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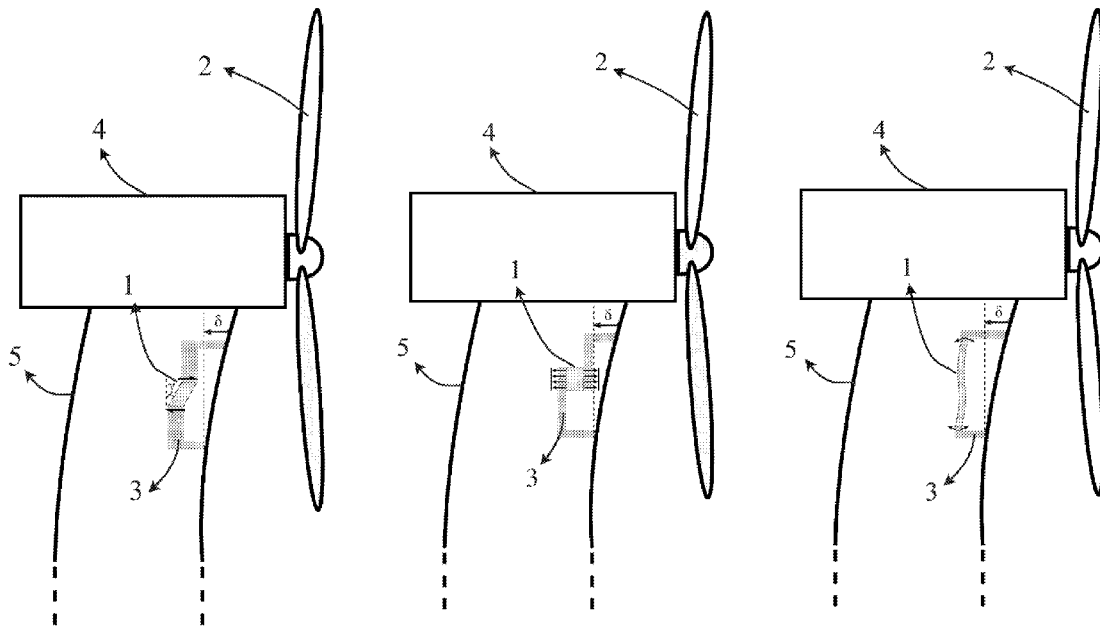


Figure-1

(57) Abstract: The invention relates to a damping element consisting of viscoelastic material and designed for damping wind turbine vibrations and increasing fatigue life of the structure.

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DAMPING ELEMENT CONSISTING OF VISCOELASTIC MATERIAL, DESIGNED FOR DAMPING WIND TURBINE VIBRATIONS AND INCREASING FATIGUE

LIFE OF THE STRUCTURE

TECHNICAL FIELD OF THE INVENTION

The invention relates to a damping element consisting of viscoelastic material and designed for damping wind turbine vibrations and increasing fatigue life of the structure.

STATE OF THE ART OF THE INVENTION (PRIOR ART)

Studies are carried out for damping the vibrations on the wind turbine tower and blades, and for increasing lifetime of the structure. These studies include active, semi-active, and passive vibration control approach methods. In the active vibration isolation approach, vibrations on the structure are damped by applying force to the structure in the opposite direction of the vibrations through a control system providing feedback, and an actuator. On the other hand, passive vibration control does not require an external force and control system [1]. In the passive vibration control, vibration absorbers generally tuned with single-degree-of-freedom are designed to fit the frequency of wind turbine mode with high vibrations, and it is aimed to take the structure's vibration upon the vibration absorber. Semi-active vibration control, on the other hand, contains the combination of passive and active vibration control methods [2].

In the literature, vibration control methods used for isolating wind turbine vibrations largely include tuned mass dampers, firstly introduced by Den Hartog [3]. These vibration dampers have single-degree-of-freedom and have a single natural frequency, and conducts vibration damping on the structure at this natural frequency. Therefore, the natural frequency of vibration dampers is tuned to be equal to the frequency of the wind turbine's mode that is considered critical. Tuned mass dampers can be used as active and semi-active vibration dampers at the same time. These methods have the purpose of controlling constantly the structure's natural frequencies which are changing by aerodynamic force, through actively changing the natural frequency of the vibration damper.

In Figure 3, a tuned mass damper positioned in a wind turbine engine room is shown [4]. The tuned vibration absorber in Figure 3, damps only the longitudinal vibrations because it moves in a longitudinal direction (against the prevailing wind). If the same vibration damper is positioned in a lateral direction, it will damp lateral vibrations.

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There are many different uses of tuned vibration absorbers for wind turbines in the literature. Stewart and Lackner [5] achieve load reduction of 5% in longitudinal and 40% in lateral axis, by positioning tuned vibration absorbers, which move in longitudinal and lateral directions, in the 5MW offshore wind turbine engine room. The reason for the gap between the damping ratios of the longitudinal and lateral axis is that the longitudinal vibrations are already damped by aerodynamic forces and thus the vibration damper added becomes less effective. The average mass of the tuned vibration absorber required for this load reduction ratio varies between 10 and 20 tons. In another study, Stewart and Lackner [6] conducted a comprehensive optimization analysis on defining mass and stiffness coefficients of the tuned mass dampers for different tower structures on offshore wind turbines. Murtagh et al. [7], achieved a 20% displacement reduction on the tip of the tower, with the vibration damper which they positioned in the engine room to damp the longitudinal vibrations. Zuo et al. [8] investigated the influence of vibration dampers at different load conditions by positioning multiple tuned mass dampers in the tower. In this study, they achieved significant vibration damping in the different earthquake, wave, and wind load combinations.

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Tuned mass dampers can also be used semi-actively or actively in certain studies [9,10]. In these studies, the natural frequency of vibration dampers is continuously tuned and brought to the basic vibration mode frequency. In this way, the vibration damper runs effectively even if the basic natural frequencies of the structure change by the aerodynamic forces.

25

In the literature, there are also studies in which the tuned mass dampers are positioned into the wind turbine blades [10,11]. These studies aim at damping the basic longitudinal and lateral vibration modes on the blades. Longitudinal vibrations on the blades can be damped by 41% thanks to the tuned mass dampers positioned into the blade.

30

One of the other vibration dampers used commonly in the literature is the tuned liquid column dampers. These dampers include a U-shaped tube and liquid therein. The natural frequency of the vibration damper is adjusted according to the amount of the liquid and the diameter of the

tube. It aims at damping the vibrations on the main structure by creating a force in the opposite direction with the shake of the liquid when the main structure vibrates. In Figure 4, an example of a tuned liquid column damper is shown [4]. In the studies of Zhang et al. [12], Colwell and Basu [13], the influence of tuned liquid column dampers is investigated.

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Another method used for damping wind turbine vibrations is the damping mechanisms having a cavity where a high-mass object moves in the cavity. When the main structure vibrates, the high-mass object in the cavity creates a force in the opposite direction because of its inertia, so it tends to damp the vibrations. [14].

10

In addition to all these passive methods, Botasso et al. [15] studied a different concept and added a passive flap that rotates freely on the wind turbine blades. The passive flaps damp vibrations by rotating in the opposite direction of the blades' lateral vibrations and creating a counter moment. Passive flaps are shown in Figure 5.

15

The studies outlined above, on damping wind turbine vibrations by using tuned vibration absorbers are specific designs for a predetermined tower or blade vibration mode. Since these vibration absorber designs have a single-degree-of-freedom structure, they are designed according to a single natural frequency, therefore they do not have the capacity of damping the vibrations arising from other vibration modes on the structure. Also, the passive designs developed above ignore the fact that natural frequencies change when the wind and blade rotation speed change.

20

Viscoelastic materials, on the other hand, display damping characteristic in a wider band because of their structures. What matters here is that the frequency and temperature range in the setting where the viscoelastic material is used, is inside the transition region. Viscoelastic materials display the most efficient vibrating action when they are inside the transition region [16,17].

25

As a result, the effects of viscoelastic links on wind turbines were not investigated before. Viscoelastic materials provide solutions for more general and broader frequency bands for damping vibrations because of their characteristics.

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BRIEF DESCRIPTION AND OBJECTS OF THE INVENTION

The present invention relates to the damping element consisting of viscoelastic material and designed for damping the wind turbine vibrations and increasing fatigue life of the structure, to eliminate the above-mentioned disadvantages and provide new advantages to the related technical field.

The viscoelastic link designed in the invention converts the vibrations in the tower into heat, by being positioned into the wind turbine tower according to certain geometrical parameters.

The designed viscoelastic material can be connected in different forms into the wind turbine tower and display different damping effects.

Descriptions of the Drawings Defining the Invention

To explain better the viscoelastic material developed with this invention, the system designed for damping the wind turbine vibrations and increasing fatigue life of the structure, the figures below are used:

Figure 1: Viscoelastic links (left: shear type, middle: extension-compression type, right: bending type)

Figure 2: Viscoelastic link parameters (left: side view, right: top view)

Figure 3: Tuned vibration absorber positioned into the wind turbine engine room [4]

Figure 4: Tuned liquid column damper [4]

Figure 5: Passive flaps added to the blades [15]

Figure 6: Weibull distribution function

Figure 7: Critical blade modes (1: 1st Blade longitudinal, 2: 2nd Blade longitudinal, 3: 1st Blade lateral)

Figure 8: Critical tower modes (1: 1st Longitudinal, 2: 2nd Longitudinal, 3: 1st Lateral, 4: 2nd Lateral)

5 Figure 9: Coordinate axis

Figure 10: NREL 5 MW wind turbine finite element model

Figure 11: The first 5 mode shapes of NREL 5 MW finite element model

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Figure 12: QBlade analysis for 12 m/s average wind speed

Figure 13: Tangential and normal aerodynamic forces on the blade

15 Figure 14: Selected points on the tower

Figure 15: Frequency response functions of the base (no-viscoelastic-connector-added) model

Figure 16: Viscoelastic links in the tower

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Figure 17: Examined viscoelastic link positions

Figure 18: Mode 1 acceleration values

25 Figure 19: Mode 2 acceleration values

Figure 20: Mode 3 acceleration values

Figure 21: Mode 4 acceleration values

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Figure 22: Viscoelastic link positioning proposals

Figure 23: Effect of the 'I' parameter in the viscoelastic links

Figure 24: Effect of the 't' parameter in the viscoelastic links

Figure 25: Effect of the 'h' parameter in the viscoelastic links

5 Figure 26: Effect of the 'w' parameter in the viscoelastic links

Definitions of the Elements and Parts of the Invention

10 The parts and elements of the damping system developed with this invention, which consists of viscoelastic material and is designed for damping the wind turbine vibrations and increasing fatigue life of the structure, are individually numbered and listed below.

1. Viscoelastic link
2. Blade
- 15 3. Rigid Connection
4. Engine Room (Nacelle)
5. Tower

DETAILED DESCRIPTION OF THE INVENTION

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In this detailed description, novelty of the invention is described by examples that have no limiting effect and aims only to explain the subject matter better.

25 In recent years, the size of wind turbines are increasing because of the increase in renewable energy investments and the need to generate more energy. An increase in the size of the wind turbine brings out vibration-related fatigue life problems on the structure because they expose the wind turbines to more aerodynamic forces. A wind turbine must be designed to operate for at least 20 years according to the IEC61400-1 standards [18]. Vibration-related fatigue life problems of wind turbines are one of the parameters affecting wind turbine designs the most.

30

Thanks to their polymer-chained structure, viscoelastic materials store strain energy and convert this energy into heat when they are deformed. Viscoelastic materials are widely used in vibration damping methods because of this feature. One of the most common ways of using

viscoelastic material is sticking them on the plate subjected to high vibration, thus their vibration can be damped.

5 The viscoelastic link designed in the study converts the vibrations in the tower into heat, by means of being positioned into the wind turbine according to certain geometrical parameters. The basic working principle of the viscoelastic link is damping the displacement gap with the damping effect of viscoelastic material, by making use of the relative displacement gap between two different points on the tower while the wind turbine is vibrating in a certain vibration mode. The viscoelastic material can be connected in different forms into the wind turbine tower and display different damping effects. Figure-1 shows the viscoelastic connections positioned into the wind turbine tower in different forms.

15 In Figure-1, the wind turbine tower becomes deformed and creates the relative displacement gap indicated by δ on the tower. Viscoelastic material is connected by rigid connections as shown in Figure 1, in order to damp this displacement gap. In this way, the relative displacement gap caused by tower vibrations can be converted into heat energy by the viscoelastic material, thereby damping vibrations.

20 Viscoelastic material can be connected into the wind turbine tower in different forms, as shown in Figure-1. On the left graphic of Figure-1, viscoelastic material is damping by being subject to shear stress. On the middle graphic of Figure-1, viscoelastic material is damping by being subject to compression and extension stress. On the right graphic of Figure-1, viscoelastic material is damping vibration by bending.

25 Rigid connections shown in Figure-1 can be connections made of aluminum, titanium, carbon fiber, and steel, for example. It has been determined by the studies that the connection of viscoelastic material to the tower is rigid because the vibrations on the wind turbine are at low frequency (0-5 Hz) and viscoelastic materials are very flexible. The important thing in connection material is the Young's Modulus. Young's Modulus value for aluminum is 70 GPa while it is 207 GPa for steel. Any material having a Young's Modulus value greater than 70 GPa can be used in this system.

Viscoelastic links can be positioned in the wind turbine towers with different geometrical and positional parameters. Positional parameters are X_l and Y_l parameters indicated in Table 1. In

this way, the damping effect of the wind turbine vibrations will be changed by the determined parameters. The parameters of viscoelastic links are shown on the graphic in Figure-2. These parameters are explained in Table 1.

h	Height of viscoelastic material
t	Thickness of viscoelastic material
w	Width of viscoelastic material
l	Distance between two rigid connection points
x	Distance between two different viscoelastic links
X_l	Position of the viscoelastic link in the tower according to the X-axis
Y_l	Position of the viscoelastic link in the tower according to the Y-axis

Table 1: Viscoelastic link parameters

These parameters must be optimized for the positioning of viscoelastic material because each wind turbine will have different dynamic characteristics and the areas where they operate will have different temperatures. For example, viscoelastic material is positioned in front of the tower to reduce the vibrations in the prevailing wind direction, while they are positioned on the sides of the tower to reduce the lateral vibrations. Besides, a more efficient result can be achieved by increasing the size of the viscoelastic link, considering the elevator and staircase positioning inside the tower. In addition, different vibration damping approaches can be provided by using a large number of small viscoelastic links throughout the tower.

A shear type connection (Figure-1, left) is the most efficient solution. This is because the shear modulus of viscoelastic material is lower than its extensional modulus and thus it shows a higher damping characteristic.

Different vibration-damping effectiveness can be seen by selecting different viscoelastic materials for the connection models shown in Figure-1. In addition, the dynamic and geometrical features of the wind turbine will affect the viscoelastic material positioning. For example, if the tower's diameter is small, a viscoelastic material high in "t" and "w" parameters could not be used because of positioning problems. For this reason, a material and

positioning low in “t” and “w” and high in “h” can be preferred. In this way, viscoelastic material will have a damping mechanism of bending type.

