are validated using experimental models [3]. The effects of soil structure interaction on dynamic properties of turbine are also studied for different soil [7]. They have performed experimental work on saturated sand and two numerical methods developed to estimate natural frequencies of system. The dynamic properties of wind turbines are also influenced by damping of foundation so bending moment at base considering foundation damping are investigated and concluded that resultant moments are decreasing due to increased foundation damping. [18]

It is possible to measure dynamic response of turbine at site using measuring instruments. The onsite experimental vibration measurement for wind mill tower considering different flange connections are also performed [6]. The strain at various locations were measured and shown that reverse balanced flanged connection has higher moment resisting capacity. In the other investigation full scale testing of wind mill turbine is done at site by applying shaker excitations and the natural frequencies were calculated experimentally and results obtained by experimental excitation are validated with FEM simulation. [11]

One of the methods to study dynamic response of wind turbine is to prepare scaled down models of prototype structure in laboratory. The scaled down model of offshore wind mill turbine supported on monopile is prepared and it is subjected to dynamic loading of wind turbines [8]. It is shown that natural frequency increases with number of cycles, but rate of increase is reduced with accumulation of soil strain level. In another research 1/350 scaled model of 2 MW wind mill turbine is prepared and detailed wind tunnel testing was carried out and effects of relative rotation direction of power production investigated [9]. They have shown that rotation direction has no effect on power generation. They have also investigated effects of number of wind turbines on power generation. The 1:100 scaled model of 3 MW wind turbine considering soil below turbine is prepared in laboratory [10]. Model is subjected to predefined cycles of rotor and change in natural frequency and damping investigated and shown that natural frequency depends on shear strain level in the soil. The foundation stiffness may influence the dynamic properties of wind turbine so 1:100 scaled model of 3MW wind turbine with soil at base of turbine is prepared in laboratory and shown that frequency of tower depends on stiffness of foundation and derived the rotational and lateral stiffness of foundation and validated trough FE modeling.[12] The wind mills are subjected to dynamic loading for very long time during its life span, in order to study long time loading effects 1:100 scaled down model of wind turbine on mono poles and tetrapod type suction caisson are prepared and model is subjected to long term dynamic loading and effect of long term dynamic loads are studied.[16]

The simulation using FE software can be used for dynamic study of wind mill towers. In order to investigate dynamic properties FE model of 60 m high tower in prepared in FE software and dynamic properties of turbine under operational loads are investigated. [13] They have shown that tuned mass dampers can be used to reduce vibrations of wind mill tower under operational conditions.

The 3-dimensional differential equations can also be used to derive dynamic properties of wind mill. the evaluated dynamic properties are also validated using FE modeling and results obtained by analytical results are validated. [14] The Euler-Bernoulli beam-column theory is used and derived a function to evaluate dynamic properties of turbine based on geometric and elastic properties considering soil at base. The results are validated by laboratory tests.[15] The Euler–Lagrangian approach is used to achieve dynamic properties of wind turbine towers and results of dynamic properties are also validated with experimental testing at site.[17] the soil properties are also considered in analysis using differential equations and acceleration spectrum graph under operational conditions of wind turbines are derived and concluded that vibration studies of wind turbines along harmonic exciting force directions are sufficient.[19] The long term loading effects are important in dynamic analysis so this effects are investigated by solving differential equations and an expression of characteristics equations are derived and proposed method is validated with practical examples.[20]

III. DYNAMIC LOADS ACTING ON WIND MILL

The modern turbines are designed in such a way that they are operational at varying speed of wind at given location. It can generate power at lower range of wind speed and higher wind speed at given location. The operational RPM of wind turbine is not a single value, but it is a range of value. Due to rotation of blades the dynamic loads are generated on supporting structure, so This rotational frequency of turbine is of almost importance. This variable rotational frequency is known as the first excitation frequency, mostly referred to as 1P.

This frequency is referred as 1P frequency of turbine. The dynamic loads are generated due to unbalances in rotor, shear due to wind and tower shadow effects. In addition to this the second excitation frequency on the structure is due to rotor blade passing frequency. This frequency is referred as 3P frequency for 3 bladed turbines or 2P frequency for 2 bladed turbines. The 3P and 2P frequencies are obtained by doubling or tripling 1P frequency for two blades and 3 blade turbines respectively. During design of turbine designer must design tower structure, so that variable rotor frequency of turbine does not operate near natural frequency of tower supporting structure, and the frequency of supporting structure does not coincide with 1P and 3P frequency of turbines.

To design the wind mill tower based on this operating frequency 3 types of structural design possible. The design may be either soft-soft, soft-stiff or stiff-stiff. If the first natural frequency of turbine is less than 1P and 3P frequency design is soft-soft. If natural frequency is between 1P and 3P frequency it is soft-stiff design and if natural frequency of supporting structure is more than 3P frequency design is stiff-stiff design.

As the height of wind mills are increased to harvest more wind energy it becomes dynamically sensitive and first natural frequency of structure may fall in 1P or 3p range resulting in resonance condition. Proposed hybrid structural system provides more stiffness due to axial load resistance mechanism and bypass resonance conditions during operation of wind mills

IV. SIMILITUDE LAWS ADOPTED FOR EXPERIMENTAL TESTING

In order to perform detailed experimental testing, it requires to derive similitude rules between physical model and prototype structures. This scaling factors are required to be decided so that behavior of prototype structure can be experimentally studied in the laboratory [4]. The researcher has derived the various scaling factors to be used for wind mill towers. In his work author has prepared 1/50th scaled model of 5MW wind mill turbine. He has performed comparison using simulation tool FAST by comparing response of full scale and scaled system to verify that results of scaling down model are consistent with the scaling of system parameters. In order to derive scaling laws, the Froud based scaling approach is used. Out of all methods the Froud scaling is most preferred scaling technique used for modeling the wind mill structures. The scaling factor λ is defined as ratio of geometrical dimension of prototype structure to geometrical dimension of physical scaled down model. In case of Froud scaling the dimensions of each parameter are resolved in 3 terms. the mass is scaled by $\lambda^{3,}$ length is scaled by λ and time is scaled by $\lambda^{0.5}$ using this approach the scaling parameters derived in research work is shown in table 1. The scaling relationships are used in present investigation as summarized in table 1.

