Dynamics of Ocean Structures
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Module - 2
Response Control of Multi-Legged Articulated Towers Using Tuned Mass Dampers
Lecture No - 10
Experimental and Analytical Studies on MLAT

So, we have been discussing the dynamic analysis of multi legged articulated towers. In this lecture we will show you some external studies carried out on this and the analytic studies carried out, so that we can understand how the response control technique can be used for controlling the response of a MLAT using a tuned mass damper.

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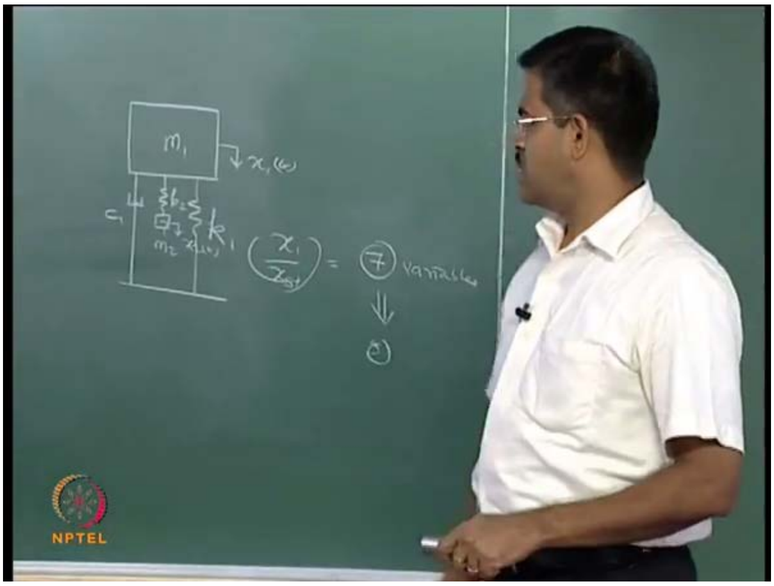

So, in the last class, we discussed about the derivation of equations of motion for a primary and secondary mass system. As we see here, is my idealized model of the tower, which has specific stiffness and damping, which we call as k1 and c1. And of course, is a mass of the whole tower, which we already computed. We have attached a secondary mass system m2 with k2 and we said this may be the response if you want to control, whereas this response is dependent on this. We found that the equation of motion with respect to the x1 of t of x static, x1 static as formed out with 7 variables. Then we found out some ratios and reduce this to 5 variables and we plotted a curve, which I will show you again now, which we discussed in the last class.

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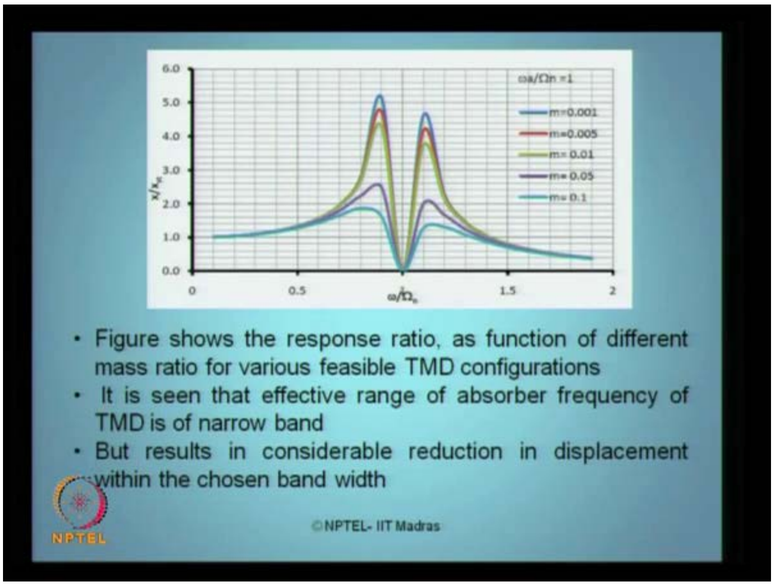

So, there is plot what I have, which varies with the frequency ratio, omega the excitation frequency and sigma is the frequency of the fundamental system; the ratio of the fundamental system. The y axis shows me the plot of x1 of t versus x static, because I am interested in the controlling the primary response of the system here x1 of t by tuning the mass of the secondary system. In my case, is the tuned mass damper. So, I have got plots and I am plotting this for different ratios of mu, which is the mass ratio, which is the ratio of m2 over m1, which will be always less than 1, and the percentage varies from about 0.1 to 10 percent of that of the primary mass.

The important observation what we made from this figure in the last class was that, at resonance, that is when the excitation frequency omega matches with the fundamental frequency of the primary mass system sigma n, we see that the response practically comes to 0 and there is an analytical solution; because this cannot be excrementally tried. Because when you excite a model or a scaled system to that of a natural or the excitation frequency to be tuned in the frequency ratio of the model, it will damage the model. So, we cannot actually study this experimentally.

So, we attempted to find out different mass ratios of mu varying from 0.1 to 10 percent, which is the ratio of the secondary mass to the primary mass system. The plot shows that at resonating frequency of the primary mass system, the response of x versus x static ratio becomes practically 0, whereas the peak is now shifted to that adjacent bands approximately at 0.4 and 1.01 approximately. So, you will get 2 peaks successive to the peak of the response ratio, that is the natural frequency peak, that is resonance frequency 1. I got 2 peaks now.