The temperature range at which viscoelastic material will work most effectively is the temperature range where the material is inside the transition region. For example, LD-400 viscoelastic material can damp more effectively between 5-30 Celsius degree. However, many different viscoelastic materials are used in the world and each viscoelastic material has different vibration damping characteristics at different temperature ranges. Therefore, to damp the vibrations on a wind turbine, the temperature range of that wind turbine area must be considered and a viscoelastic material must be chosen accordingly.

In said invention, at first the effect of structural damping ratios in critical vibration modes on the loads and lifetime of wind turbines is studied. In this study, the FAST code is used which is developed by the National Renewable Energy Laboratory and approved by Germanischer Lloyd for the wind turbine design and certification, because wind turbine design is maintained by combining a large number of disciplines. FAST is a multi-disciplined code written for wind turbine aeroservoelastic simulation.

The method is implemented by completely considering the international wind turbine standard IEC61400-1 [18]. Firstly, the 5 MW wind turbine designed by NREL for being a reference in international studies was modeled in the FAST code. Briefly, the parameters of this model include mass, inertia, and stiffness values of the structure, CL and attack angle values of the blades, and control system parameters. All the parameters of the model are obtained from the NREL’s database.

Afterward, turbulence inputs are modeled as specified in the IEC61400-1 standard. The turbulences are modeled to last for 1 hour for each average wind speed, between 2 m/s and 24 m/s average wind speed with 2 m/s intervals. These turbulence inputs are implemented on the structure and load values are specified.

The highest bending moment and stress values are obtained from the roots of the tower and blades as the wind turbine tower and blades act as a beam having an almost rigid connection. The stresses are also high in this transition region because the cross-section of the blade transits sharply from the structural part towards the aerodynamic part [19,20]. However, the

invention is based on only the force and moment values on the blade and tower's roots, and the force and moment values are found on the tower and blade roots for each average wind speed in the time scale.

- 5 After the force and moment values are found, Damage Equivalent Load (DEL), an approach developed by NREL, is found. These loads are equivalent loads by associating the short-term analysis to wind turbine lifetime. In this approach, firstly, the analyses on the time-scale are undergone a rain flow counting algorithm, and the average of each load cycle, amplitude value, and cycle count is obtained. The average of each load cycle is different, so the
- 10 Goodman correction is implemented on these load cycles and it is considered as if these load cycles have a fixed average value. Afterward, the number of cycles obtained for each average wind speed analysis is multiplied by the probability distribution function and the resulted loads are multiplied by the wind turbine lifetime. In this study, the Weibull distribution function which is proposed in the standards and shown in Figure 6 has been used. By
- 15 obtaining lifetime damage from the number of cycles found according to wind turbine lifetime, the amount of the load which has a single cycle and gives the same damage, namely the damage equivalent load is found.

The damage equivalent loads are found separately according to the structural damping ratio of

- 20 1%, 5%, 10%, 20%, and 30% for each critical mode. The critical blade and tower modes selected for this study are shown on the graphics in Figure-7 and Figure-8.

The coordinate axis and load definitions used in the study are indicated in Figure-9. In this context, on the blade root, RootFxb1 and RootMyb1 indicate longitudinal forces and

- 25 moments; RootFyb1 and RootMxb1 indicate lateral forces and moments; RootFzb1 and RootMzb1 indicate axial force and torsion. On the tower base, TwrBsFxt and TwrBsMyt indicate longitudinal forces and moments; TwrBsFyt and TwrBsMxt indicate lateral forces and moments; TwrBsFzt and TwrBsMzt indicate axial force and torsion.

The relation between the structural damping ratios of critical modes shown in Figure-7 and Figure-8, and damage equivalent loads are indicated in Table 2.

Tower Load	Mode	Baseline Load ($\zeta = 1\%$)	5%	10%	20%	30%	Blade Load	Mode	Baseline Load ($\zeta = 1\%$)	5%	10%	20%	30%
TwrBsFxt (kN)	Tower 1st F-A	183.33	-3.75	-6.55	-9.83	-11.88	RootFxb1 (kN)	Tower 1st F-A	190.36	-0.05	-0.08	-0.10	-0.11
	Tower 2nd F-A		-7.10	-9.30	-11.36	-12.58		Tower 2nd F-A		-0.03	-0.08	-0.13	-0.15
	Tower 1st S-S		-0.04	-0.05	-0.06	-0.07		Tower 1st S-S		0.00	-0.01	-0.02	-0.03
	Tower 2nd S-S		0.04	0.09	0.07	0.00		Tower 2nd S-S		0.00	-0.02	-0.02	-0.14
	Blade 1st FW		-2.77	-5.15	-8.16	-9.88		Blade 1st FW		-0.76	-1.59	-2.82	-3.81
	Blade 2nd FW		-4.87	-7.83	-10.34	-11.32		Blade 2nd FW		-0.87	-1.56	-2.33	-2.74
	Blade 1st EW		-0.78	-1.50	-2.63	-3.45		Blade 1st EW		-0.06	-0.09	-0.20	-0.32
TwrBsFyt (kN)	Tower 1st F-A	74.77	1.07	2.27	4.01	5.10	RootFyb1 (kN)	Tower 1st F-A	304.82	0.00	0.00	-0.01	-0.01
	Tower 2nd F-A		-0.57	-0.60	-0.56	-0.54		Tower 2nd F-A		-0.04	-0.06	-0.07	-0.08
	Tower 1st S-S		-23.85	-29.20	-32.41	-33.61		Tower 1st S-S		-0.01	-0.01	-0.02	-0.02
	Tower 2nd S-S		-10.49	-13.07	-15.20	-16.52		Tower 2nd S-S		-0.02	-0.03	-0.04	-0.05
	Blade 1st FW		-1.97	-3.61	-5.36	-5.91		Blade 1st FW		-0.14	-0.26	-0.42	-0.52
	Blade 2nd FW		-2.56	-4.22	-5.38	-5.37		Blade 2nd FW		-0.05	-0.08	-0.13	-0.16
	Blade 1st EW		-8.53	-12.08	-14.36	-14.85		Blade 1st EW		-0.63	-0.76	-0.83	-0.82
TwrBsFxt (kN)	Tower 1st F-A	49.52	0.00	0.01	-0.06	-0.09	RootFxb1 (kN)	Tower 1st F-A	332.67	0.01	0.01	0.00	0.00
	Tower 2nd F-A		-0.12	-0.33	-0.62	-0.84		Tower 2nd F-A		-0.08	-0.11	-0.14	-0.15
	Tower 1st S-S		-0.06	-0.12	-0.26	-0.39		Tower 1st S-S		0.01	0.01	0.02	0.01
	Tower 2nd S-S		-0.01	0.01	0.01	0.28		Tower 2nd S-S		0.01	0.01	0.00	0.01
	Blade 1st FW		-2.22	-4.40	-7.18	-8.83		Blade 1st FW		-0.05	-0.12	-0.21	-0.26
	Blade 2nd FW		-0.80	-1.49	-2.48	-3.18		Blade 2nd FW		-0.05	-0.08	-0.12	-0.15
	Blade 1st EW		-10.98	-13.34	-14.45	-14.50		Blade 1st EW		-0.17	-0.21	-0.23	-0.24
TwrBsMxt (kN.m)	Tower 1st F-A	5026.92	1.66	3.44	5.93	7.44	RootMxb1 (kN.m)	Tower 1st F-A	6424.65	0.00	-0.01	-0.01	-0.02
	Tower 2nd F-A		-0.10	-0.13	-0.11	-0.11		Tower 2nd F-A		-0.01	-0.03	-0.06	-0.07
	Tower 1st S-S		-37.89	-48.03	-54.52	-56.99		Tower 1st S-S		-0.01	-0.02	-0.04	-0.06
	Tower 2nd S-S		-2.40	-3.01	-3.50	-3.97		Tower 2nd S-S		-0.02	-0.03	-0.05	-0.06
	Blade 1st FW		-0.41	-0.71	-1.08	-1.23		Blade 1st FW		-0.28	-0.53	-0.89	-1.10
	Blade 2nd FW		-0.57	-0.93	-1.23	-1.22		Blade 2nd FW		-0.04	-0.09	-0.16	-0.23
	Blade 1st EW		-2.28	-3.50	-4.66	-5.26		Blade 1st EW		-1.76	-2.11	-2.27	-2.25
TwrBsMyt (kN.m)	Tower 1st F-A	12477.63	-5.75	-10.07	-14.92	-17.68	RootMyb1 (kN.m)	Tower 1st F-A	6675.36	-0.05	-0.07	-0.13	-0.16
	Tower 2nd F-A		-1.55	-2.07	-2.58	-2.89		Tower 2nd F-A		-0.04	-0.07	-0.10	-0.12
	Tower 1st S-S		-0.06	-0.05	-0.07	-0.09		Tower 1st S-S		-0.02	-0.04	-0.03	-0.05
	Tower 2nd S-S		0.00	0.02	0.01	-0.08		Tower 2nd S-S		-0.01	-0.02	-0.01	-0.12
	Blade 1st FW		-1.13	-2.21	-3.86	-5.04		Blade 1st FW		-0.97	-1.92	-3.36	-4.29
	Blade 2nd FW		-1.08	-1.77	-2.37	-2.61		Blade 2nd FW		-0.54	-0.89	-1.24	-1.44
	Blade 1st EW		-0.18	-0.34	-0.59	-0.76		Blade 1st EW		-0.02	-0.06	-0.18	-0.28
TwrBsMxt (kN.m)	Tower 1st F-A	2691.89	0.00	-0.01	-0.02	-0.01	RootMxb1 (kN.m)	Tower 1st F-A	127.52	0.24	-0.07	0.07	0.44
	Tower 2nd F-A		-0.11	-0.22	-0.36	-0.41		Tower 2nd F-A		0.42	0.19	0.00	0.04
	Tower 1st S-S		-0.01	-0.01	0.01	0.02		Tower 1st S-S		0.24	0.12	0.27	0.46
	Tower 2nd S-S		0.01	-0.01	-0.02	0.10		Tower 2nd S-S		0.44	0.65	-0.20	-0.21
	Blade 1st FW		-3.22	-6.28	-10.31	-12.65		Blade 1st FW		-0.26	-1.00	-1.83	-2.12
	Blade 2nd FW		-2.70	-4.52	-6.38	-7.26		Blade 2nd FW		0.41	-0.09	-0.05	-0.29
	Blade 1st EW		-0.54	-0.82	-1.21	-1.55		Blade 1st EW		-2.00	-1.92	-2.55	-2.46

Table 2: Lifetime damage equivalent loads for different damping ratios

5 It is seen briefly in Table 2 that the tower's lateral loads are more influenced by added damping ratios, and 33.61% lateral force and 56.99% lateral moment damping is obtained with a 30% damping ratio on the 1st Lateral mode. Besides, 11.88% and 17.68% decrease occurred in the longitudinal force and moments, with the ratio of 30% damping ratio on the tower's 1st longitudinal mode.

10

Modeling of Viscoelastic Connection

The finite element model of the NREL 5 MW wind turbine is created to evaluate the efficacy of viscoelastic links in increasing the structural damping ratio. This model created in the Nastran platform is shown in Figure-10. The stiffness and mass features of the model are

15

obtained from NREL's database. In the model, the tower is modeled with QUAD elements, the blades with BEAM elements, the engine room, and the gear hub with point mass elements. The connections of the blades to the gear hub and the tower's engine room are modeled as rigid. The tower is connected rigidly to the ground in the same way.

5

Damper elements are used for modeling the damping ratio of aerodynamic forces resulting from turbulence in the finite element model. A total damping ratio of 4% in the 1st longitudinal bending mode of the tower for 12 m/s average wind speed is approved in the literature [21,22]. Therefore, a damper element (CBUSH) to reach this value in the longitudinal axis is defined.

10

The reason of selecting 12 m/s is because it is the speed at which the NREL 5MW wind turbine and the other similar wind turbines generate the most power. On the assumption that the system is linear, it is estimated that the efficacy of viscoelastic links will not change at the other wind speeds, or change negligibly.

15

To verify the finite element model created, with the FAST aeroservoelastic model, modal analysis in the Nastran platform is conducted and the natural frequencies and mode shapes of the system are obtained. These mode shapes are shown in Figure-11. The comparison of the natural frequencies of finite element models with the FAST model is shown in Figure-3. According to the results given in Table-3, it can be deduced that the dynamic characteristics of the finite element model and the FAST model is compatible.

20

Mode	FAST [3] [Hz]	Finite Element Model [Hz]
Tower 1st lateral	0.312	0.302
Tower 1st longitudinal	0.324	0.304
Blade 1st asymmetrical longitudinal (yaw)	0.666	0.624
Blade 1st asymmetrical longitudinal (pitch)	0.668	0.657
Blade 1st collective longitudinal	0.699	0.686

Blade 1st asymmetrical lateral (pitch)	1.079	1.036
Blade 1st asymmetrical lateral (yaw)	1.090	1.053
Blade 2nd asymmetrical longitudinal (yaw)	1.934	1.848
Blade 2nd asymmetrical longitudinal (pitch)	1.922	1.704
Blade 2nd collective lateral	2.021	1.952
Tower 2nd longitudinal	2.900	2.942
Tower 2nd lateral	2.936	2.797

Table 3: Natural frequency comparison of FAST and finite element model

For the efficacy of viscoelastic links, the frequency response analysis method in the Nastran platform is preferred. In this method, firstly frequency response analysis is implemented on the base (no-viscoelastic-connector-added) finite element model, and then frequency response functions are extracted from the defined points. QBlade [23] program is used for modeling the aerodynamic force input to be used in the frequency response analysis. The outer geometry of the NREL 5 MW wind turbine blades is determined primarily for QBlade. Afterward, a turbulence model having an average speed of 12 m/s is created and a rotation speed of 12.1 rpm is given to the wind turbine blades. The reason for selecting the defined wind and blade rotation speed is that the wind turbine studied can generate the 5 MW force under these conditions, which is its maximum capacity. An exemplary QBlade analysis image is given in Figure-12.

Tangential and normal aerodynamic forces on the blade are found in these conditions. These obtained forces are shown in Figure-13 along the blade length.

To find out the forces on the tower, the formula given below are used:

$$F_{tower}(z) = \frac{1}{2} \rho_a C_{D,T} D(z) V_r^2(z)$$

In this formula, $C_{D,T}$ is drag coefficient, $D(z)$ is the outer diameter of the tower, z is height above ground, and ρ_a is air density. At last, the aerodynamic forces on the blades and tower obtained for an average wind speed of 12 m/s are scattered as points on the finite element model and these forces constitute the inputs of frequency response analysis.

5

Certain reference points on the tower are chosen to find out the damping ratios of critical modes for the base model and the viscoelastic-connector-added model from frequency response functions. These points are shown in Figure-14. These points are 572 (X-axis), 568 (Y-axis), 432 (X-axis), and 428 (Y-axis), and the frequency response functions on these points are used for the determination of the damping ratios in the later analyses.