TABLE 1SCALING FACTORS FOR WIND MILL TURBINES [4]

Sr no	parameter	Scaling law
1	Run Time and Time Step	$\lambda^{0.5}$
2	Rotational frequency	$\lambda^{-0.5}$
3	Height of tower	λ
4	Nacelle center of mass to top of tower distance	λ
5	Mass of components	λ^3
6	Eccentricity of rotor blade	λ

Before preparing scaled down model for experimental testing it is required to decide scale down factor to be adopted depending on prototype structure and facilities available in laboratory. The prototype structure selected to prepare physical model in laboratory is 78.23 m high tower [5]. In his work researcher has done detailed seismic analysis in FE software. The geometrical details including diameter and heights of wind mill towers are mentioned by the author. The present investigation is carried out in structural dynamics laboratory of applied mechanics department at sardar Vallabhbhai national institute of technology, Surat. Depending on facilities available at laboratory the following points were considered for determination of proper scaling factors.

Major criteria to select scaling factor is height of the prototype structure and maximum height of model that can be accommodated in laboratory for experimental testing. The height available at laboratory is 2.8 m. but depending on clearance above the physical model 2 m high model can be procured so 78/2 =39 so a scale factor of λ= 40 is decided.

1) The rotational frequencies to be applied in experimental testing and the capacity of the equipment's used to be available in the laboratory.
2) The scaled down masses of nacelle and rotor to be applied at top of the tower.
3) Geometrical dimensions of materials available and availability of various material to prepare physical model in the laboratory.
4) The distance of the center of mass of nacelle from top of tower and eccentricity of center of mass of rotor from center line of the tower.
5) Maximum rotational mass of rotor of prototype structure to be applied on the experimental model in the laboratory

Considering the above scaling down criteria the scaling down factor λ= 40 is decided. Depending on λ= 40 following dimensions are decided from 78.23 mt high tower. [5]

1) The bottom diameter of prototype model is 3650 mm so considering scaling factor 90 mm bottom diameter of physical model is determined. The top diameter of 60 mm is determined based on 2282 mm top diameter of prototype structure.
2) Height of mass of nacelle is kept as 45 mm which is 1800 mm in prototype structure.
3) Eccentricity of the rotor in prototype structure is 3447 mm, so in experimental model 87 mm eccentricity is decided for center of mass of rotor.
4) In case of masses the scaling factor is λ^3. In the present experimental work, the nacelle is provided in form of motor at top of tower. the mass of nacelle in prototype tower is 52000 kg so a motor in form of nacelle mass having 0.8125 kg mass is used at top of tower

5) The blades of tower are not modelled in prevailing investigation work but depending on scaled down mass of rotor the fixed mass is procured on the axis of rotating motor

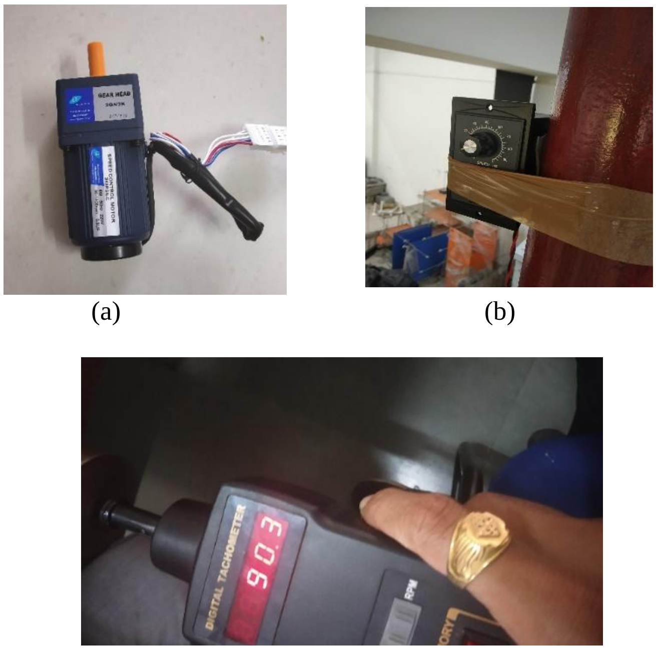
It is required to fix the model securely with fixed base to avoid any excessive vibration during dynamic testing of tower. A square base plate of 300 mm size is provided at bottom of physical model of the tower. To fix the base plate firmly with the foundation sufficient holes at equal distances along all four sides of plates are drilled. After preparing the model the verticality is checked with plum bob to avoid any eccentric loadings due to self-weight during the testing work. The model prepared for experimental work in laboratory with nacelle and rotor fixed at top of tower is shown in fig.2

In order to validate the results obtained in experimental work FE modeling is carried out. The input parameter in any FE software for material is yield stress and modulus of elasticity. It is required to evaluate this property of material such as yield stress and modulus of elasticity of steel in laboratory. Detailed tensile testing is carried out on 16 mm diameter metal bar of material to be used in preparing experimental model. The yield strength of given bar is obtained as 250 N/mm^2 and modulus of elasticity of steel as 2X10^5 N/mm^2