Whereas you will see that instead of the response shooting up to infinitely very high value, it controls at around 5, as I keep on increasing my mass ratio from 0.1 percent, which corresponds to this to 10 percent, which corresponds to this. I am able to control my response drastically from a value ratio of around 5, the value ratio of around 1.06, so I am able to control. So, what attempted was the response control of the primary system using an additional secondary mass system, which is one of the common algorithms being used for passive control technique methodology in land based structures. This was not attempted very often in offshore structures.

So, which frequency or which response we are controlling here is x1 is nothing but the displacement of the deck. Of course it is a function of the tower rotation theta as we all understand now, but still the response control here is x1 of t, which is displacement of the deck for operational convenience of the platform. So, the figure shows that the response ratio as a function of mass ratio for different mu values; it is spotted as ‘m’ here. It has been seen that the effective range of observer frequency of the TMD is the narrow band, because now the width what you have here is practically narrow. This was the narrow band.

So, it is effective only in a bandwidth of from here to here as well as from here to here. So, the demerit what you get in this case is, instead of having single shoot of frequency value, it is having two response peak shooting up adjacent to or closer to resonance band, so you get 2 peaks. But of course the peak value is controlled. So, this shows a considerable reduction in the displacement within the chosen bandwidth, any question here?

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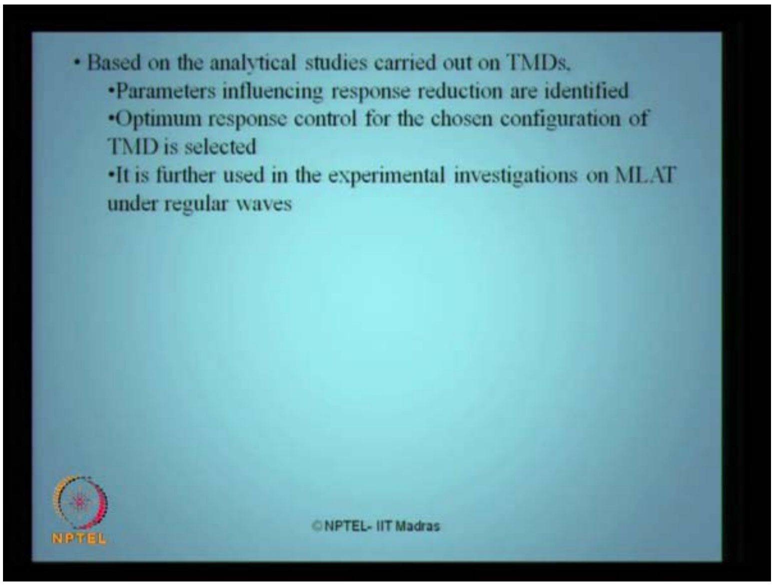

Now, let us see how this experiment was conducted? So based on analytical studies carried out the uptime different ratios of secondary mass to the primary mass system, that's why we call just tuned mass dampers. I got to find out, which mass proportion of mu will comfortably work at the bandwidth of (( )) frequency the wave from which chosen fundamental frequency sigma.

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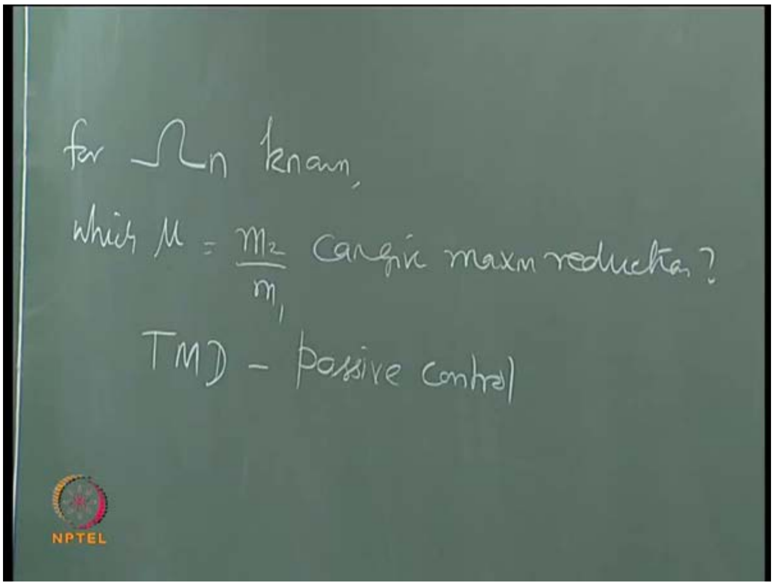

For a chosen fundamental frequency sigma which is nothing but the fundamental frequency of the primary system for for sigma n known which mu that is nothing but m2 versus m1, where m2 is the mass of the secondary system and m1 is the mass of the primary system, which mu can give maximum reduction that is the optimization parameter here. Since, we are tuning the mass the whole exercise is called tuned mass. Since I am controlling the response this is damped; I call this is tuned mass dampers system. This is one of the practical technique of passive control of structures, which is being generally used for land based structures. There is no first attempted in case of offshore structures.