10

Frequency response functions on selected reference points for the no-viscoelastic-connector-added base model are shown in Figure-15. 4 critical modes are numbered as seen in these frequency response functions. Definitions of these modes are given in Table 4.

15

Mode no.	Definition
1	Tower 1st longitudinal
	Tower 1st lateral
2	Blade 1st collective longitudinal
3	Blade 2nd collective longitudinal
4	Tower 2nd lateral

Table 4: Selected Critical Modes and Definitions

In this study, viscoelastic links are modeled parametrically in the Nastran platform. Parameters are explained in Figure-2 and Table-1. The viscoelastic material is provided with a solid element, HEXA8, while the connections of viscoelastic material into the tower are provided with rigid elements, RBAR. Using aluminum or steel connections instead of rigid connections gives exactly the same results.

20

To position viscoelastic materials into the tower parametrically, a code is written in the Matlab platform, viscoelastic links are positioned into the tower according to the entered parameters and an input file is created for the Nastran platform. This input file created for the viscoelastic link is combined with the base model's input file and frequency response analysis is performed. The damping ratios of the modes specified in Table-4, from the frequency response functions of critical points are obtained and the efficacy of viscoelastic links is evaluated.

Viscoelastic links positioned inside the tower parametrically are shown in Figure-16.

Positions of the examined viscoelastic links are shown in Figure-17. The arrow in the figure represents the wind direction. Viscoelastic links can be connected in the bending type connection on the wind turbines where tower diameter is less than 2.0 meters. Furthermore, in the cases where the “h/t” (height/thickness) ratio is greater than 5.0, viscoelastic material has a bending type damping mechanism.

On the wind turbines where tower diameter is greater than 2.0 meters, on the other hand, they can be connected in both the shear and the compression-extension type connection.

In the study, firstly the position of the viscoelastic links in the tower according to the X- and Y-axis, namely the effect of X_1 and Y_1 parameters is observed. Viscoelastic link scheme where $w = 0.5\text{m}$, $t = 0.5\text{m}$, $h = 4.38\text{m}$, $x = 0.05\text{m}$ is created accordingly. In this state, 20 viscoelastic links are positioned from the bottom to the top of the tower. The tower's acceleration responses in selected points and directions are examined for different X_1 and Y_1 parameters.

Acceleration values of different modes and points for different viscoelastic links' positions are specified in Figures 18, 19, 20, and 21. These acceleration values are the maximum accelerations at the frequencies of the modes specified in Table-4.

Considering Figures 18.a and 18.b, two types of viscoelastic connection schemes are proposed, because the 1st longitudinal and lateral mode of the tower is the most driven. Thus, it is aimed to minimize the vibrations coming from the 1st longitudinal and lateral mode. These two proposed positioning configurations are shown in Figure 22. In this way, while they are used for damping the vibrations on the longitudinal tower mode specified in Case A,

they are used for damping the vibrations caused by lateral tower mode specified in Case B. In Case B reason for viscoelastic materials are between the X- and Y-axis is because lateral vibrations interact with longitudinal vibrations.

- 5 The efficacy of viscoelastic links is evaluated separately for the two configurations shown in Figure 22. Firstly, the efficacy of the “l” parameter, which stands for the distance between two viscoelastic connection points and specified in Figure 2, on increasing damping ratio is evaluated. Hence, the efficacy of the “l” parameter on a viscoelastic link positioning is examined, where h, t, w, and x values are, respectively, 0.1m, 0.4m, 0.4m, and 0.05m.

10

Turning to Figure-23, the effect of increasing the “l” parameter is important for the two critical modes (tower 1st longitudinal and tower 1st lateral).

- Figure-24 shows the effect of the “t” parameter which is the thickness parameter on a viscoelastic link positioning, where l, w, h, and x values are, respectively, 5.0m, 0.4m, 0.1m, and 0.05m. In Figure-24, the efficacy of viscoelastic links increases to a certain level as t increases, and then this efficacy decreases with the change of dynamic characteristics because of the increasing mass of the wind turbine.

- 20 Figure-25 shows the effect of the “h” parameter which is the material height parameter on a viscoelastic link positioning, where w, t, x, and l values are, respectively, 0.4m, 0.4m, 0.05m, and 5.0m. In Figure-25, it is shown that the efficacy of viscoelastic links decreases as h increases. The reason for that the viscoelastic material’s length increases as h increases, and that it shows bending deformation instead of shear deformation. Viscoelastic materials perform better vibration damping in shear deformation. Therefore, bending of the material reduces performance.

- Figure-26 shows the effect of the “w” parameter which is the material width parameter on a viscoelastic link positioning, where t, x, l, and h values are, respectively, 0.4m, 0.05m, 5.0m, and 0.1m. In Figure-26, it is shown that material width increases the damping ratios at a certain level but then the damping ratios decrease.

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In the approach of the parametric viscoelastic link modeling, the results of which are indicated above, it is observed that a significant increase of structural damping ratio is

obtained for the wind turbine tower. The structural damping ratio of 0.094 and 0.064 is obtained with appropriate parameters for 1st longitudinal and lateral tower modes, respectively. These structural damping ratios are obtained with the parameters where $w = 0.4\text{m}$, $t = 0.4\text{m}$, $x = 0.05\text{m}$, $l = 5.0\text{m}$ and $h = 0.1\text{m}$, and more efficient results can be obtained with different positioning and parameters. For example, structural damping ratios of longitudinal and lateral tower modes can be increased by using case A and case B positioning together.

When damping ratios of 0.094 and 0.064 obtained with viscoelastic links for 1st longitudinal and lateral tower modes, damage equivalent load values are examined (Table-2), these correspond to a decrease of 6.2% and 9.5% in longitudinal force and moment, 25.0% and 41.0% in lateral force and moment on the tower base.

These ratios obtained are significant design improvement in terms of wind turbine design and these results have the potential of improvement with different viscoelastic link positionings.

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CLAIMS

1. A damping system developed for damping the wind turbine vibrations and increasing fatigue life of the structure, **characterized in that**; it comprises the following:
 - **At least one** viscoelastic link (1) that enables to convert the vibrations on the tower (5) into heat energy by positioning inside the wind turbine
 - **At least one** rigid connection (3) that enables to connect the viscoelastic link to the wind turbine tower.
2. Damping system including viscoelastic link according to Claim 1, **characterized in that**; the viscoelastic link (1) is connected in a shear type connection to damp by being exposed to shear stress.
3. Damping system including viscoelastic link according to Claim 1, **characterized in that**; the viscoelastic link (1) is connected in a extension-compression type connection to damp by being exposed to compression and extension stress in the wind turbines where the tower diameter is greater than 2.0 meters.
4. Damping system including viscoelastic link according to Claim 1, **characterized in that**; the viscoelastic link (1) connected in a bending type connection to damp vibrations by bending, where the tower diameter is smaller than 2.0 meters.
5. Damping system including viscoelastic link according to Claim 1, **characterized in that**; the viscoelastic link (1) is positioned on the windward side of the tower to reduce vibrations in the direction of the prevailing wind on the wind turbine.
6. Damping system including rigid connection (3) according to Claim 1, **characterized in that**; the rigid connection (3) is made of aluminum.
7. Damping system including rigid connection (3) according to Claim 1, **characterized in that**; the rigid connection (3) is made of steel.
8. Damping system including rigid connection (3) according to Claim 1 **characterized in that**; the rigid connection (3) is made of titanium.

9. Damping system including rigid connection (3) according to Claim 1, **characterized in that;** the rigid connection (3) made of carbon fiber.

5 10. A viscoelastic link (1) modeling method in the damping system developed for damping the wind turbine vibrations and increasing fatigue life of the structure according to Claim 1, **characterized in that;** it comprises the following steps:

- Creating finite element model of the wind turbine (NREL 5 MW) in the finite element analysis program,
- 10 • Using of damper elements for modeling the damping ratio of aerodynamic forces resulting from turbulence,
- Conducting modal analysis in the finite element analysis program and extracting the natural frequencies and mode shapes of the system to verify the created finite element model with the FAST aeroservoelastic model.

15 11. An efficacy control method of the viscoelastic links (1) in the damping system developed for damping the wind turbine vibrations and increasing fatigue life of the structure according to Claim 1, **characterized in that;** it comprises the following steps:

- 20 • Selecting frequency response analysis method in the finite element analysis program,
- Implementing frequency response analysis on the finite element model of the no-viscoelastic-connector-added base and extracting the frequency response points from the defined points,
- 25 • Establishing outer geometry of the wind turbine blades on the simulation software where the aerodynamic force input to be used in frequency response analysis is modeled,
- Creating a turbulence model having an average speed of 12 m/s and providing a rotation speed of 12.1 rpm to the wind turbine blades,
- 30 • Finding tangential and normal aerodynamic forces on the blade,
- Finding the aerodynamic forces on the tower by using the equation given below,

$$F_{tower}(z) = \frac{1}{2} \rho_a C_{D,F} D(z) V_r^2(z)$$

- Finding the aerodynamic forces on the blades and tower and scattering them as points on the finite element model to compose frequency response analysis input.

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12. A method of positioning viscoelastic links (1) into the tower in the damping system developed for damping the wind turbine vibrations and increasing fatigue life of the structure according to Claim 1, **characterized in that;** it comprises the following steps:

10

- Positioning the viscoelastic links according to the entered parameters in order to create an input file in the finite element analysis program,
- Performing a frequency response analysis by combining the created input file with the input file of the base model,
- Obtaining the damping ratios of the specified modes (Table-4) by the frequency response functions obtained from critical points and evaluating the efficacy of viscoelastic links.

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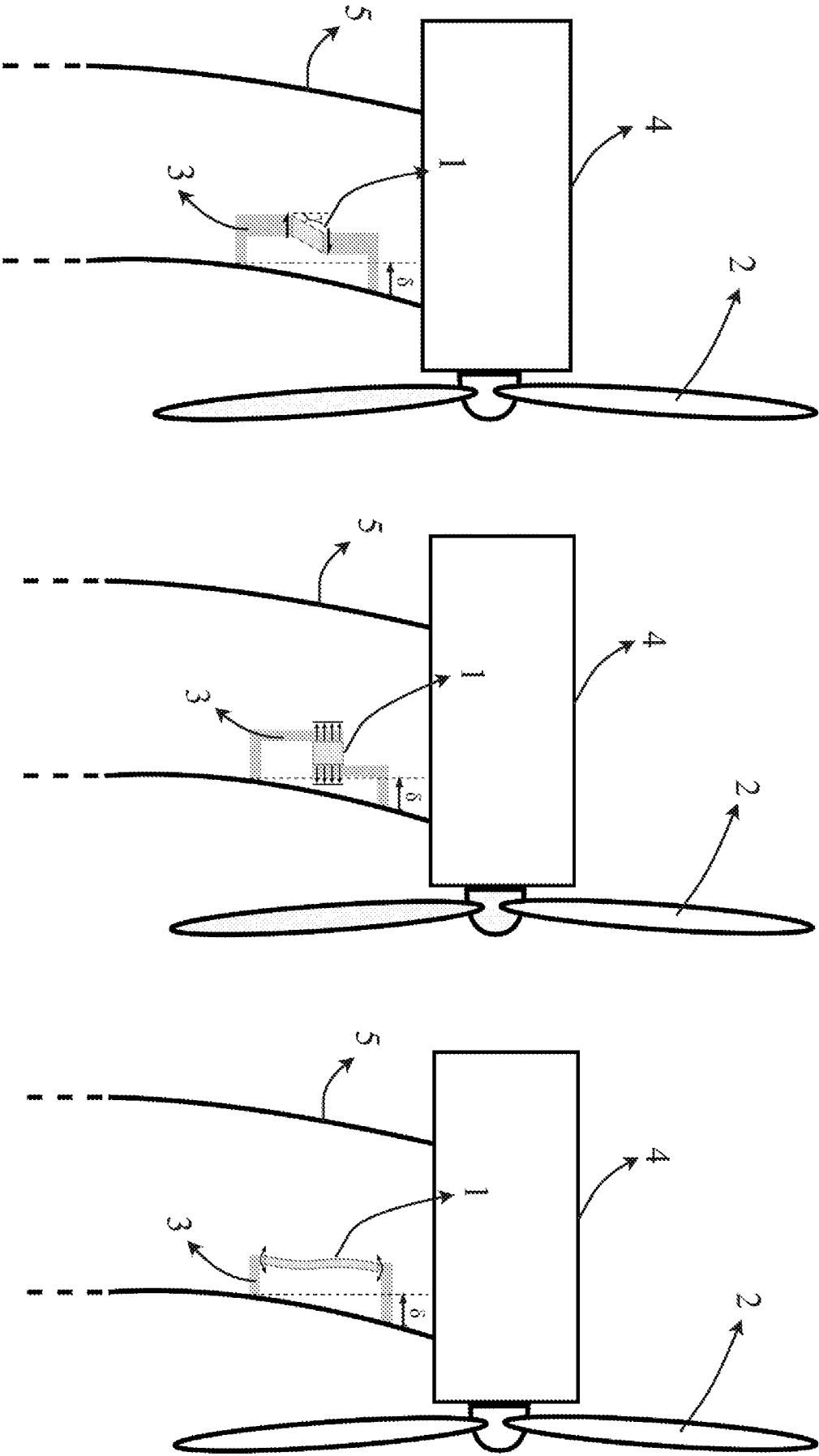


Figure-1

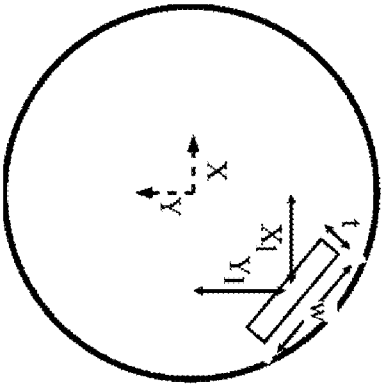
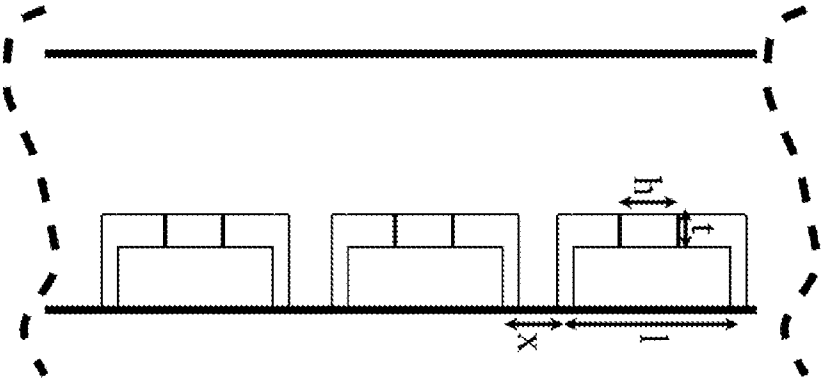