V. CALIBRATION OF EQUIPMENT AND PREPARATION OF EXPERIMENTAL TESTING

As discussed earlier the wind mill towers are operated at varying frequencies. This rotational frequency depends on velocity of wind at given location. In the present investigation AC motor having weight equals to scaled mass of nacelle is used to model nacelle in laboratory. In the present research 1P frequency of the tower is 10.8 RPM to 14.4 RPM (0.18 to 0.24 Hz) and 3P frequency of prototype structure is 32.4 RPM to 43.2 RPM (is 0.54 to 0.72 Hz). In order to study the dynamic behavior of tower, lower and higher range of 1P and 3P frequencies are selected in present investigation. Based on scaling factors mentioned in table 1, the 1P frequency of scaled down model is 70 RPM to 90 RPM and 3P frequency is 205 RPM to 275 RPM. The frequencies obtained after scaling down shows that range of frequency to be applied in experimental testing ranges from 70 RPM to 275 RPM. In order to achieve correct simulation of proto type structure, it is required to procure motor capable to produce variable rotational frequency.

For the purpose of testing 6W 50Hz motor with 90 to 1400 RPM range model no 2GN3K as shown in fig.1 is procured in the laboratory. The mass of motor selected is according to scaled down mass of nacelle. The frequency of procured motor is 90 to 500 RPM so to control rotating frequency of motor a special type of controller is procured in the laboratory. This controller can control voltage and ampere input to motor which in turn changes the rotational frequency of the motor. The controller has 0 to 100 percentage scale with least count of 2.5 percentage. Before applying rotational frequency to physical model of tower the calibration of motor along with its controller is required. The tachometer is connected with the axle of motor as shown in fig.1 the rotating frequency of motor is changed by controller attached with motor and it is rotated at different rotational frequency. The variation in rotational frequency of motor and different percentages to be kept on controller of motor are recorded. Table 2 summarizes the details of calibration of the motor.



(a) (b)

(c)

Fig.1 (a) Motor (b) Frequency controller unit and (c) calibration for rotational frequency.

TABLE 2 CALIBRATION OF MOTOR

Sr no	RPM of motor	Percentage on controller
1	70 RPM	12.5
2	90 RPM	17.5
3	205 RPM	42.5
4	275 RPM	47.5

After performing calibration of motor, it is secured at top of the tower. The distances are selected in such a way that center of mass of motor is at scaled CG distance of nacelle.

One of the modeling methods of rotating blade in experimental work is to procure mass of rotor at the scaled down eccentric distances. In the present investigation the blades are not modelled but it's scaled down masses are prepared in the laboratory. This fixed mass is procured on the axis of the motor. It is secured properly with the axis of motor and motor is secured at top of tower so that vibrations generated by rotating mass at top of the tower can be transferred to tower structure and response of structure can be studied.

At the bottom of the model base plate with appropriate holes are provided. The model is fixed on rigid base prepared in laboratory with help of bolts. The location of bolts is accurately determined to model the physical model in FE software. In case of tall structural system to transfer vibrations and to avoid any bending stresses, true vertical position of model is important, so verticality of model is checked with plum bob and it is examined that model is fixed in true vertical position

VI. PREPARATION OF HYBRID SUPPORTING SYSTEM FOR EXPERIMENTAL TESTING

The main aim of present investigation is to compare the dynamic response of mono and hybrid supporting system for the tall wind mill towers.