So, based on the analytical studies carried out, we found out the different parameter effecting and try to find out the optimal response control for the chosen configuration. Then we verified this for different ratios and confirm it from experimental investigation. It is very interesting, because the study cannot be done experimentally, because I cannot tune the mass m2 versus m1 experimentally, because I may damage the primary model. So, I do it analytically, then select these ratios, because analytically I understand from the previous curve I showed you, that when I attach a secondary mass to the primary system, my response is getting shifted from the resonant band; it means I am saving the primary structure which is not resonating at all.

So, now I can try with different mass ratios and try it to find out the response control and verified experimentally and see which is the feasible tuned mass which can be deployed for this specific system. So, it is problem specific, it is site specific, it is actually frequency specific. It cannot operate for larger bandwidths, it means it cannot cover your wide range of frequency for application, it has got its limitations. But within that applied limitation, it is very effective. It is an inherence system; you do not have to actually attache a separate secondary mass, as we have shown in the model, analytical model.

It can be inherently build, for examples ships, have sloshing tanks or have buoyancy tanks, which has liquid contained in it, that property can be used for tuning the response of the primary system. In that case, we call this as tuned liquid mass dampers T L M D S. We will try to find out what is the volume effective, which can be used to tune the response of the primary system. In my case, I am not using tuned liquid mass damper using a physical mass, I call this is tuned mass dampers.

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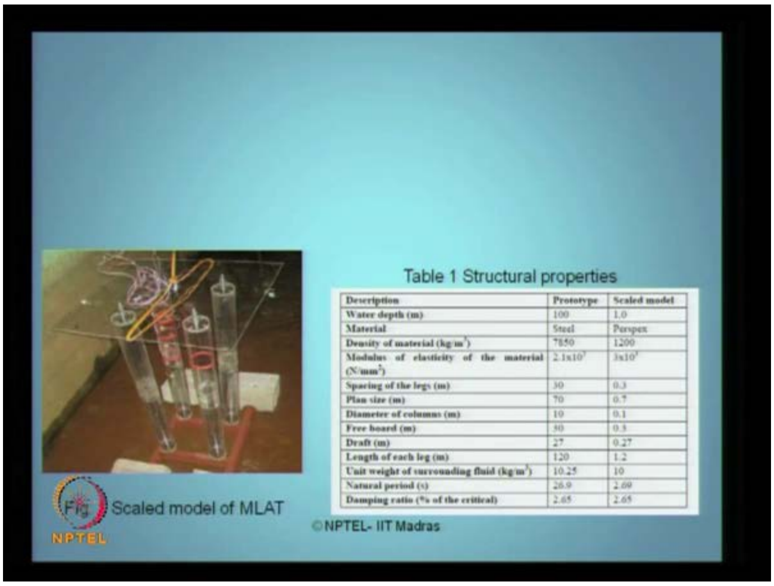

Table 1 Structural properties

Description	Prototype	Scaled model
Water depth (m)	100	1.0
Material	Steel	Perspex
Density of material (kg/m^3)	7850	1200
Modulus of elasticity of the material (N/mm^2)	2.1×10^7	3×10^3
Spacing of the legs (m)	30	0.3
Plan size (m)	70	0.7
Diameter of columns (m)	10	0.1
Free board (m)	30	0.3
Draft (m)	27	0.27
Length of each leg (m)	120	1.2
Unit weight of surrounding fluid (kg/m^3)	10.25	10
Natural period (s)	26.9	2.69
Damping ratio (% of the critical)	2.65	2.65

So, that is the (( )) of the here, it is a four legged articulated tower. You can see the articulation of the bottom here; it is an articulation here at the bottom and of course, there is an articulation at the top also. Because this articulation at the top is only to reduce the bending moment at the rigid body connection, between the decks at the tower which you saw in the earlier case of single legged eighties. This was one of the geometric innovations by providing an additional hinge at the connectivity in the tower in the deck; you can reduce the response of the rigid connection. Of course, you will realize now, at this point of time of understanding.

The point where I am providing the top hinge, this particular point has no wave action at all, because this is a very much above the means sea level. So, there is no wave action here. So, this will not get corroded, because this is very much away from the clear heat sea condition of the wave, from the upper tide level or high tide levels okay. So, the bottom one of course, is the functional characteristic structural configuration which is already present in the singular tower also that is nothing but a structural hinge. So, that is a (( )) of course, you see lot of instrumentation on the deck here.

I will explain that very quickly, because the focus in this lecture is not to explain, how the experiment was done. The focus here is how we are obtain the tuned mass configuration from this experiment and how the results look like, that is what we are interested in. Of course, you must understand the structural properties of the system, because that is important how the tuning was done. The attempt was made for a 1 is to 100 scale, because the prototype tide is about 100 meter water depth, the scale model of is 1 meter water depth, so 1 is to 100 scale has been attempted.

You may wonder why very intensive scale has not been attempted, because of the limitations in terms of attaching a mass I am looking for a mass ratio of 0.01 onwards. If I go for a larger scale then I am not able to operate the upper mu ratios, we go for a smaller scale I will not be able to operate the lower mu ratios. So, I picked up the scale model which can accommodate my mu ratios that is mass m 2 m 1 ratio, which can suite my experimental setup. Of course, the density of the material, density of model of velocity all has been attempted. The size of the platform attempted here 70 meter square, which confirms around 0.7 meter for a scalar 1 is to 100. Of course, the free draft, the free board draft, length of the legged are all available to us there, free wave was conducted and we found out the natural period is close to around 2.7 seconds for the model.