Figure-2

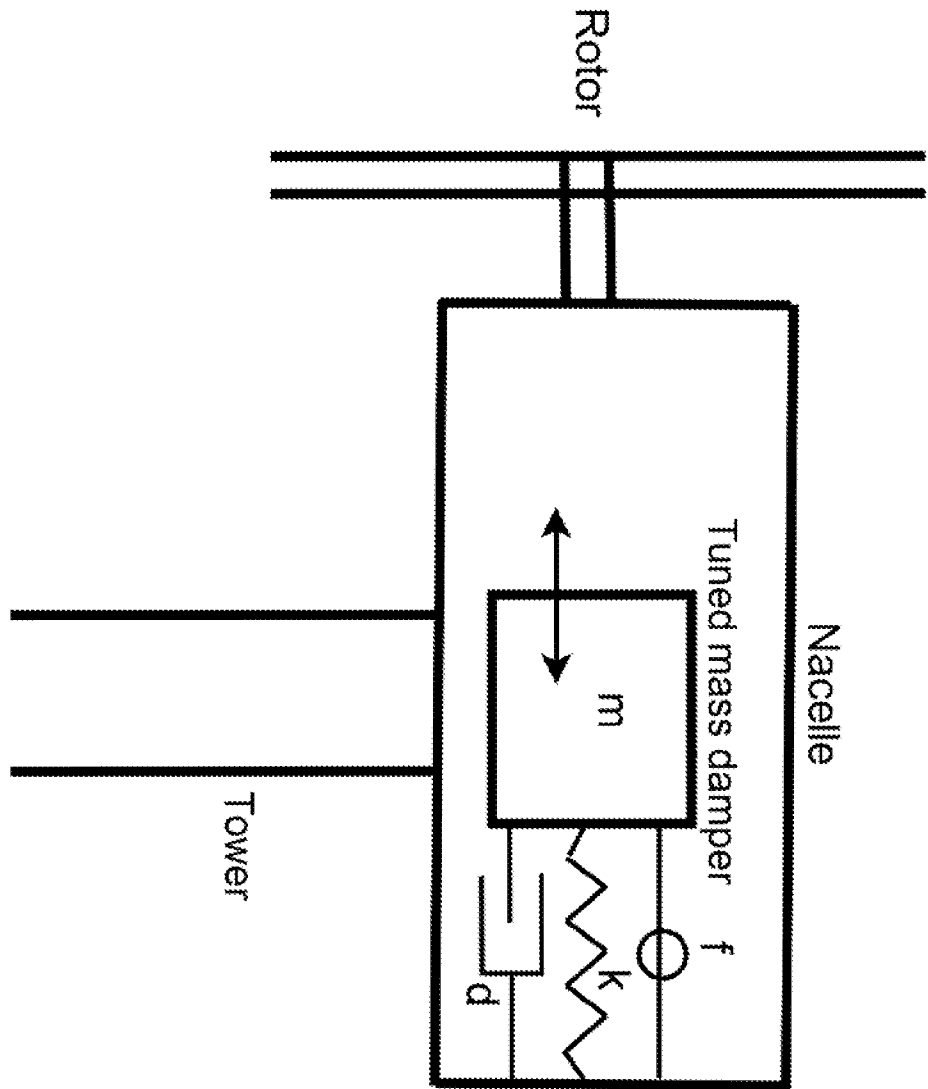


Figure-3

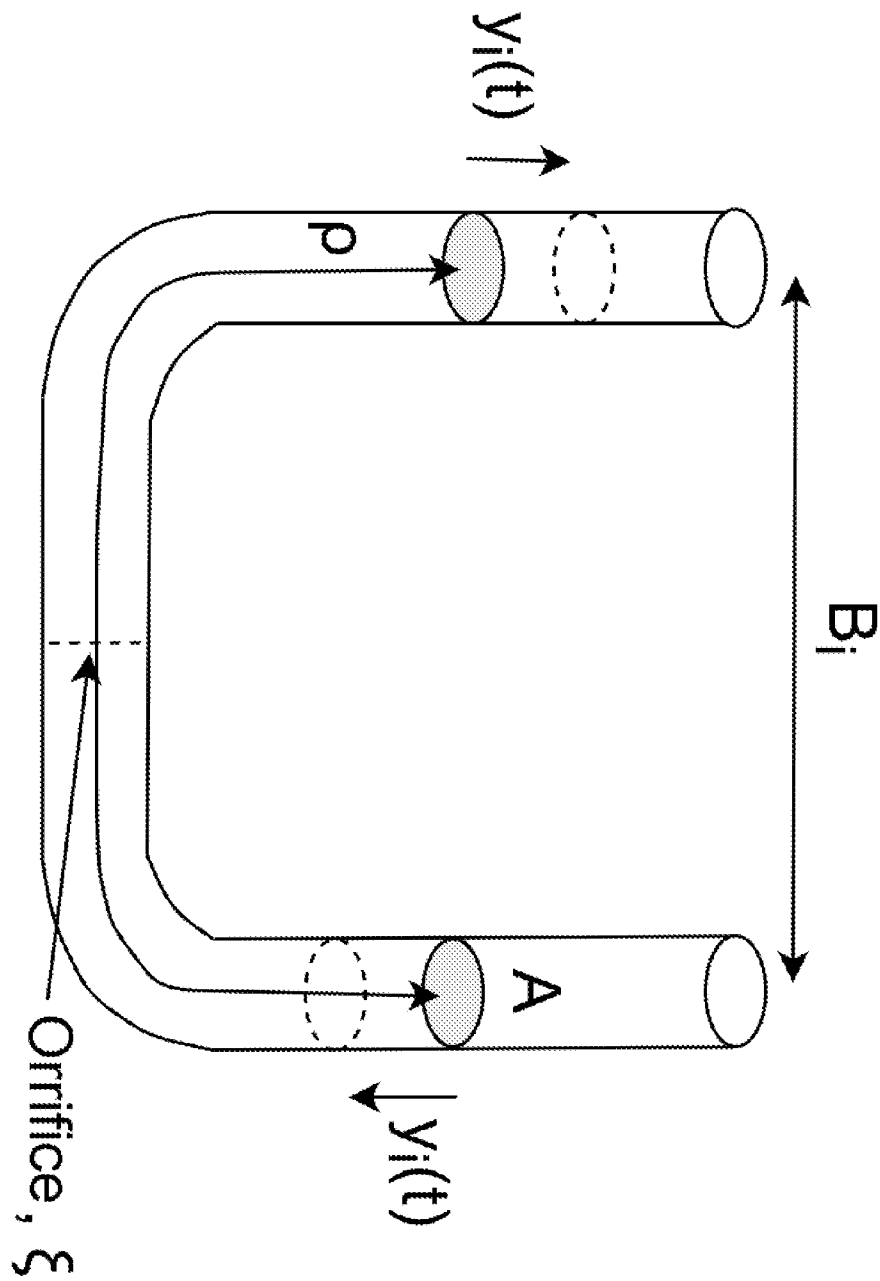
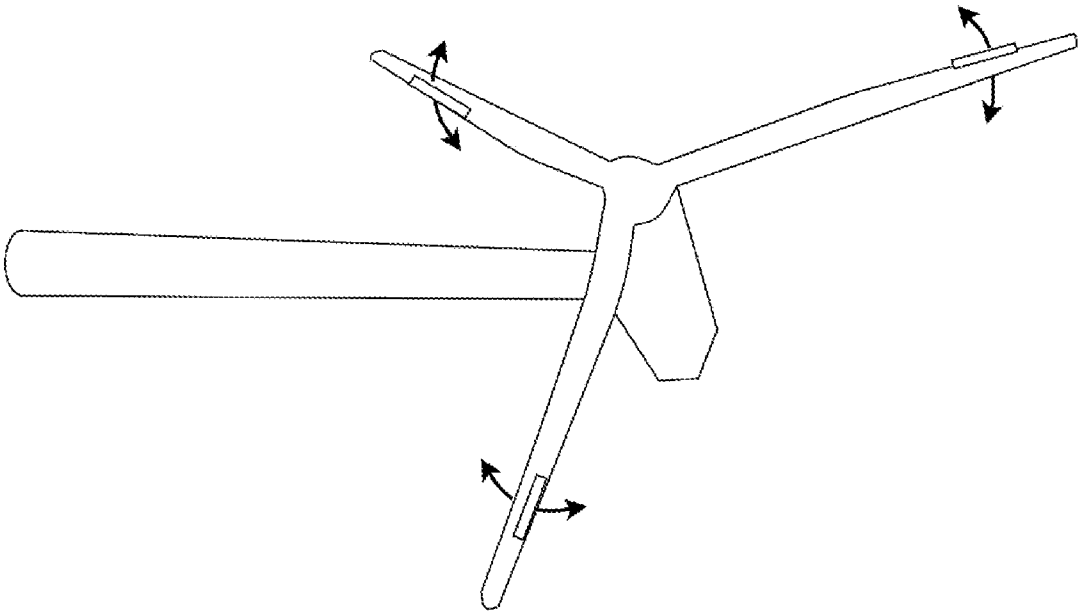