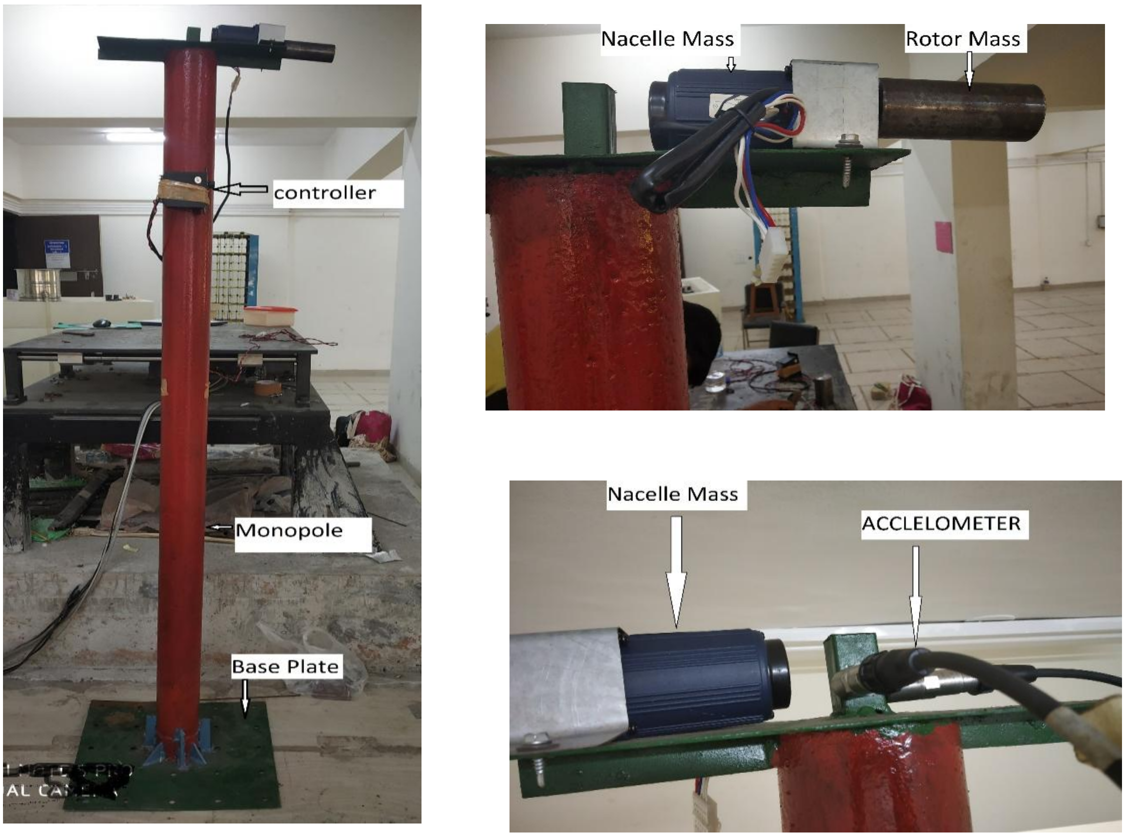


Fig 2 Details of Monopole tower and data acquisition system

To compare the response of both structural system another model of hybrid supporting system is prepared in the laboratory. This hybrid structural system is combination of mono and lattice system having mono system at higher elevation and lattice system at lower elevations. The bottom lattice portion will resist the forces by axial action and top mono system will resist forces by bending action of tower. The important parameter of resemblance of two structural system is to keep equal mass of hybrid structural system and mono structural system. The physical model of hybrid system prepared in such a way so that mass of both systems is identical with difference of one percentage. The total height of physical model of monopole supporting system is 1950 mm. To convert this system in hybrid supporting system bottom 1000 mm portion is constructed with lattice structural system. The square plate of 300 mm size is provided at tower base and width of tower is reduced to 150 mm at 1000 mm height from 300 mm at base of tower. The holes are provided in base plate to secure tower rigidly with the foundation. In lattice potion main leg members are provided with 4 mm diameter continuous bars. The main leg members are secured continuously along length without any joint. The main leg member will buckle under action of axial forces acting on it, to avoid this buckling additional structural members in form of bracing are provided. In present investigation lattice portion is divided in 6 identical parts and cross type bracings are provided in each part. The top 1000mm to 1950 mm level of tower is constructed using conventional monopole system. The diameter of monopole system is kept as 90 mm at 1000 mm level which is reduced to 65 mm at the top as shown in fig.3.

In hybrid structural system joint between mono and lattice system at 1000 mm level is constructed in such a way that it will not fail during testing and forces and moments from top portion of tower can be transferred securely to foundation through lattice structural system. The motor and rotor mass are secured on top of tower rigidly to transfer the dynamic loads generated due to rotation of the rotor mass

VII. TESTING OF SCALED MODEL

To evaluate the response of structures it is required that monopole and hybrid structural systems are subjected to same types of dynamic loading. For experimental work 70 RPM, 90 RPM, 200 RPM and 275 RPM rotational frequencies are selected. It is required that rotor mass is to be rotated at the identified frequencies for stipulated time. The rotor mass is securely fixed with axis of motor as shown in fig.2 and 3.To evaluate response of tower in terms of displacement the accelerometer is fixed at top joint in the Centre of tower. The tower is secured with rigid base by connecting base plate of tower using bolts at appropriate position and the controller of motor is connected with the motor. The response of structure is evaluated in terms of displacement at top of tower. The accelerometer of national instrument model no NI cDAQ-9174 is used to measure acceleration values.