It is very important for you to remember, because I will show you at this particular point of 2.7 you are suppose to see a decrement in the response. Because at resonance it has to show lesser response that is the aim objective of this is it not? So, we will show you how it is happening, so 2.7 and of course, the damping ratio critical was about 2.6 percent, generally it varies from anywhere 1.5 to 3.5 for hydrodynamics structure like offshore structures, because the damping is extraordinary. This is the damping ratio of the critical of the structure. So, that the structural property what we have for the setup.

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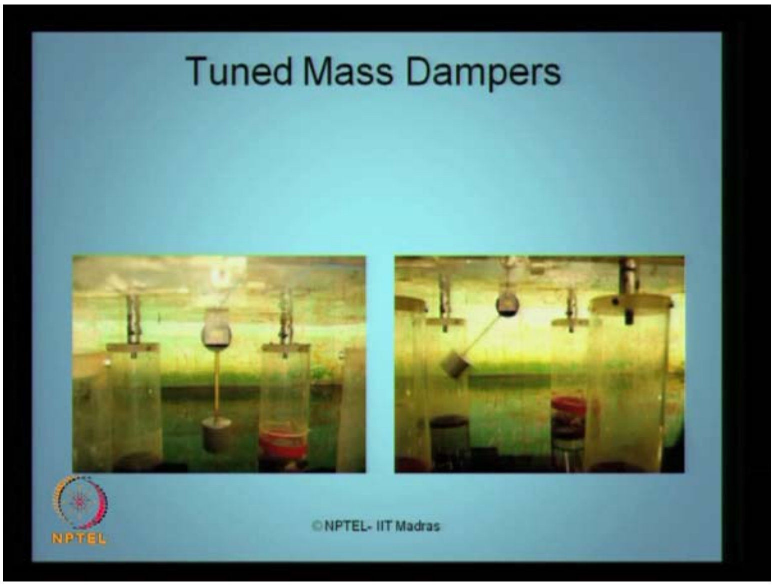

This is actually the setup, which will show you the video; Nnow I got to shift the system, I will show you the video. You can see here, there are two pictures the left one shows you that it is at a static install condition and the right pictures shows you that it is in the displaced condition. You will see when the mass or the secondary mass is getting (( )) to its maximum you will see the primary system is not displaced at all. There is an out of phase relationship between the, this is exactly what we call as tuning. So, now we will show you video how this is done, then we will go to the results.

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This is actually a collaborate study what IIT M did with one of the engineering student of P h D in university of Naples in Italy, he came here to do the experiment. This is our wave flume setup is one of the interesting setup what we have in our department in IIT Madras. So, this video will run for few minutes, let us watch this, because it is interesting for us to know how the wave setup is. Because for listeners, which are was seeing it for the first time is interesting for us to know how the wave was generated is a piston type wave maker, which is 1 meter water deep flume where I can generate current also.

So, that is a piston which is activator for a specific signal. Now, we are having a long time period wave, the period of wave is very long, let us see how the wave propagates and how it treats the model and how the model was installed. You can see that is the length of flume we have and we have placed the model apart from the interference of the boundaries. That is the model which has four legs where instrumentation is done. You can see the wave pro in the beginning to check the wave height which is reaching the model. These videos will show you the experimental setup and of course the motion characteristic of the model.

So, it has been online configuration has been attain by looking at the system instead and the whole data has been acquired instantaneously as the model response to the wave. So, there is second thing how actually comfortably secondary mass can be pressed in the system. So, because of the top hinge provided connecting the tower and the deck, one can easily remove the tower, of course for the experimental facilities, one can remove the deck easily from the tower and place it secondary mass.

So, that is the hinge joint what we have which is connecting the tower and the deck. You can see on the top is the triaxial accelerometer, which is at the center mark with the C G of the deck, which is measure in the acceleration response of my deck, which I will show you subsequently. So, the deck can be easily displaced off from the tower under the install condition, there is an install condition actually. So, one can do this; it is not that easy; when you do in the real size, because 70 meter size it is not that simple, but in the model at least it can be easily done.

You can see it that is the secondary mass system where the pendulum what is picking out of a specific configuration of m 2, for a specific length of l 2. So, there is an arrangement below the C G of the deck which is going to hang the secondary mass. The secondary mass system m 2 with k 2 has been connected to the system now to the primary system, it has been tighten to maintain the l 2. That is a simple pendulum, which is one of the simplest way of doing a passive control, which has been attempted by earlier people in seventies and eighties for land based structure and the deck is replaced on the hinges is ready for experiment now.

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That is the response of the tower without the secondary mass system. You can see here now the deck is displaced for effective rotation of theta of the tower, which has been constantly on online acquired. So, the test has been conducted, having given enough pass between the successive matrices, so that to have a calm sea state and the, acquire the data. So, now let us see how this is getting modified when I attach a tuned mass damper. Now, when the system with the tuned mass damper is subjected to the wave action as generated from the piston type wave maker, as a wave approaches the model as you see here, the tower is practically static, because it is a calm sea state, now the wave is heating the model.