Figure-4

Figure-5



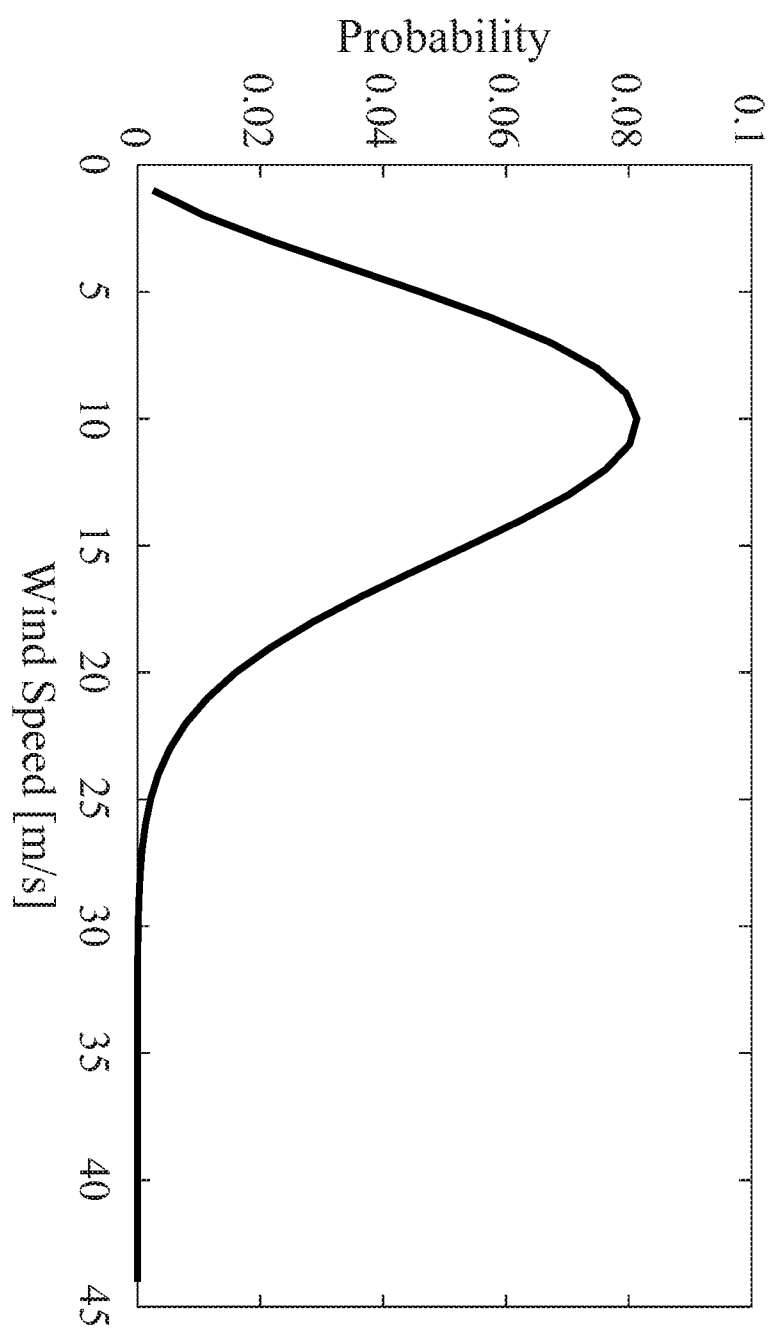


Figure-6

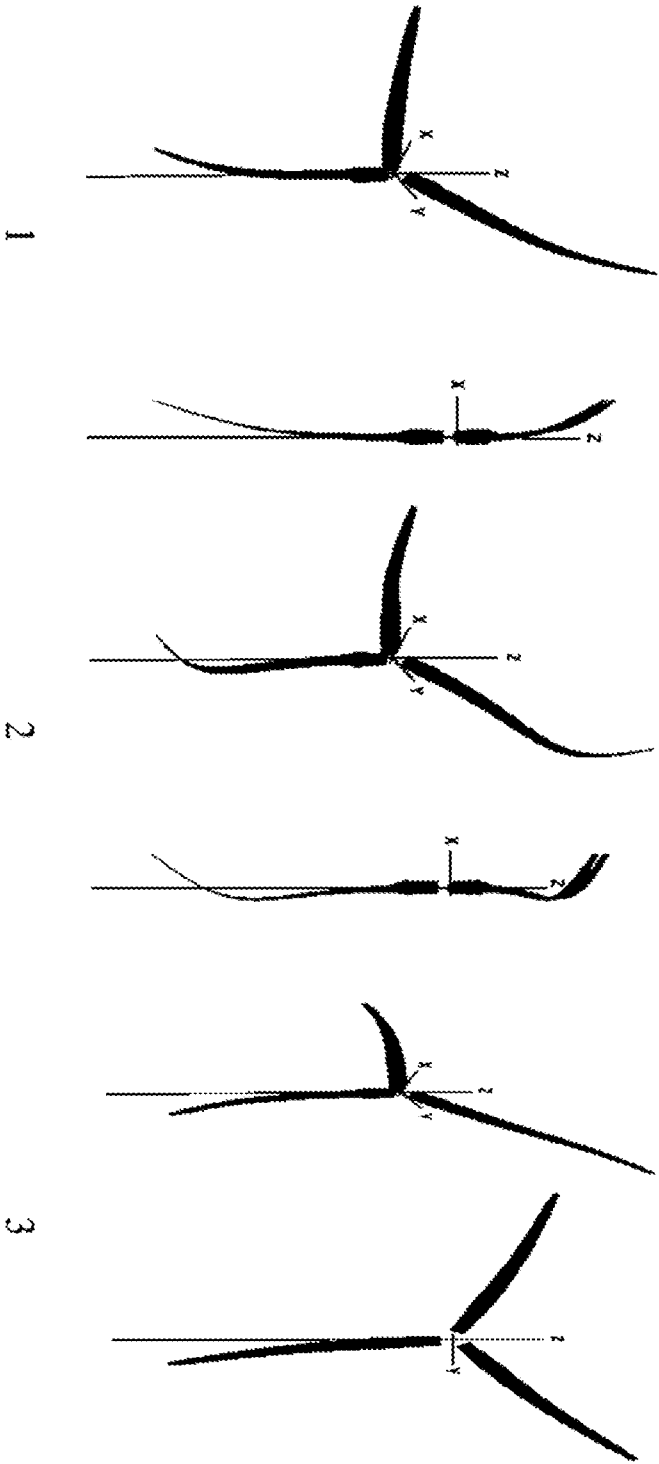


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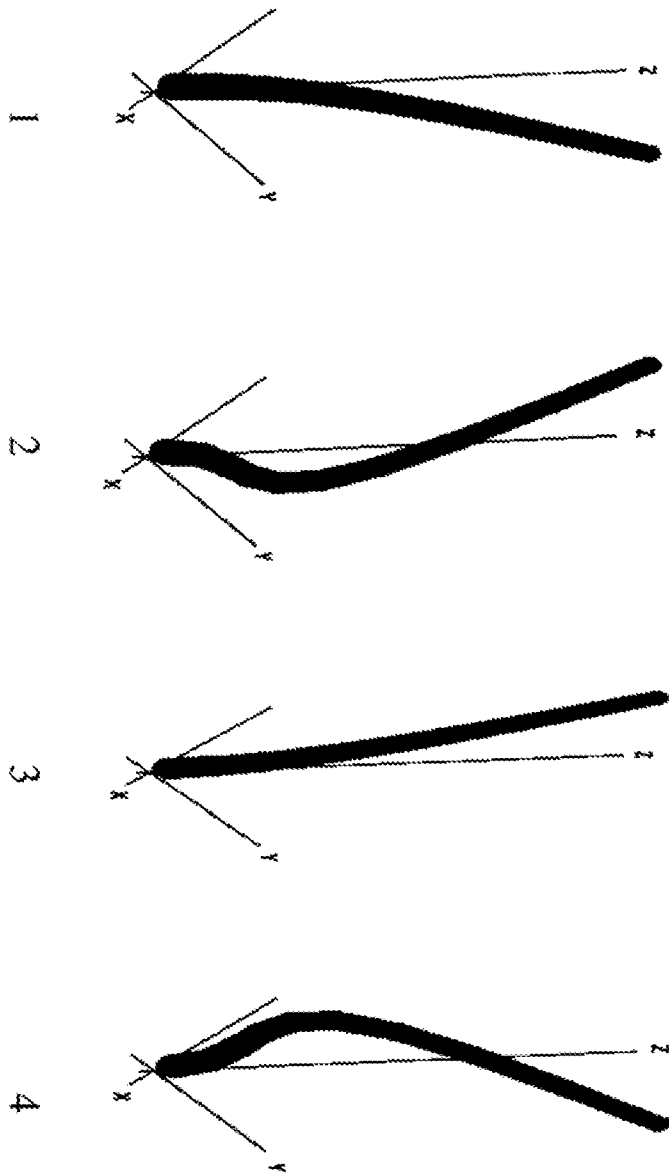


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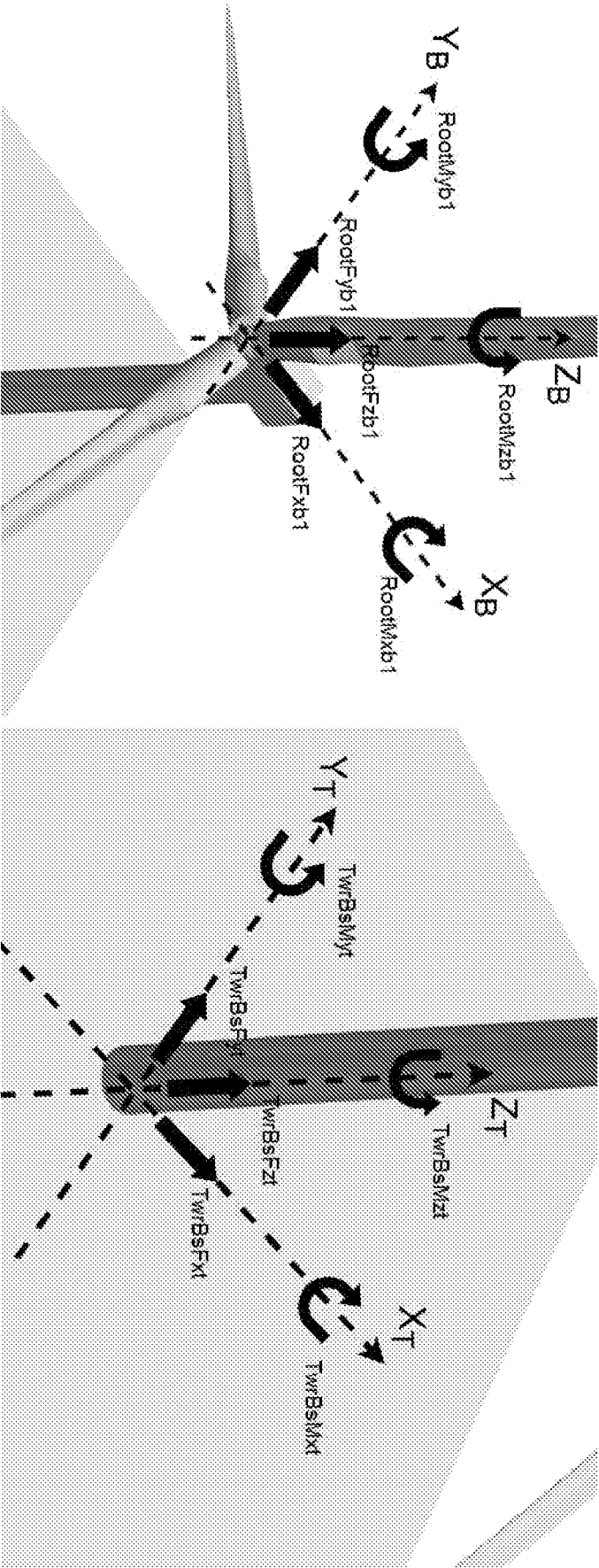


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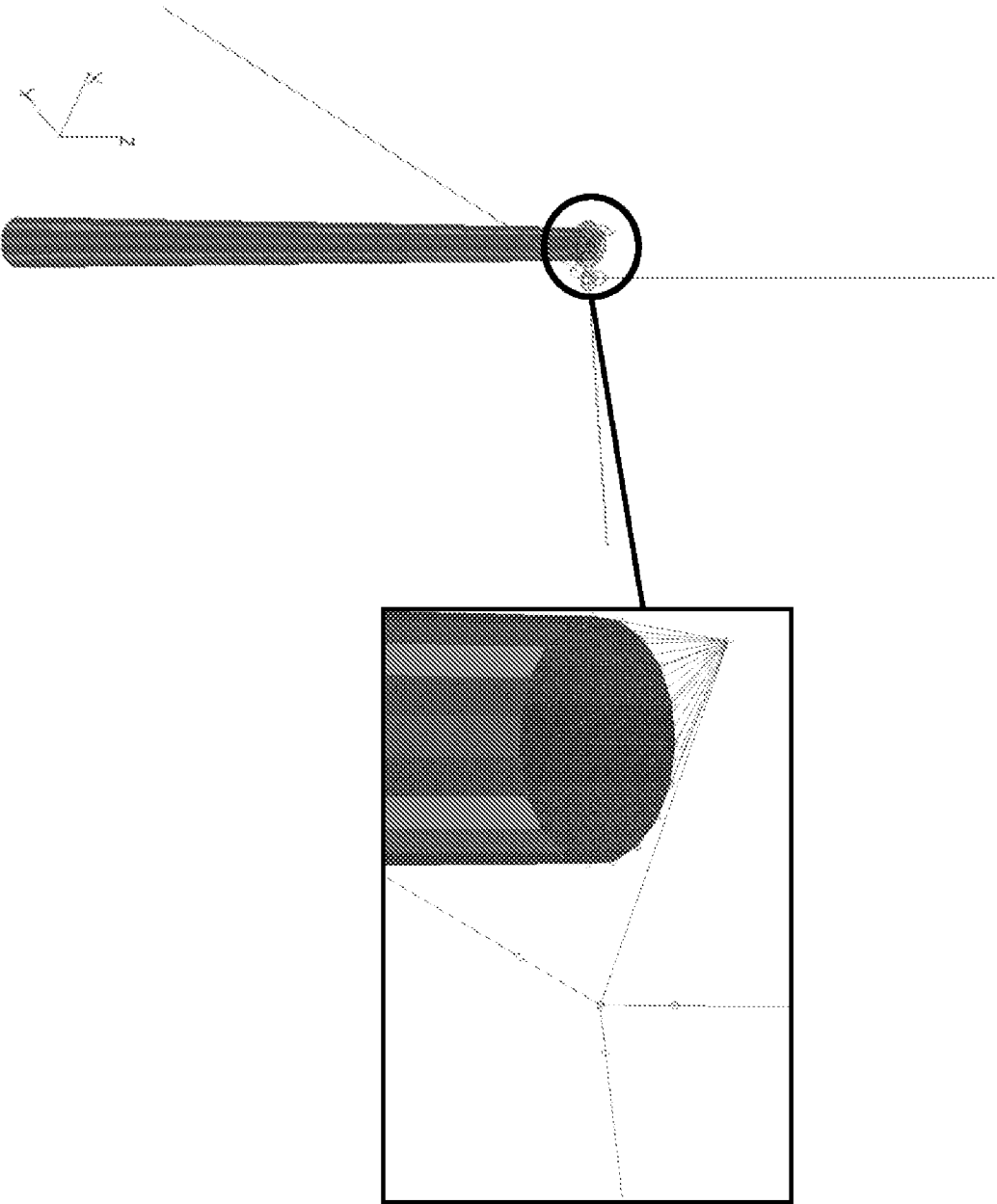