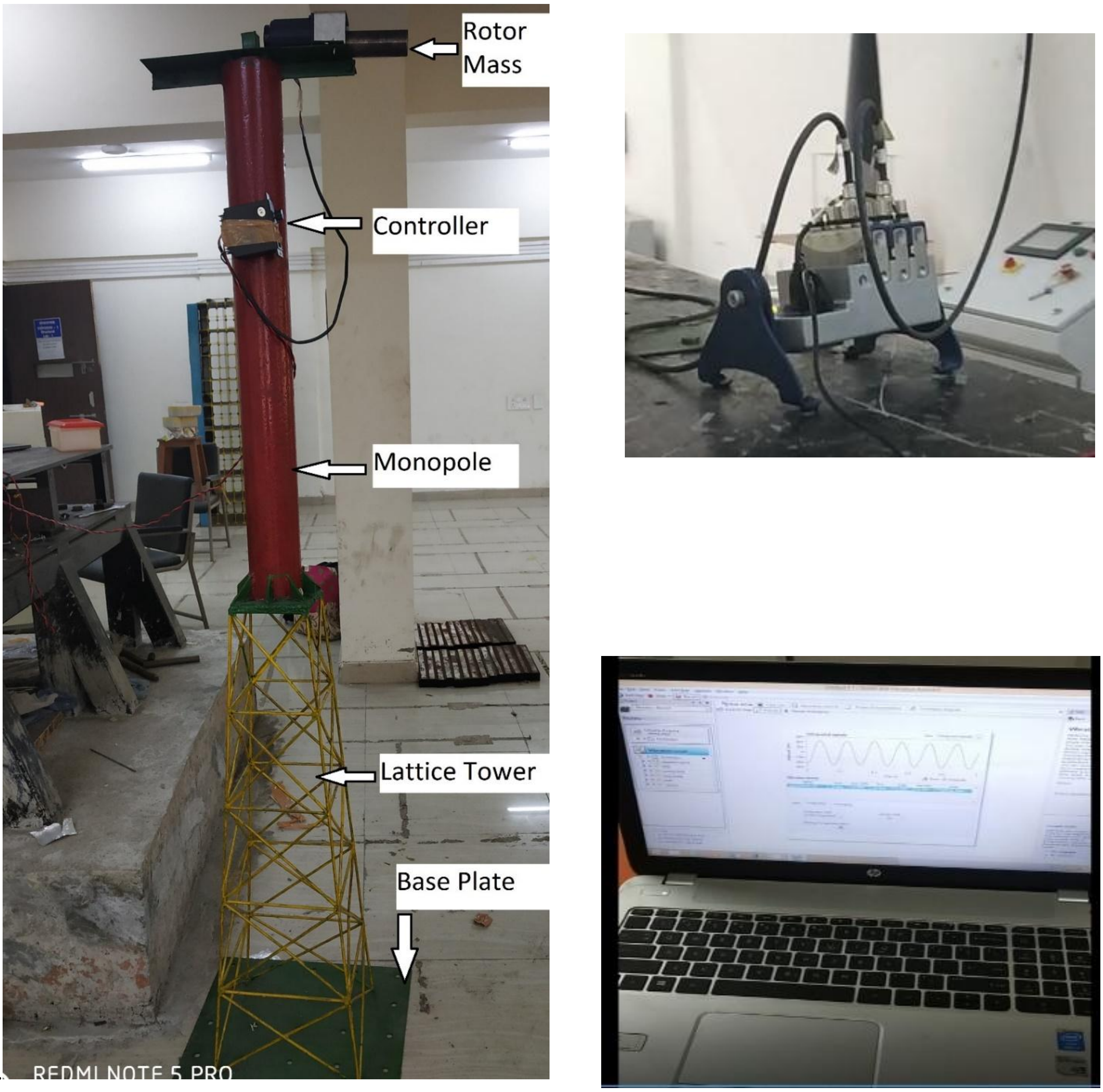


Fig 3 Details of Hybrid Tower and Data Acquisition System

This data acquisition system is linked to computer having lab view software as shown in fig.3. The acceleration recorded in time domain can be converted to displacement in time domain by performing double integration. Lab view software is able to convert the acceleration achieved during experimental work in to displacement in time domain. After completing all necessary preparations, the verticality of model is checked with help of plum bob. The motor is rotated at four different rotational frequencies by changing percentage of controller as presented in table1.

VIII. NUMERICAL SIMULATION AND VALIDATION OF EXPERIMENTAL WORK

After evaluating response of structure by experimental work it is required to validate the result by numerical simulation. In order to validate experimental result three-dimensional model of both structural systems developed in FE software. The FE program is able to simulate dynamic behavior of wind mill structures by defining length, thickness and size of different structural members and inputting the material properties. The rotational frequencies applied on wind mill can also be replicated in FE software and response of structure in form of stress, displacement, shear etc. can be studied. Various types of modeling elements such as line, thin shell, thick shell solid is given in FE software to model the behavior of real structure. In present investigation wall of monopole tower is modelled as thin shell element. The properties of material such as modulus of elasticity, unit weight, yield stress evaluated earlier were inputted in the software. The base plate of actual thickness is modelled as shell element at the base of tower. choosing appropriate aspect ratio meshing of all shell elements are done. To replicate boundary conditions prevailing at base in actual structure in FE software, the nodes are identified where bolts are fixed in base plate and all these nodes are restrained against displacement in all directions. To compare response of hybrid tower, the top monopole is modelled using thin shell element as described above.

The frame elements are used to simulate behavior of bottom lattice structure. In physical model lattice structure is made using bar elements, the geometrical and physical properties of bars are inputted in software. The main leg of tower in the experimental model of lattice tower is assembled without any joint, therefore, in simulation main leg of tower is modelled as continuous members. The cross-bracing system of physical model is simulated in modeling, the degree of freedom of all end nodes of bracing systems are restrained against rotation in all directions. The connection of mono system and lattice system at 1000 mm level is important in simulation work. It should be correctly modeled so that dynamic response of structure can be evaluated, to connect mono and lattice parts two joint rigid link elements are used in numerical simulation. The nacelle and rotor of the wind mill tower are not modelled in FE software, but their masses are applied as joint mass at their respective center of mass in FE simulation. The distance of center of mass of nacelle from top of tower and eccentricity of rotor mass is evaluated before physical model preparation. For correct FE analysis it is required to transfer these masses of nacelle and rotor to rower structure, two joint rigid link elements given in FE software is used to transfer these masses to tower structure. Fig.12 shows the simulation of physical model prepared in FE software for mono and hybrid structural system. It is required to simulate the rotational frequency of rotor applied at top of tower correctly in FE software. The dynamic load case is defined, and the time period of applied frequency is inputted in FE software. Each frequency is analyzed for 20 no of cycles and for each cycle 1000-time steps are defined. The dynamic load case is defined for each rotating frequencies and rotor masses are assigned to defined dynamic load case. The detailed dynamic analysis for all four frequencies is carried out using periodic time history load case. The joint where displacements are recorded in time domain in experimental works are described in FE software and displacement response of that joint in time domain in desired direction is evaluated for all rotational frequencies of rotor.

IX. RESULT AND DISCUSSION

In the present investigation scaled down model of prototype structure prepared in laboratory and it is exposed to dynamic loads due to rotation of blades. Various scaled down rotational frequencies are applied on mono and hybrid structural system and to study repose of structure the acceleration of top joint is measured by accelerometer fixed at top joint of tower. This acceleration is converted to displacement in time domain by double integration method with the help of lab view software. In order to validate the experimental results simulation of physical model of both structural systems executed in FE software. The boundary conditions prevailing in physical model is bolted at base plate so in FE simulation same boundary conditions are given by checking displacement of bottom nodes in all three directions. The rotating rotor loads are simulated in FE software is defined using sine function given in time history definition and detailed periodic time history analysis is performed in software. The number of modes considered for modal frequencies are such that dynamic participation factor is more than 90 percentage. To achieve the results of joint displacement in simulated FE model the nodes where accelerometers are equipped in physical model are identified and displacement in time domain are extracted for same location. The displacement attained by experimental work from lab view software and extracted from the simulation in FE software are plotted in one graph. The displacement obtained by physical model is and simulation is cyclical form varies in time domain with positive value and negative value.