The secondary mass has picked up the displacement much larger compare to the primary mass system and a very high response you will see, slowly when the secondary mass becoming maximum the primary mass has controlled out and this was operating a 2.07 seconds. Now, the wave action has stopped, because the period of application is only 20 seconds and that is how it has been acquired directly. So, you can see it has been reapplied once again for a maximum displacement, you will see there are 2 peak regenerated now, I must show you both the peaks in the deck response. You can see for a larger displacement of the secondary mass, primary mass is almost static earlier it was not so without the T M D, any question here?

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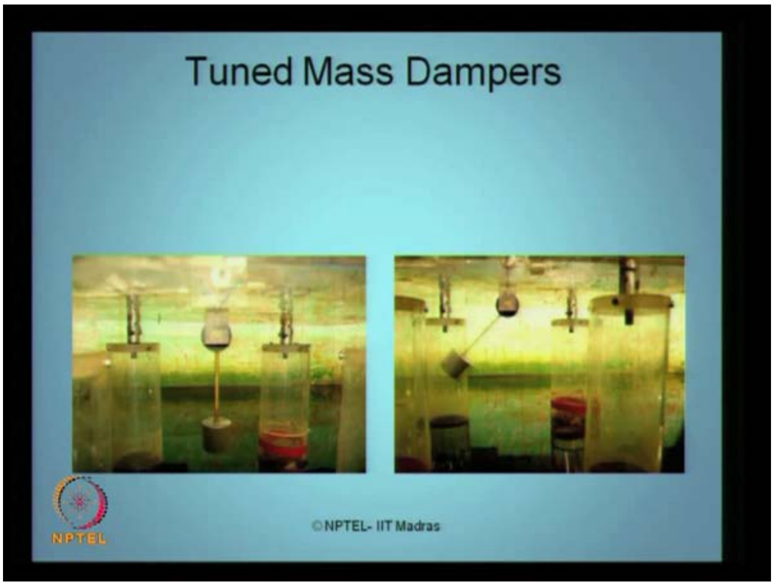

So, this was the external setup what we had and we had seen the video how the experiment was done. The left hand side image shows the static condition of the installed model, whereas the right hand side shows the maximum displacement of the secondary mass system at omega equal sigma. When the primary system is supposed resonate to the maximum response it is not happening here, because of the advantage of secondary mass attached. It's a very simple algorithm tried and let us see the benefits. Now, which are the focus points in dynamic point of view as far as the, this problem is concern? What we are interested in the following.

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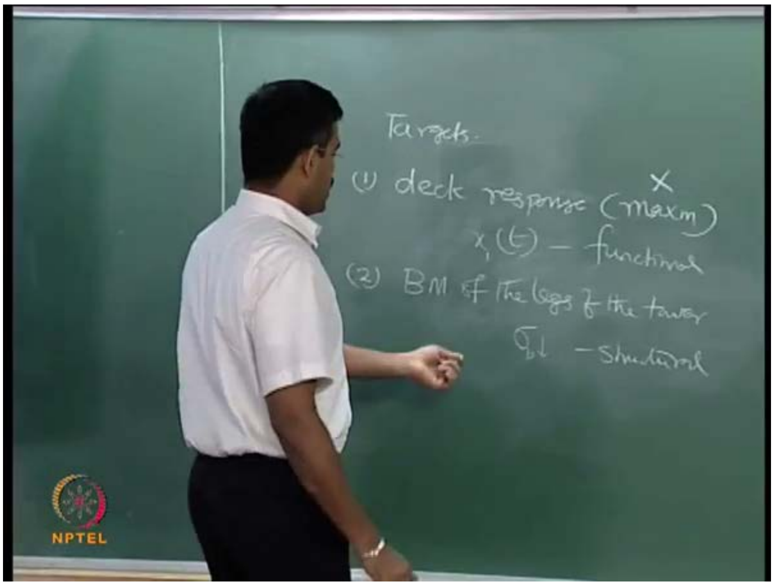

The target isthe following, of course the deck response is not the maximum response I am not looking at the maximum response, I am looking at the response time history. Also, of course I want to know is there reduction in the bending moment of the tower legs. The moment I know the bending moment reduction in the tower legs I can always work out whether there is any reduction in this stresses, bending stress of course in the leg.

So, I can also protect my legs when the bending stress exceeds the (( )) of the value in the material by the same technique, so secondary advantage we derive. The primary advantage is functional, the secondary advantage is structural, is that clear? It is function a, because I do not want (( )) larger for operational point of view. The secondary advantage is structural; I can reduce the bending stress also in the tower. Let us see both now, of course I will show you the reverse order first I will show you the secondary benefits, and then I will talk about the primary benefits.