Figure-10

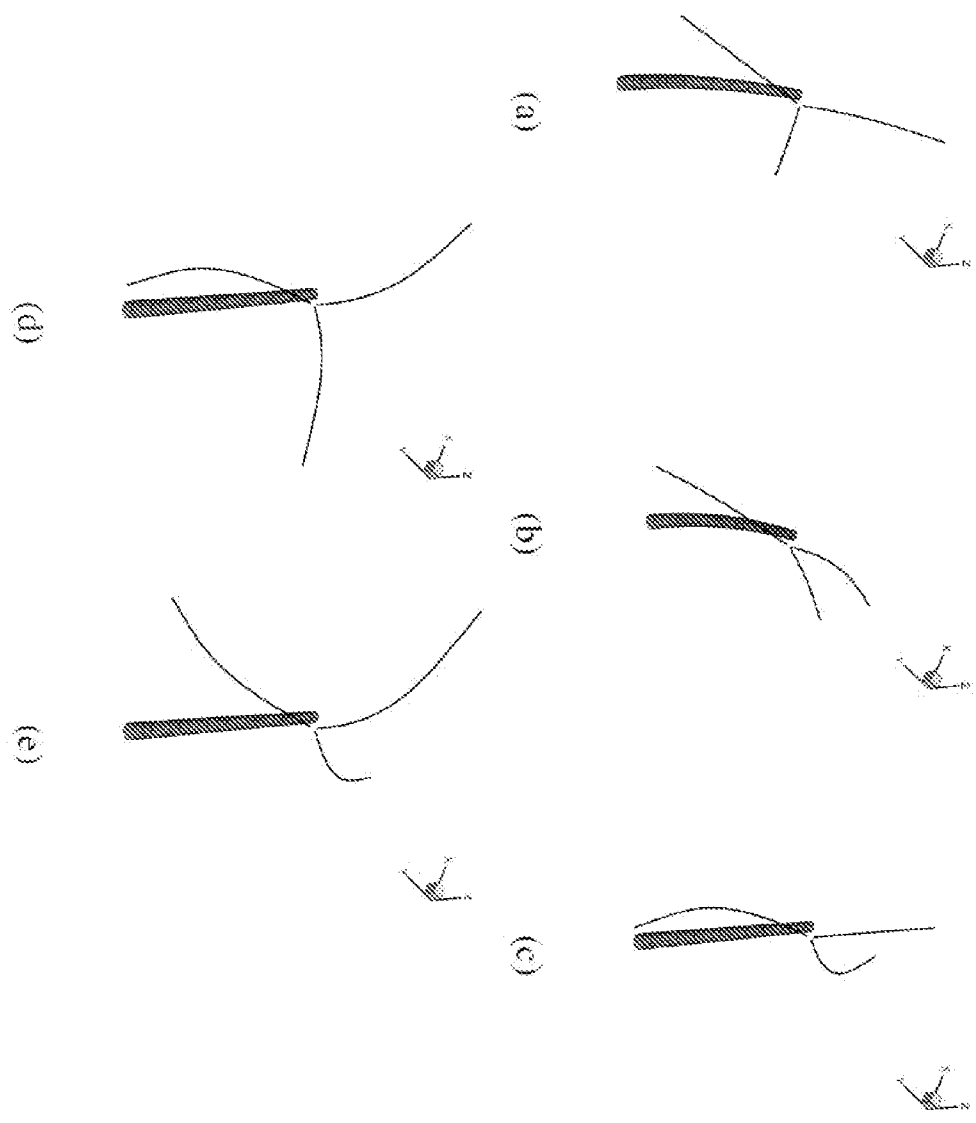


Figure-11

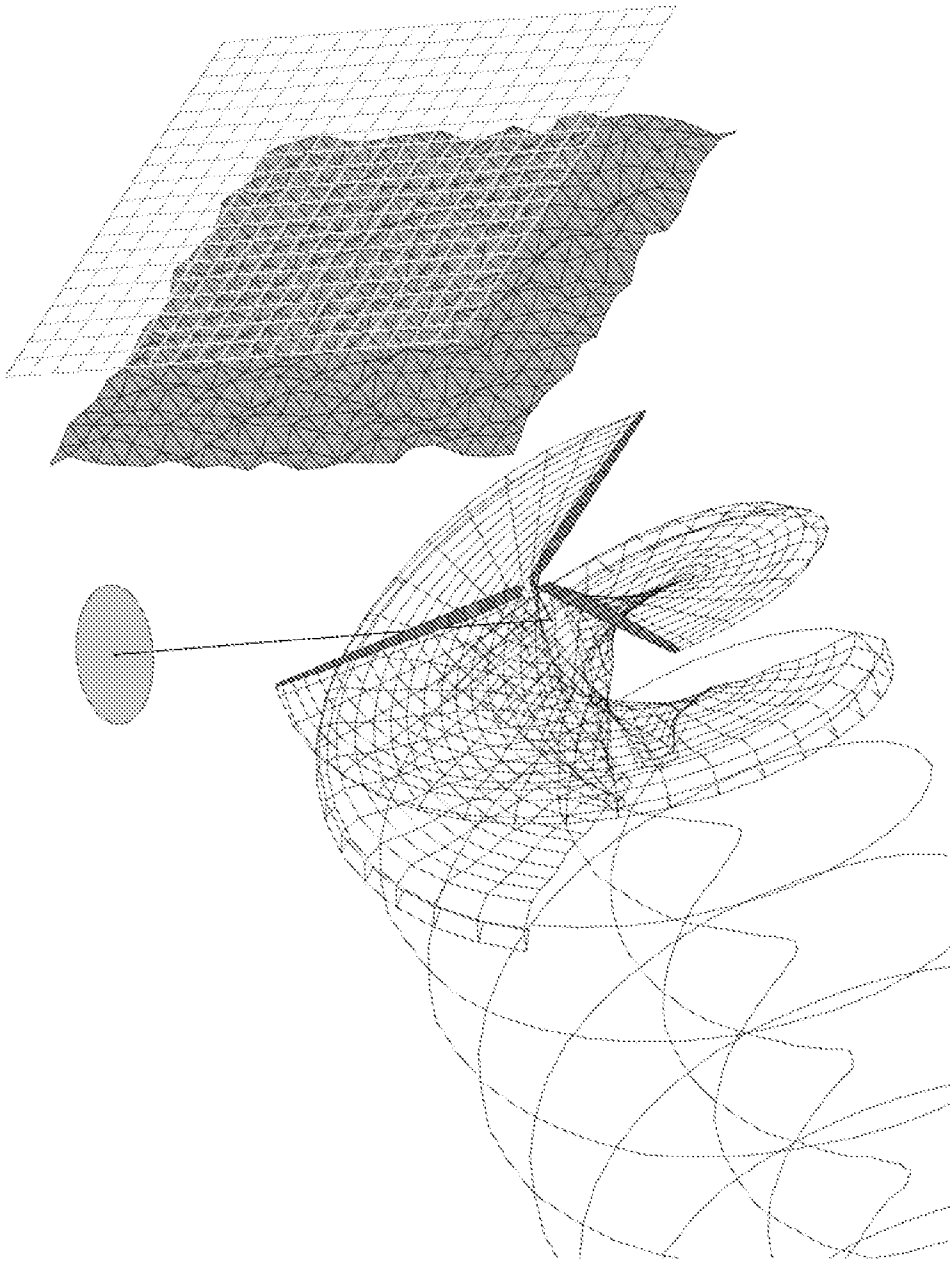


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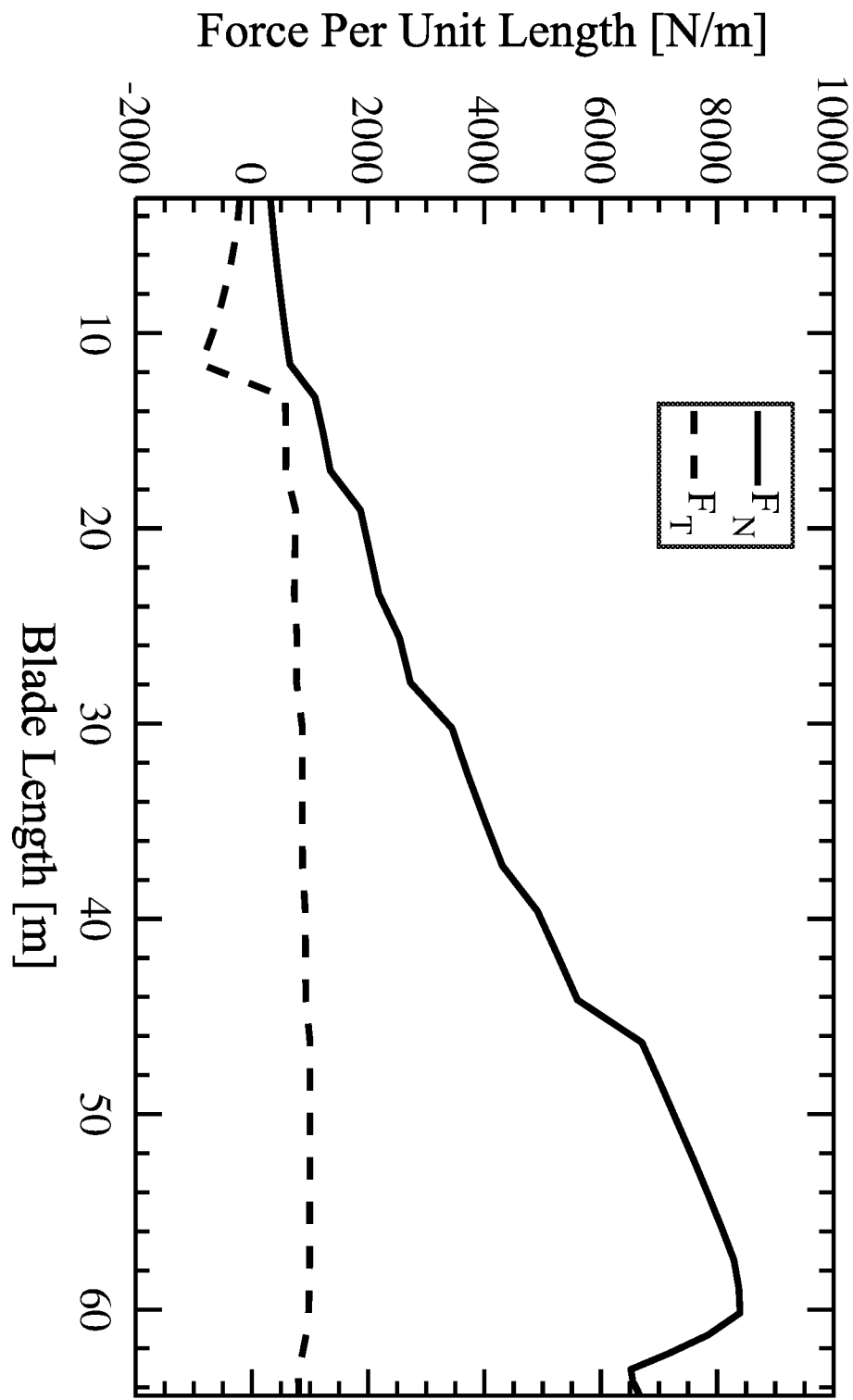
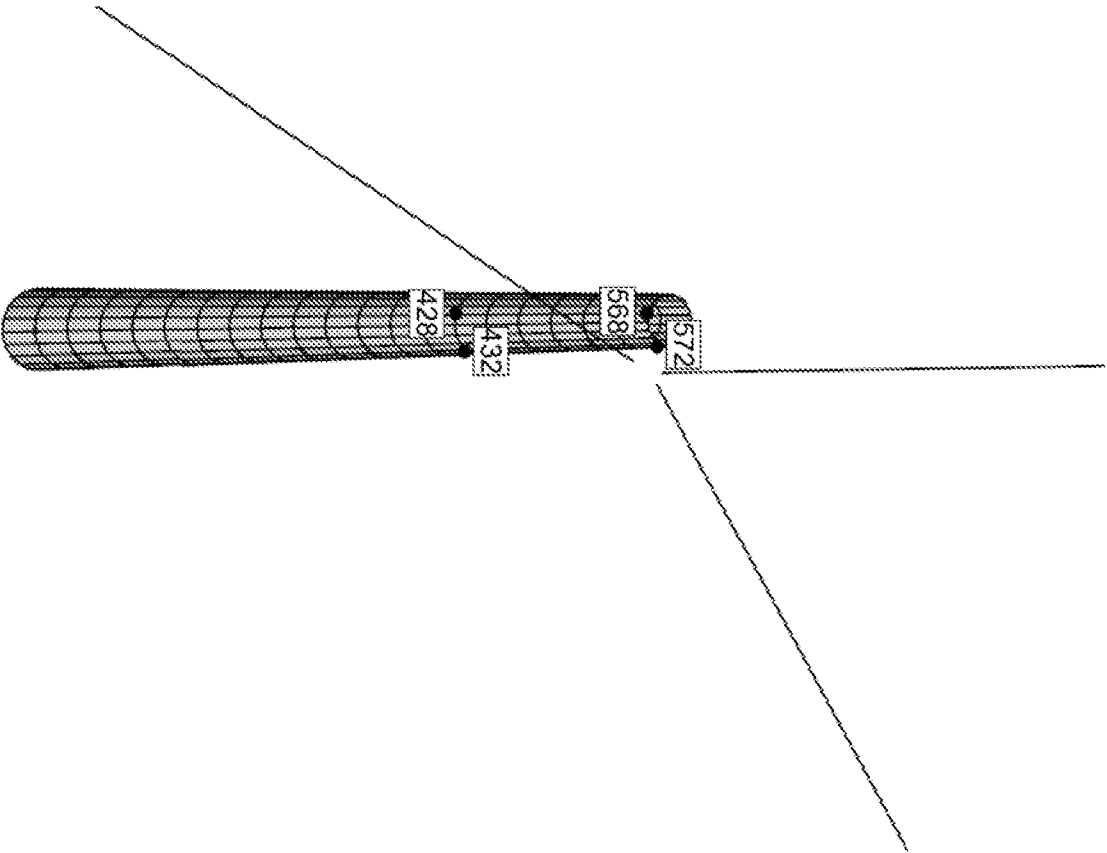