A. Discussion for monopole system

The comparison of displacement in time domain by experimental work and numerical work for 70 to 275 RPM for monopole supporting system is presented in Fig. 4 to fig. 7 by comparing the results presented for 70 RPM in fig.4 and for 95 RPM in fig.5 for monopole structural system, it is noticed that results of experimental testing in laboratory is closely identical to numerical simulation. In the experimental recording of displacement some noise is observed in low frequencies of 70 RPM and 95 RPM. The possible reason for noise may be that rotor frequencies are applied to structural system and structural system will also respond to the external loading of dynamic loading. In lower frequency it takes long time to complete one cycle so vibrations of structural systems are recorded as noise in accelerometers.

As presented in Fig.4 to Fig 7 at higher frequencies the time period of one cycle is very less, so before system responds another cycle is applied from the rotor so less noises are observed at 205 RPM and 275 RPM. The plot of time V/s displacement in time domain for 205 to 275 RPM shows that the amplitude and time period of lateral displacement obtained by experimental work is closely identical to displacement obtained by its FE simulation.

The amplitude and time period of vibrating frequency is constant in time domain and periodic in nature. Upon comparing the results of experimental work, it can be noticed that the amplitude and time period of displacement of top joint agreeing with dynamic excitation applied at top of tower. The displacement values obtained by integrating accelerometer values from experimental work is adequately identical with the FE simulation work with less than 5 % difference.

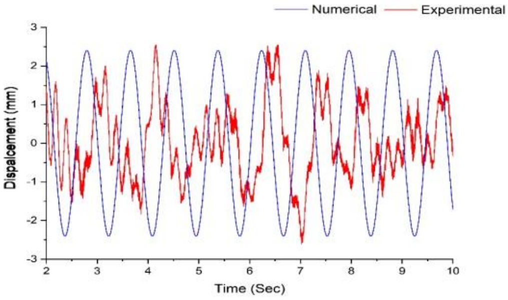


Fig.4 Displacement in time domain for monopole for 70 RPM

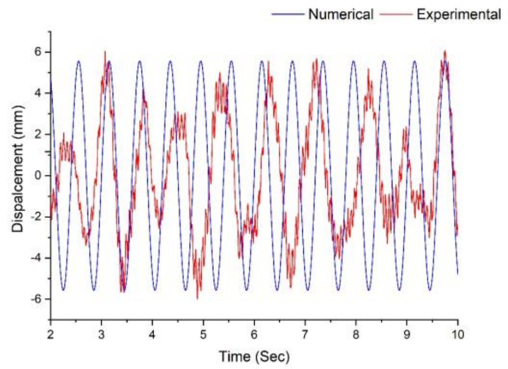


Fig. 5 Displacement in time domain for 90 rpm for monopole

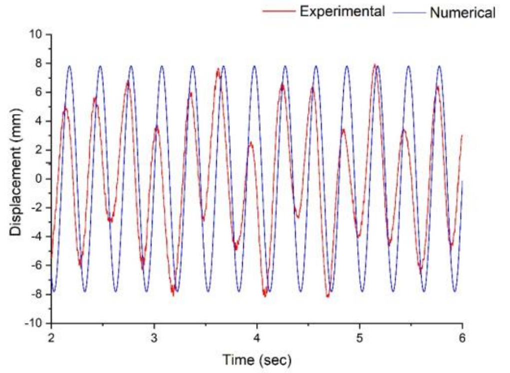


Fig. 6 Displacement in time domain for 205 rpm for monopole

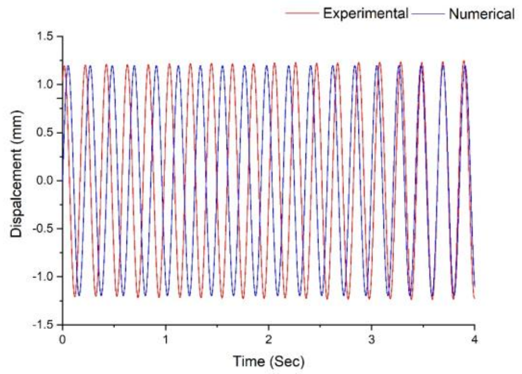


Fig. 7 Displacement in time domain for 275 rpm for monopole

B. Discussion for Hybrid system

The variation of lateral displacement attained by accelerometer at top joint of hybrid tower under excitation of various frequencies are plotted in Fig 8 to Fig 11.The variation in lateral displacement of same node identified from experimental work is also presented in graph. As observed in case of monopole towers the variation of displacement obtained by experimental work is identical to FE formulation with accepted accuracies. As presented in fig 8 to fig.11 comparison graphs it can be observed that displacement pattern obtained from experimentally work is absolutely matching to results obtained from its FE simulation. The amplitude and time period of vibrating frequency is constant and having repeating nature. By studying results achieved from experimental work it is noticed that acceleration and displacement obtained from experimental work are identical to rotor frequencies applied on tower. In case of hybrid structural system only some noise is observed in 70 RPM frequency but for all other frequencies very less noise is observed. The variation of displacement in time domain obtained by experimental work and its simulation is closely identical to its FE simulation with acceptable differences. In the higher frequencies if excitation the time period is very less so number of cycles recorded in 205 RPM and 275 RPM is more compared to lower frequencies.