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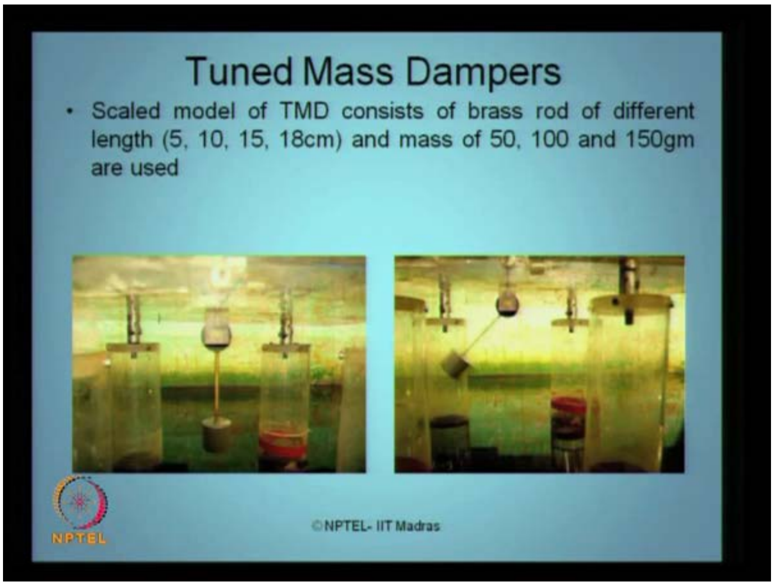

The scale model of T M D of brass rod of different lengths of different 5, 10, 15, 18 centimeter have been tested with different mass of 50, 10, 100, 150 and 230 I have been used in the study, which corresponds to the mu ratios of various percentage as we analyzed in the previous example.

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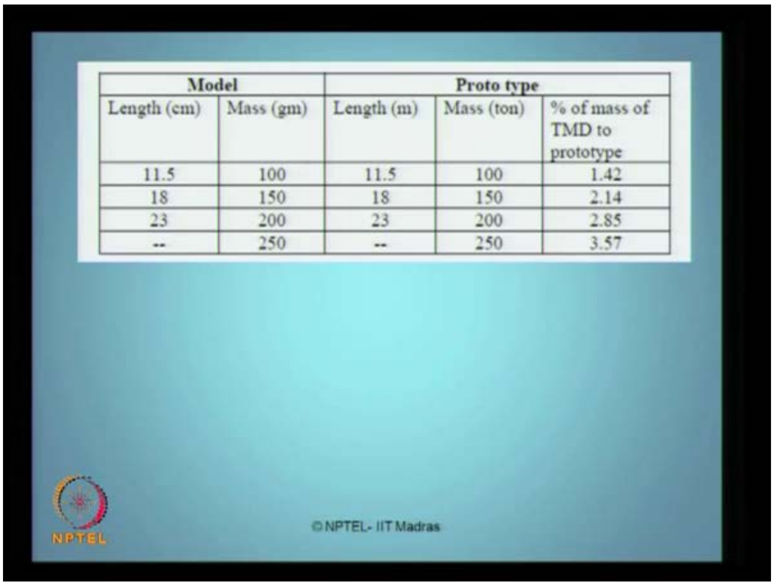

Model		Proto type		
Length (cm)	Mass (gm)	Length (m)	Mass (ton)	% of mass of TMD to prototype
11.5	100	11.5	100	1.42
18	150	18	150	2.14
23	200	23	200	2.85
--	250	--	250	3.57

So, these were the different configuration and these were the percentages of the mass of T M D to prototype, it varies approximately from 1 percent to 4 percent, for the present study. So, this can be achieved either having the different diameter of the member in term of its leg of the secondary mass can also vary the length of the pendulum, can also vary the mass of the pendulum in grams, of course corresponding to so many terms.

One may wonder how I can suspend your 250 ton or 200 ton pendulum, I am talking about the structure whose weight is around 17000 tons. Because my percentage is only 2.85 look at the value do not look at the mass of the pendulum, look at the percentage of that mass of the pendulum it is to the original prototype, so it is just 2 percent, this can be easy. So, it cannot be suspended as simple as you saw in the experimental setup, there are mechanisms that is got to be attempted how to handle this. But the advantages are what we are going to see now which are important.

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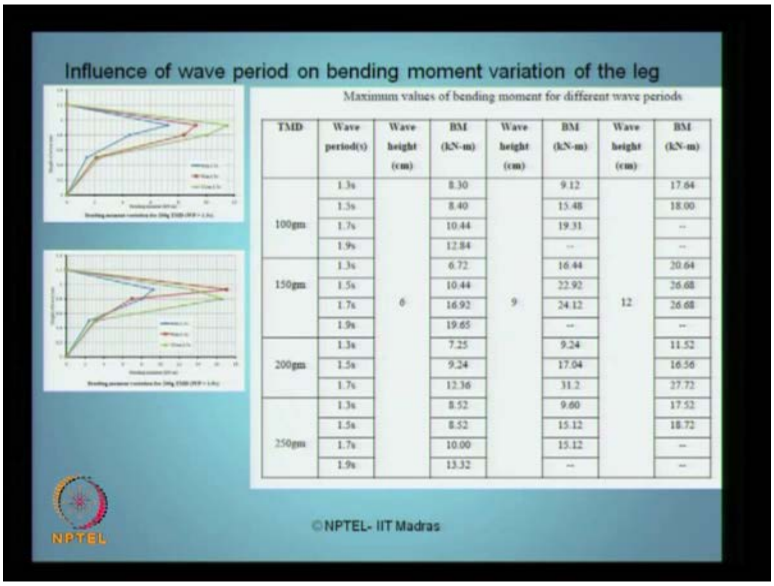

If you look at the maximum value of the bending moment, because I meant to be showing the reduction of the bending moment, I am sorry for this, I think small size of the figure. But I think if you look at the same figure in a screen of a computer I think it will be sharp enough I am sorry, because you are not seeingfrom the distance. But anyway qualitatively we will discuss it quickly; quantitatively it is not important for you to know the numbers. Qualitatively this is the point where I have may top hinge which is connecting the deck on the tower, there is the point where I may have bottom hinge which is connecting the tower and the foundation.