Figure-13

Figure-14



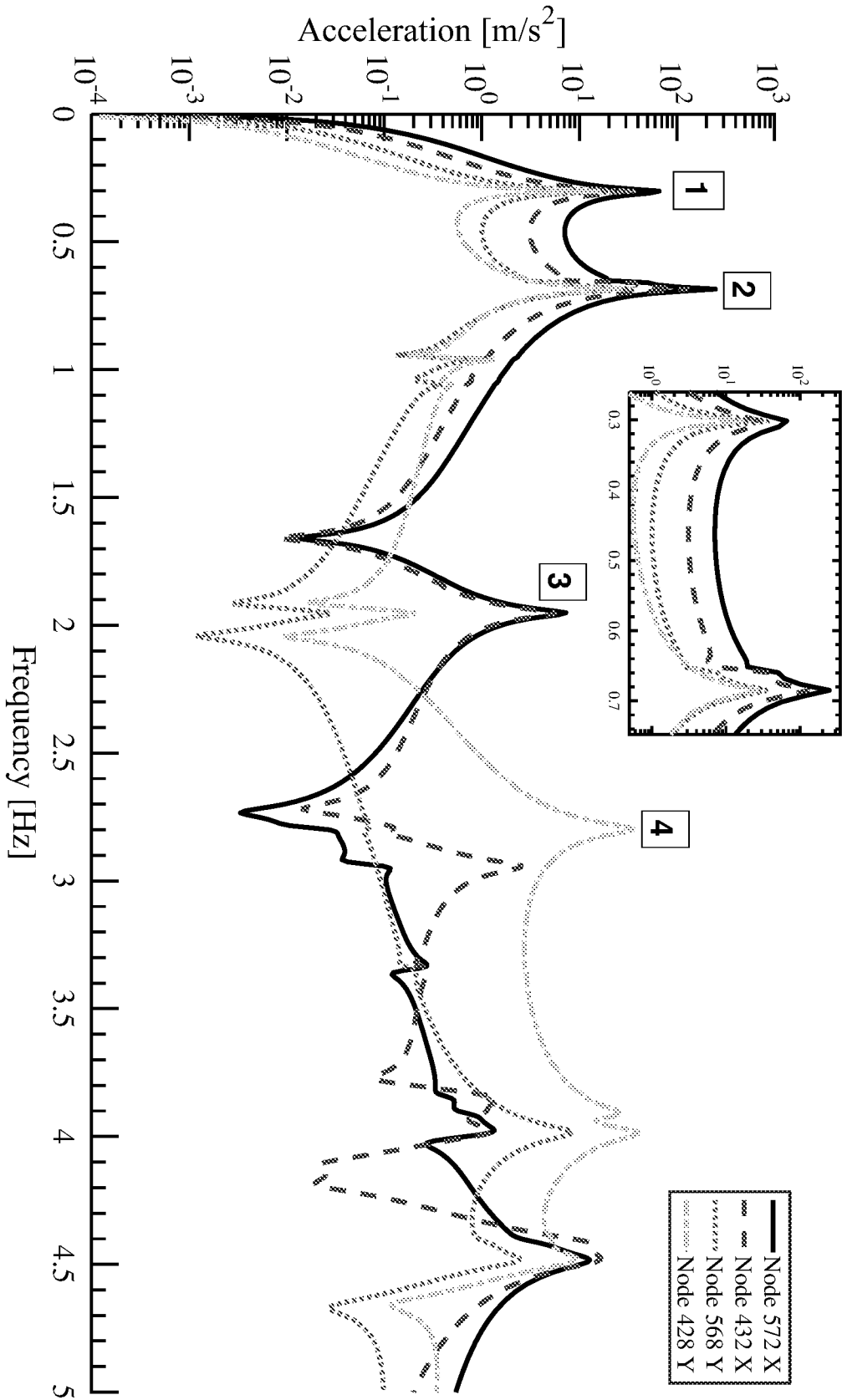


Figure-15

Figure-16

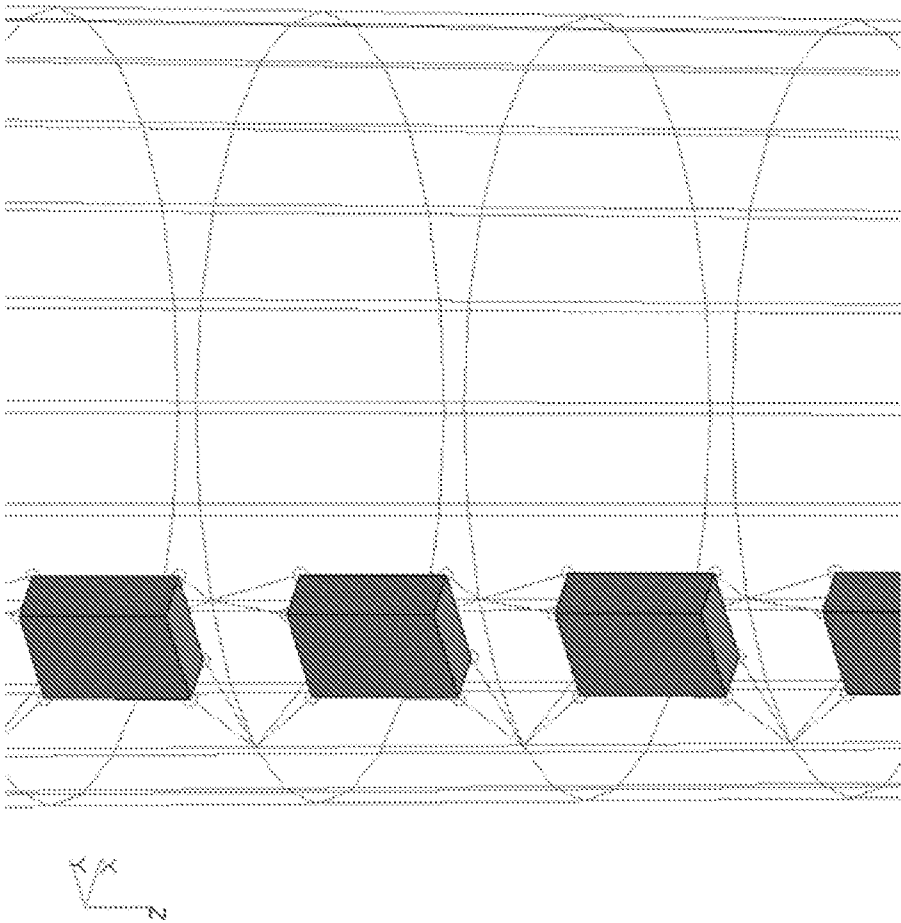
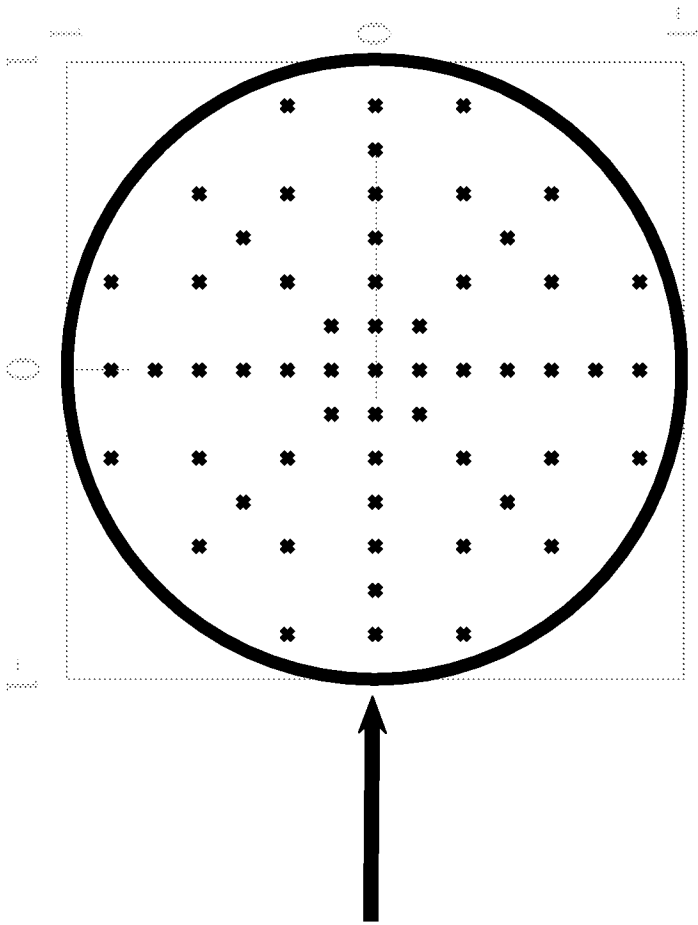
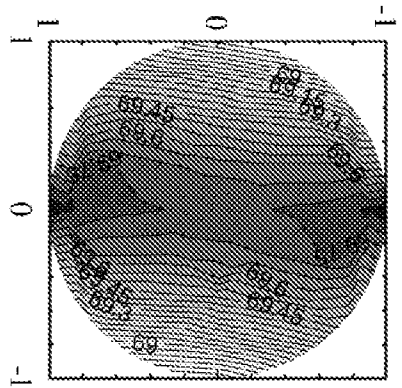


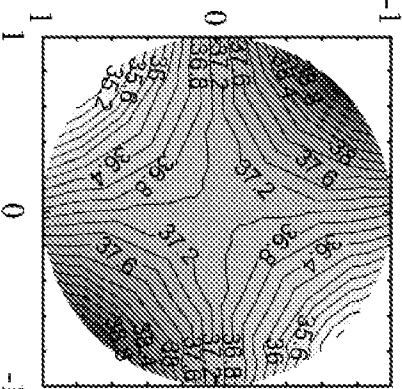
Figure-17



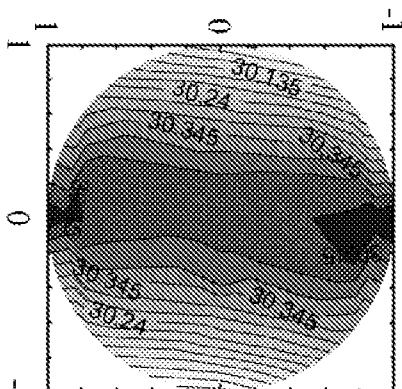
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(b) Node 568 Y



(c) Node 432 X



(d) Node 428 Y

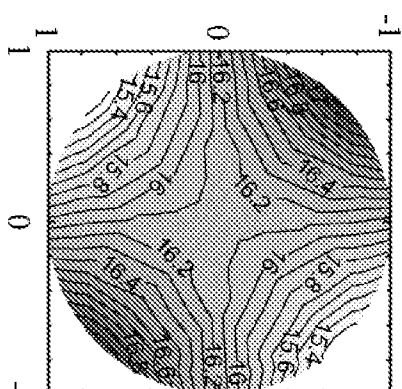


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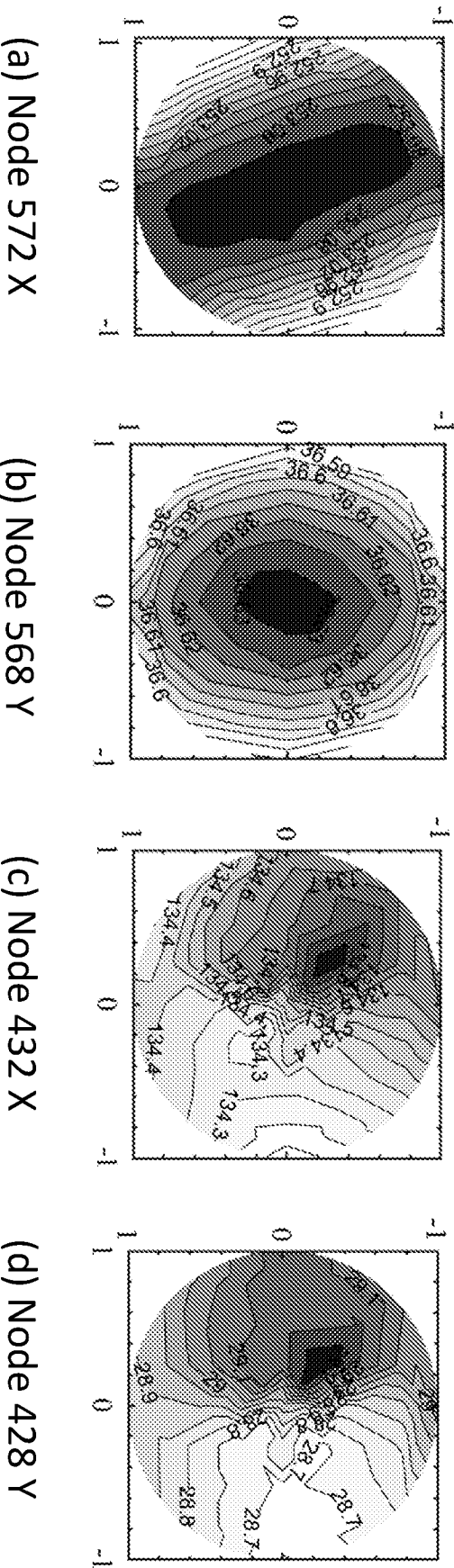


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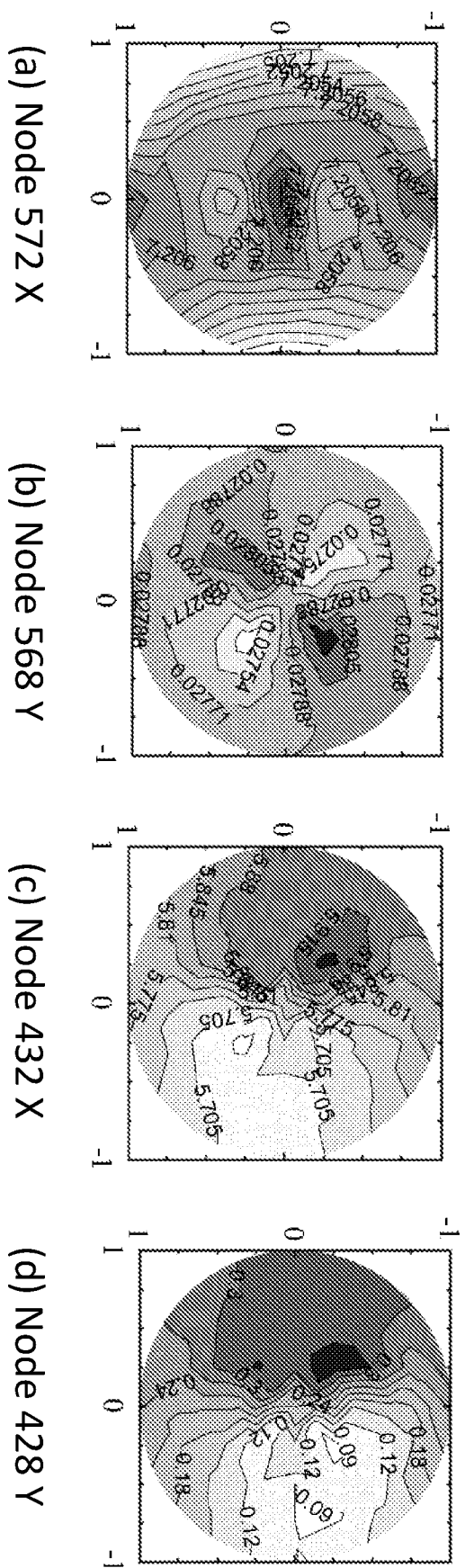


Figure-20

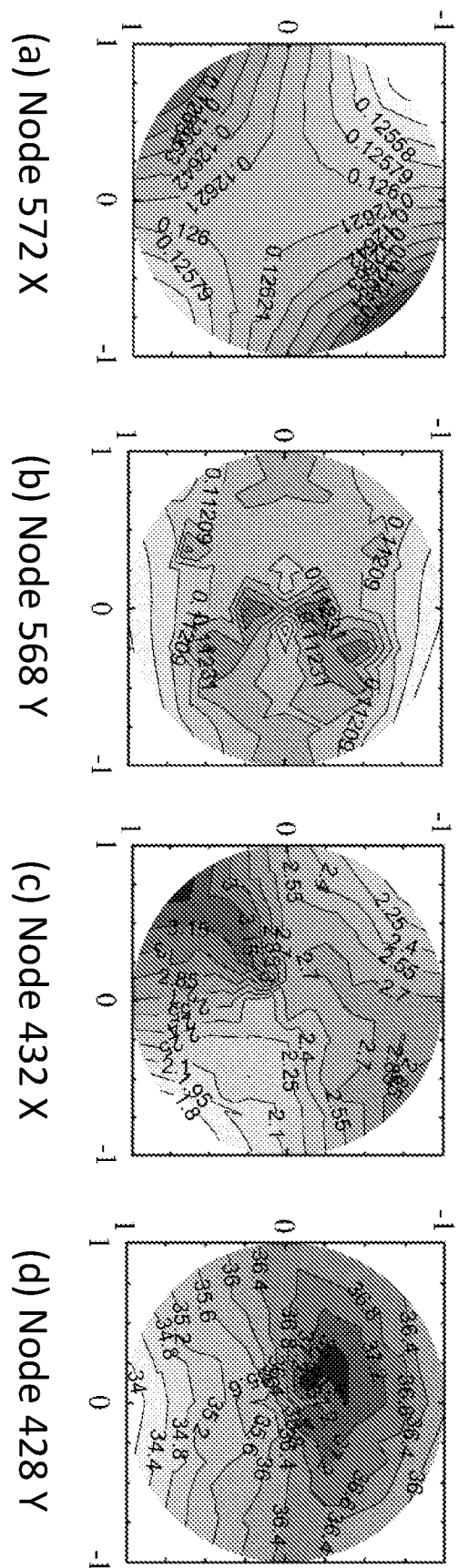
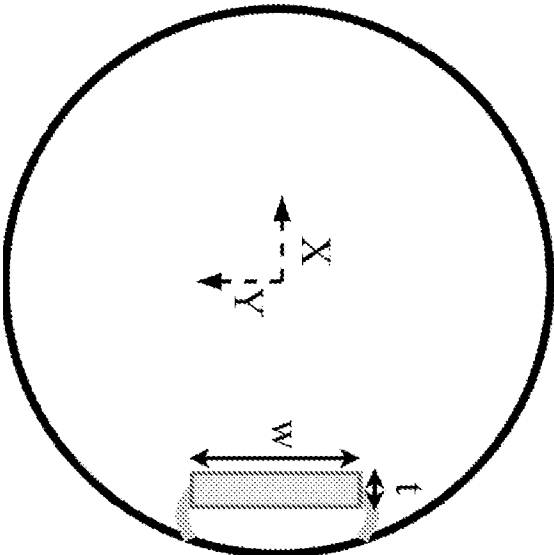