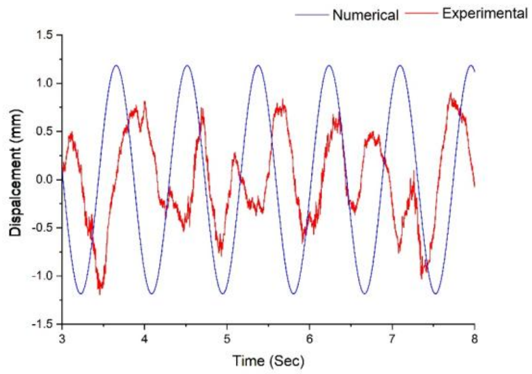


Fig. 8 Displacement in time domain for 70 rpm for hybrid

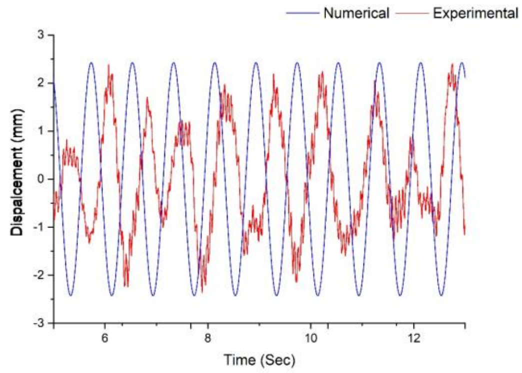


Fig. 9 Displacement in time domain for 90 rpm for hybrid

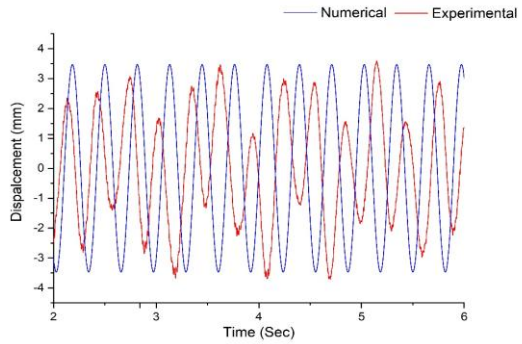


Fig. 10 Displacement in time domain for 205 rpm for hybrid

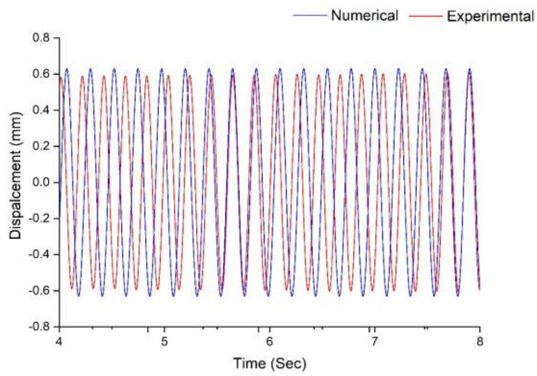


Fig.11 Displacement in time domain for 275 rpm for hybrid

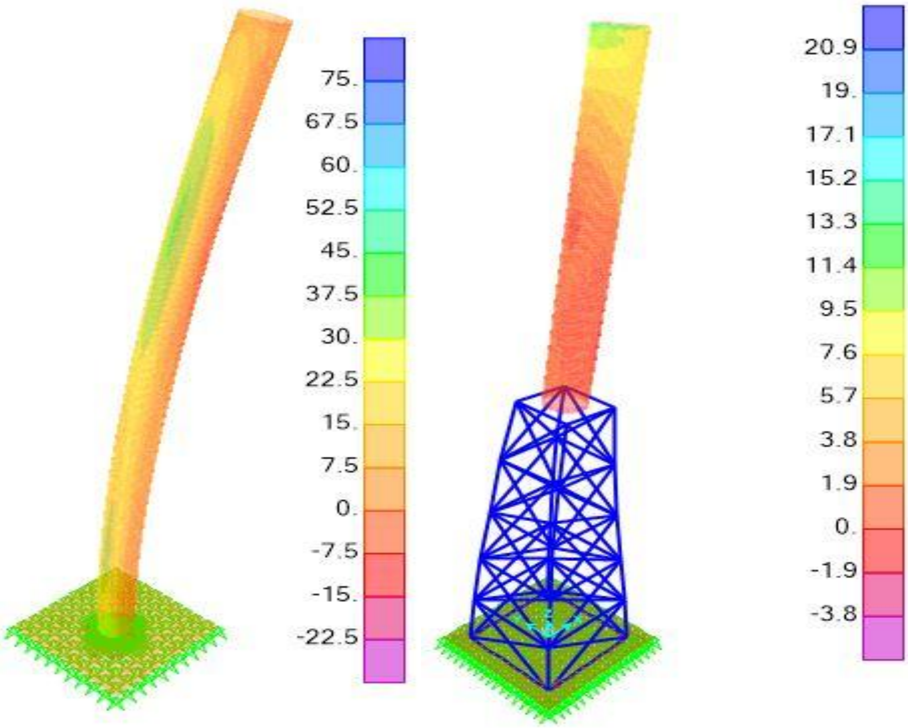


Fig 12 Distribution of stresses in mono and hybrid structural system

C. Variation of stress

One of important parameter to compare the response of structural system is principal stresses developed in shell element of wind mill tower. The dynamic loads applied on top of tower due to rotation of blade will change in time domain. Due to this the wall of towers are subjected to reversal of stresses. Due to rotation of mass at top of tower wall elements are subjected to tensile and compressive stresses varying in time domain. In order to study stresses generated in wall of both structural system, time of generation of peak stresses are evaluated and peak stresses generated at evaluated time are obtained from FE analysis. Fig. 12 shows variation of stresses in shell element and frame elements of the tower. It is noticed that in case of mono structural system peak stresses are generated on opposite side of nacelle and they are generated at 1.6 mt level.