So, practically I have bending moment 0 in this (( )), these bending moments are apply measure directly from the experiment these are all experimental results. These are the points where they have been measured using strain gauges. The dots what you see here are the discrete points at this places where the strain was measured from the strain, the structure remains elastic, therefore we are computed the bending stress. That is why the figure is not continuous, it is discrete, it is breaking, because these are the points where they having measure directly from the tower.

So, if you look at the maximum response, in terms of bending moment. Let us look at this case, which talks about 200 grams T M D, this is also 200 grams TMD where I was the wave period (( )) the different cases. So, the maximum bending moment occurs approximately at about one-third of the height of the tower from the top. So, I say keep on increasing the wave period the wave period for the same wave height for example, let us say 200 grams T M D. I have the wave height of 6 centimeters in the experiment I keep on increasing the wave period 1.3, 1.5, 1.7, of course the bending moment in terms of kilo into meter keeps on increasing, in respect to the increase wave height.

So, qualitatively presence of secondary mass does not alter the bending moment characteristic of tower qualitatively, without T M D also the same scenario was notified, I will show you comparison later. So, the bending moment will increase with the increase in wave height for or same wave height for wave periods, qualitatively it is not. Also there is no apparent shift of the maximum bending moment, because of T M D (( )). The location where the maximum bending moment occurs in the leg remains almost same. So, the critical cross section with in T M D remain same, so you are not able to shift that. What you are seeing is reduction in magnitude only that is important. It means T M D provisional or secondary mass provisional system qualitatively is not altering the structural behavior, in terms of bending moment.

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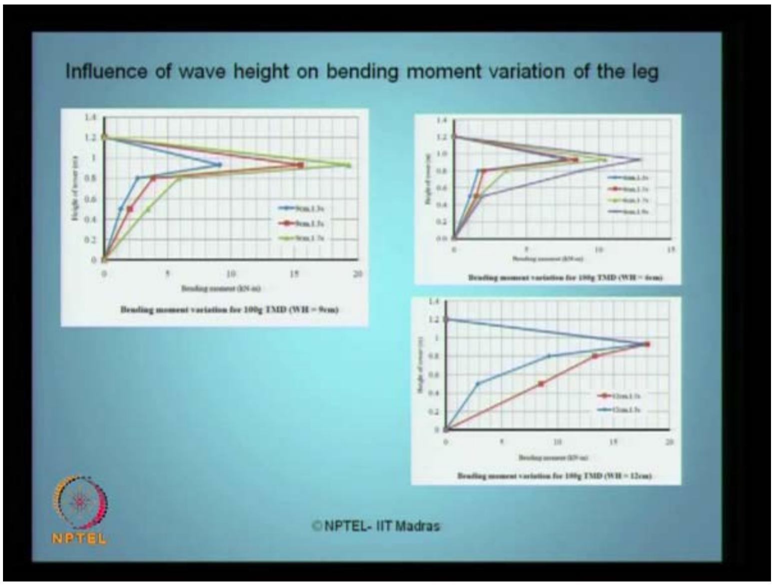

Let us see what happens when I change the wave heights, because the earlier case were constant wave height. Now, I change the wave height for T M D 100 grams, 9 centimeter, 6 centimeter, 12 centimeter, I am changing the wave height, of course the plot is also showing different period as well. Again you see qualitatively the bending moment maximum occurs for all the cases at the same point, right? But there is a reduction quantitatively in the bending stress or in the bending moment.

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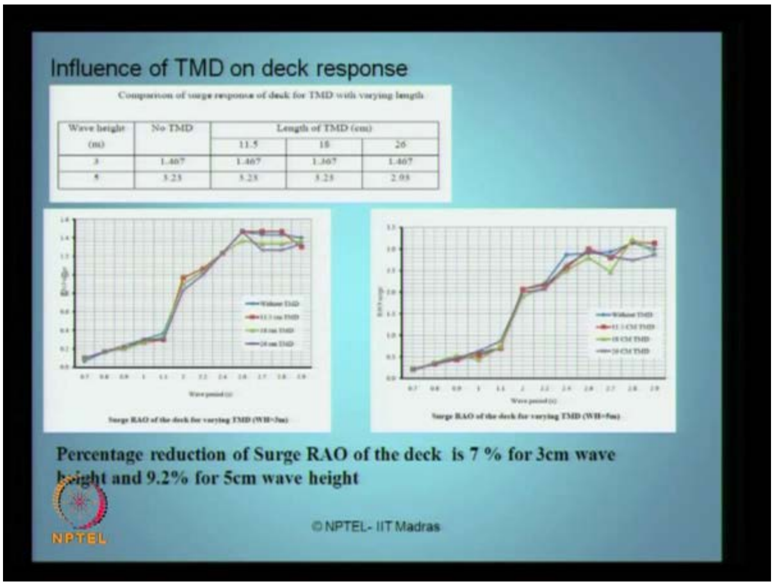

If you look at the influence of T M D on deck response to the functionally require x 1 of t here, what we saw just then was the structural requirement. Now, we see the functional requirement, if you look at the wave height 3 and 5 centimeters for no T M D case, the deck response was around 1.5 and 3.2 centimeters in the model. When I attach 11.05 and 26 centimeters of long T M D for a specific mass of 200 grams, let us say I do not actually get a synonym reduction in the deck response. It means tuning is not done for all values of wave height and wave. It is also depending what is a sea state.