Figure-21

a) Case A



b) Case B

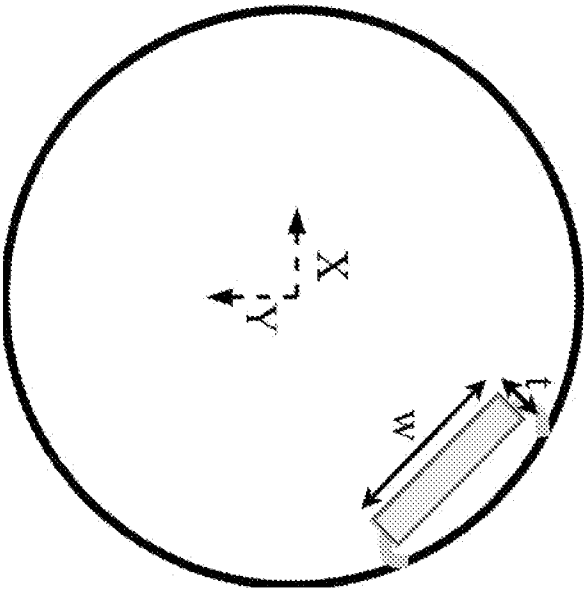


Figure-22

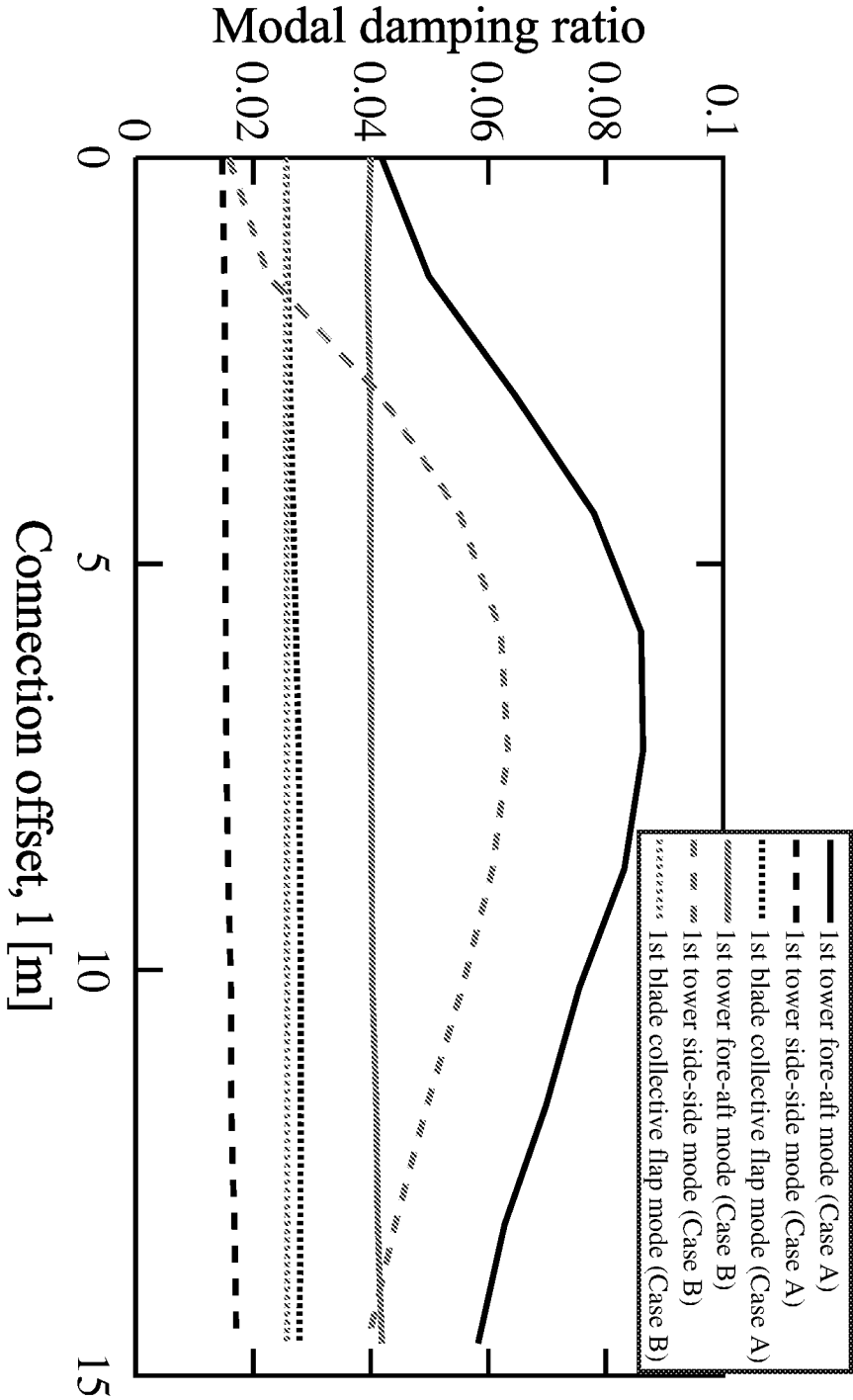


Figure-23

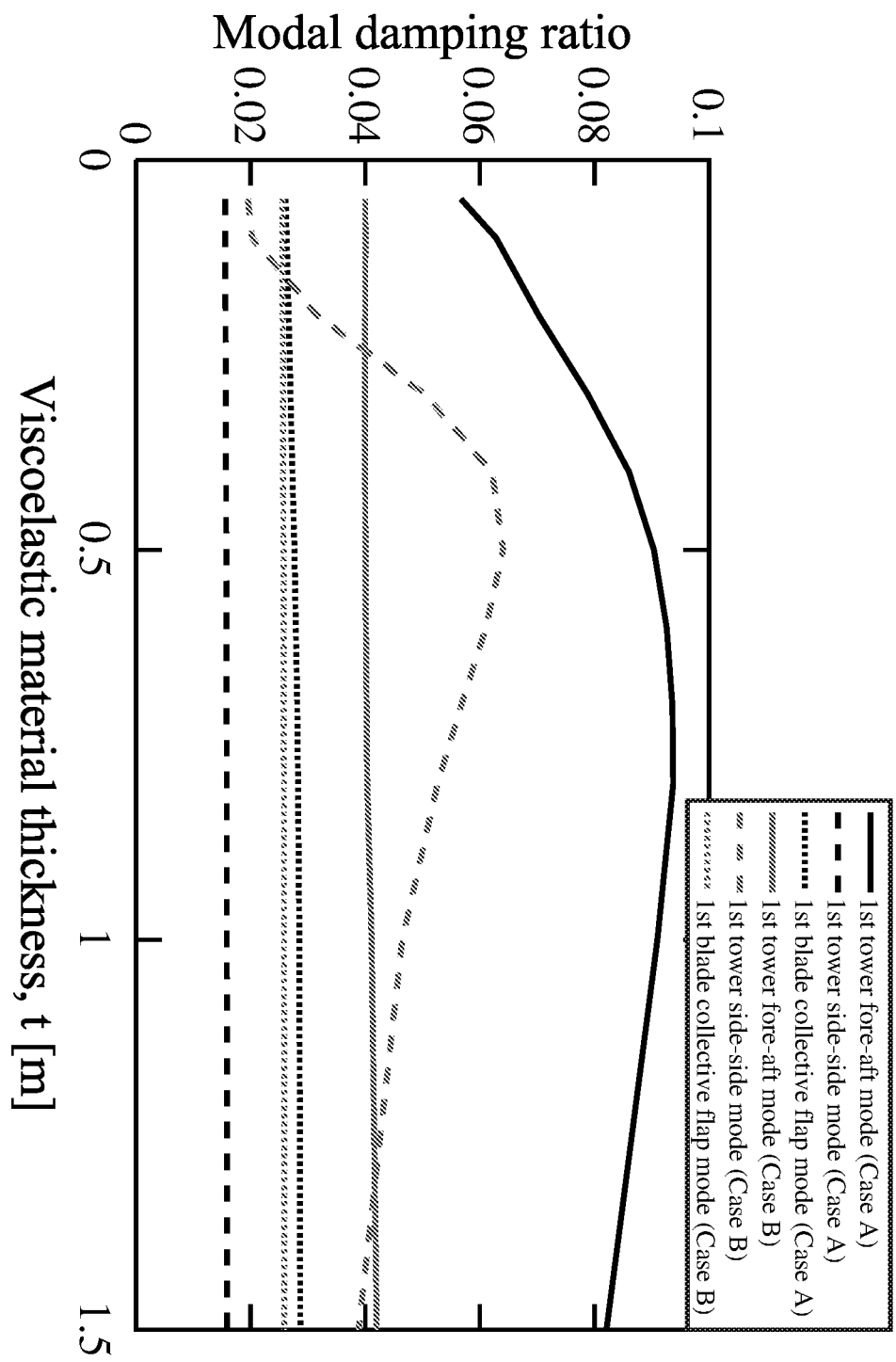


Figure-24

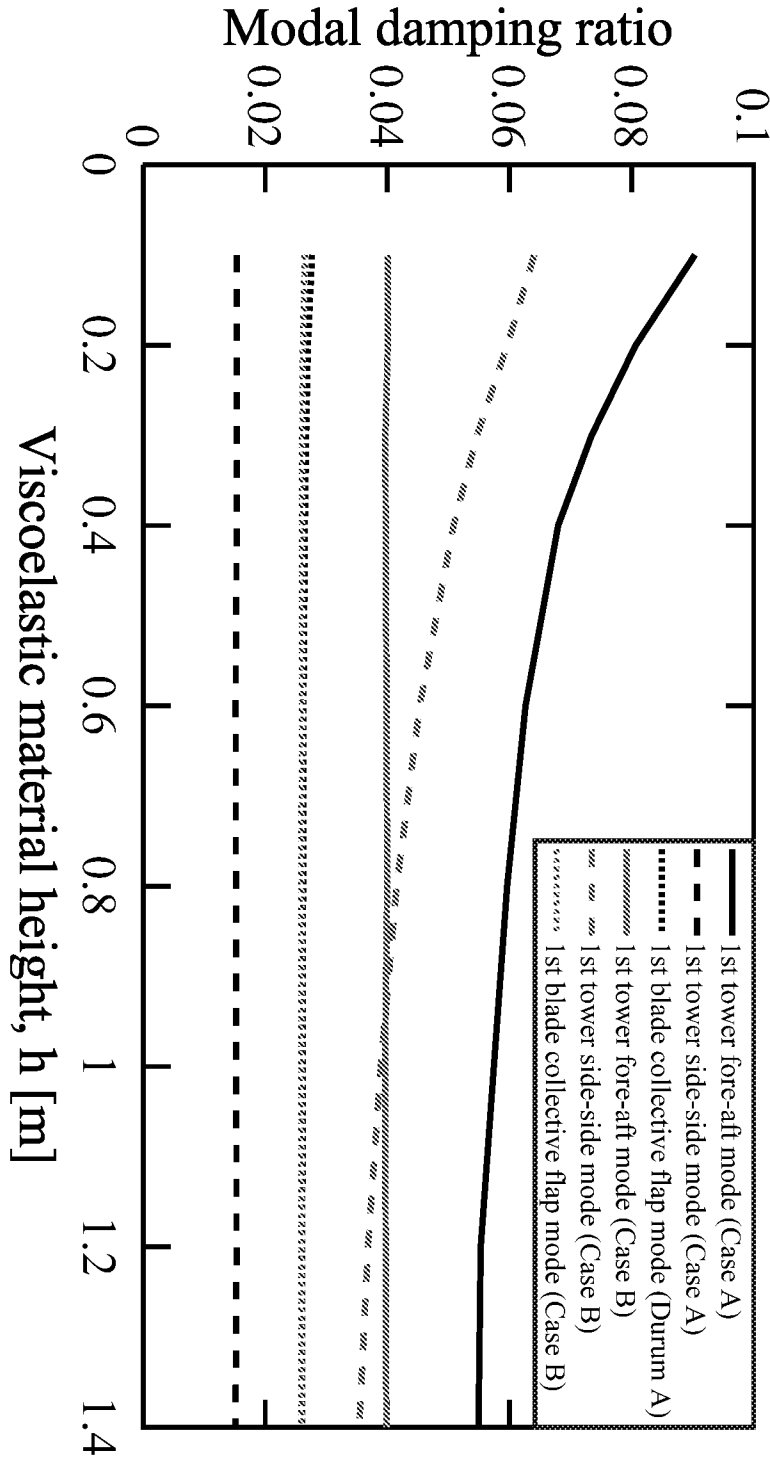


Figure-25

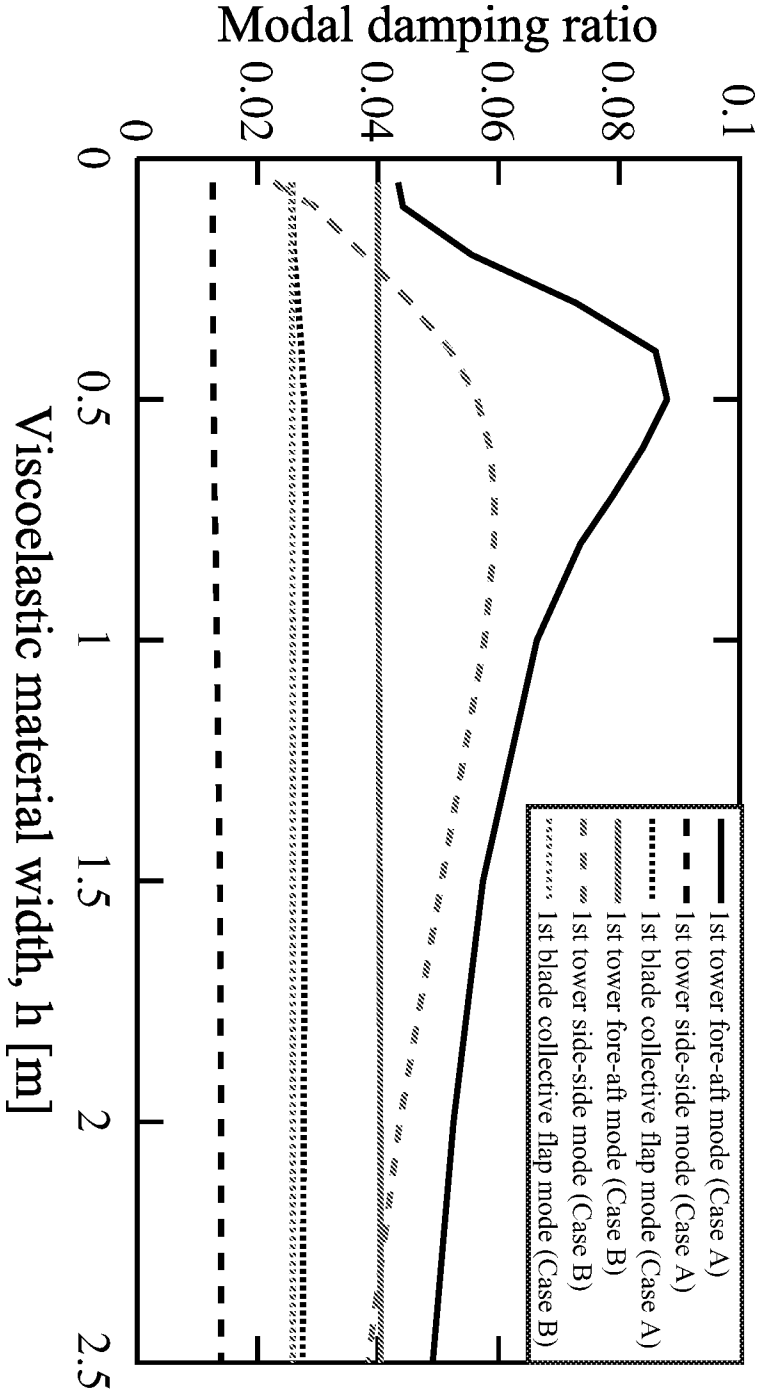


Figure-26

INTERNATIONAL SEARCH REPORT

International application No.

PCT/TR2021/050889

A. CLASSIFICATION OF SUBJECT MATTER		
F03D 13/00 (2016.01); F03D 80/00 (2016.01); F16F 7/00 (2006.01); F16F 15/00 (2006.01)		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) F03D; F16F		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched TURKPATENT Database		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPODOC		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Koçan, Ç (September 2019). STRUCTURAL VIBRATION CONTROL IN WIND TURBINES [Master's Thesis, Middle East Technical University] https://etd.lib.metu.edu.tr/upload/12624526/index.pdf	1-12
☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
* Special categories of cited documents: “A” document defining the general state of the art which is not considered to be of particular relevance “D” document cited by the applicant in the international application “E” earlier application or patent but published on or after the international filing date “L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) “O” document referring to an oral disclosure, use, exhibition or other means “P” document published prior to the international filing date but later than the priority date claimed “T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention “X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone “Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art “&” document member of the same patent family		
Date of the actual completion of the international search 04 January 2022		Date of mailing of the international search report 04 January 2022
Name and mailing address of the ISA/TR Turkish Patent and Trademark Office (Turkpatent) Hipodrom Caddesi No. 13 06560 Yenimahalle Ankara Turkey Telephone No. (90-312) 303 11 82 Facsimile No. +903123031220		Authorized officer Serhat GÖKHAN Telephone No. 0090 312 303 10 00 (1616)