In hybrid structural system peak stresses are generated near the nacelle. By comparing stresses, it is noticed that maximum stress in wall of mono structural system is 45 Mpa which is reduced to 14 Mpa in hybrid structural system. In addition to that it is also observed that peak stresses are reduced from 75 Mpa to 20.9 Mpa in hybrid structural systems

D. Deflection comparison of hybrid and mono system

The main aim of present investigation is to compare the response of monopole and hybrid structural system in terms of acceleration and displacement obtained under excitation of heavy rotor mass. From the present investigation displacement in time domain is obtained for both supporting system for various frequencies are plotted in Fig.13. It is revealed that the variation of absolute lateral displacement observed in both system by experimental work is identical to displacement obtained from its FE simulation. From fig. 13 It is noticed that hybrid structural system reduces the displacement by 56 to 60 percentage for lower frequencies of excitation and lateral displacement is reduced by 49 to 54 percentage for higher frequencies of tower. the variation of displacement observed along height of tower considering both structural systems are presented in fig. 14. It is observed that displacement is maximum at top of tower. fig 14 shows that peak displacement in mono structural system for 205 RPM is 8 mm which is reduced to 3.5 mm for 205 RPM in hybrid structural system.

By studying the results, it is also noticed that lateral displacement will increase with increase in rotational frequency of tower up to 205 RPM and after that it is reduced, so less lateral displacement is observed in 275 RPM. It can be concluded that displacement in hybrid supporting system is less compared to conventional mono structural system under operation of wind mill turbines.

1.

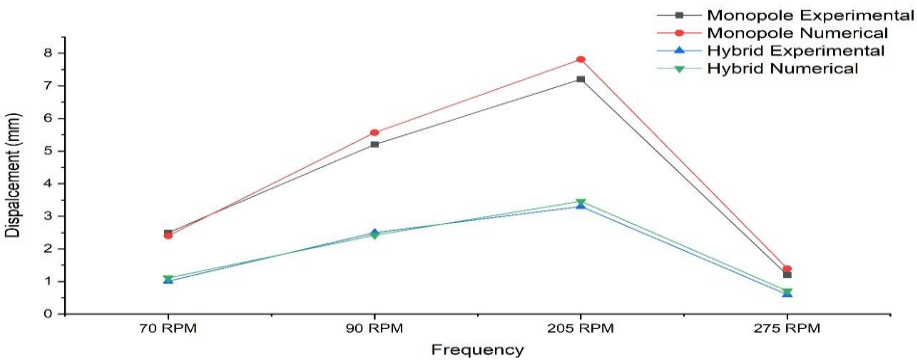


Fig 13 comparison of displacement for mono and hybrid structural system

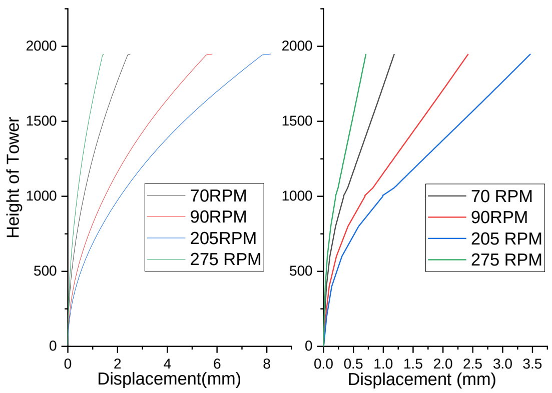


Fig 14 Variation of Displacement in (a) mono tower (b) hybrid tower

E. VARIATION OF BASE SHEAR

From the present investigation the base shear obtained for various frequencies of turbine are presented in Fig.15. Upon comparing values of base shear obtained from FE analysis for all frequencies, it is revealed that base shear is 66 percent less in hybrid system compared to mono system for 70 rpm. The reduction of base shear is in hybrid system is 70 percentage, 66 percent and 56 percent for 90 rpm, 205 rpm and 275 RPM respectively.

From these results shown in fig. 15 it can be noticed that due to more axial stiffness of tower hybrid structural system reduces base shear by 60 to 70 percentage under operational conditions of wind mill tower.

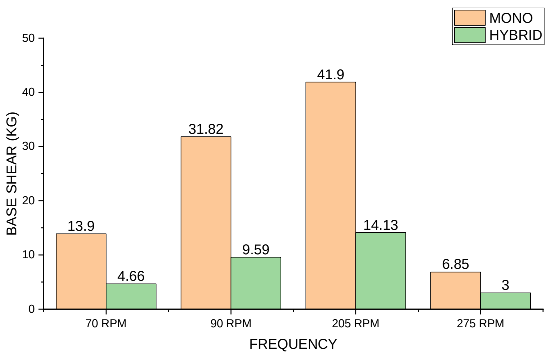


Fig. 15 Variation of Base shear

X. CONCLUSION

In the present investigation hybrid structural supporting system which is combination of lattice and monopole is proposed and its dynamic response is compared with conventional monopole system under rotating loads of blade acting on rotor.

In order to compare the response of structural system experimentally scaled down model of prototype monopole structure is prepared in laboratory, in addition to this a model of hybrid system is prepared in laboratory in such a way that total mass of mono and hybrid structural system remains identical. To get accurate results in experimental work for detailed dynamic analysis calibration of rotating system is carried out in laboratory. The scaled down dynamic loadings considering four operating frequencies are applied on both structural systems. The response of structure is recorded in form of acceleration at top of tower in time domain and from this displacement in time domain is obtained by double integration method.

After performing experimental work, the simulation of physical model of both structural systems are performed in FE software. The dynamic loads and actual boundary conditions prevailing in both physical models are applied in FE software. The response in form of displacement attained by FE model is closely agreeing with experimental work with accepted accuracy proves that test procedures and methods used in experimental work are correct.

In the tall wind mill tower the forces and moments are large at lower compared to greater heights, so resistance obtained by axial stiffness by lattice system proves advantageous in hybrid system compared to conventional monopole system which resist forces by bending action. From the present investigation it can be concluded that hybrid structural system which is combination of mono and lattice structural system is less sensitive to dynamic forces acting on it compared to conventional monopole structural system and can be used as structural system for tall wind mill towers.

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