So, in this example for specific case for a 3 centimeter wave height 18 centimeter long T M D with 200 grams gain is reduction of about 7 percent. When we look at 5 centimeter wave it give me reduction of 9.2 percent, but the length of T M D is different. So, it is very difficult to exactly find out what is that T M D I suspend to my primary mass system which can remain effective in all ranges of wave period and wave heights. Therefore people generally do not attempt with single mass tuned dampers, they go for series of T M D with different lengths and different weights. So, one of them will be effective in one range of wave period and wave height. So, there is a reduction of about 10 percent approximately.

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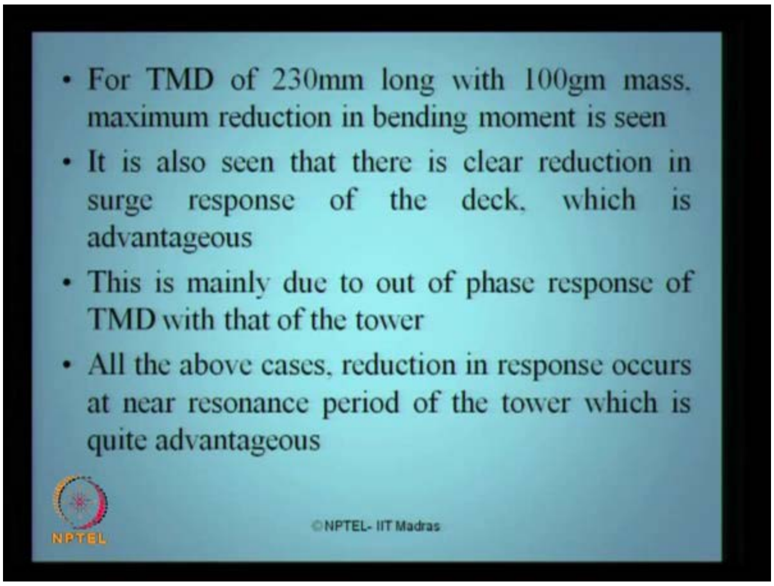

So, for a T M D of 230 mm long with 100 mm gram mass, the maximum reduction of the bending moment is seen. It is also seen that there is a clear reduction in the surge response of the deck for about 10 percent, which is advantageous. This is mainly due to out of phase response of T M D with respect to the response of the tower, which we saw in the video. So, in all the above cases, please note that the response reduction occur at the frequency of the tower 2.7 seconds, the reduction occur at a resonating frequency or near resonating frequency of the tower.

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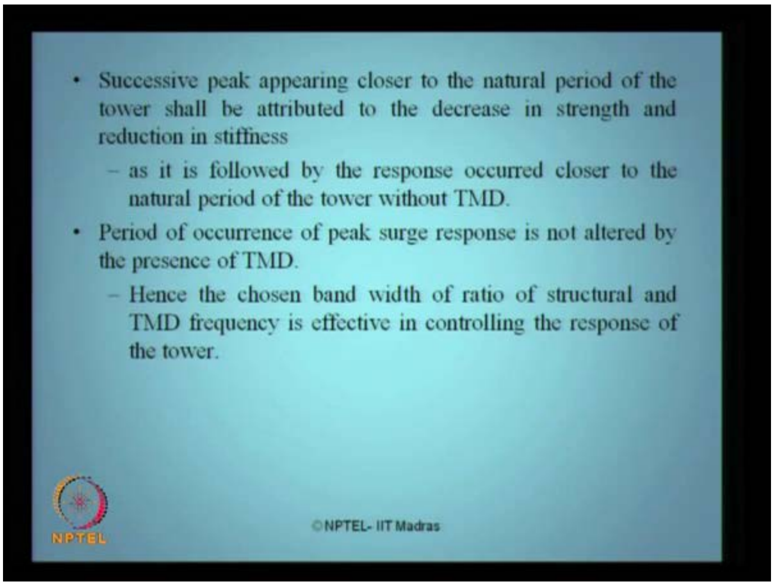

So, we can see major conclusion from the scanned of works. Let us say that successive peak appearing closer to the natural period of the tower shall be attributed to the decrease in strength and stiffness. Because I am saying whenever the tower reaches the resonating period at which the excitation frequency matches with the frequency of the tower, there is degradation of stiffness in the tower. So, there is a shift of frequency also because of k is getting alter. At this time T M D assist or the secondary mass assist the primary system for response reduction. We all say also note that the response reduction is maximum at the natural period of the tower when the T M D is attached otherwise it is maximum without T M D, which is a simple observation in dynamic cases.

The period of occurrence of the peak surge response is not altered as I said, qualitatively it is occurring in the same it is not altering. Therefore one can say that the chosen bandwidth ratio of the structural T M D frequency is effective in control in the response only with the chosen bandwidth, only at that bandwidth is effective. If you go beyond the bandwidth of 2 peaks which we saw then it is not effective.

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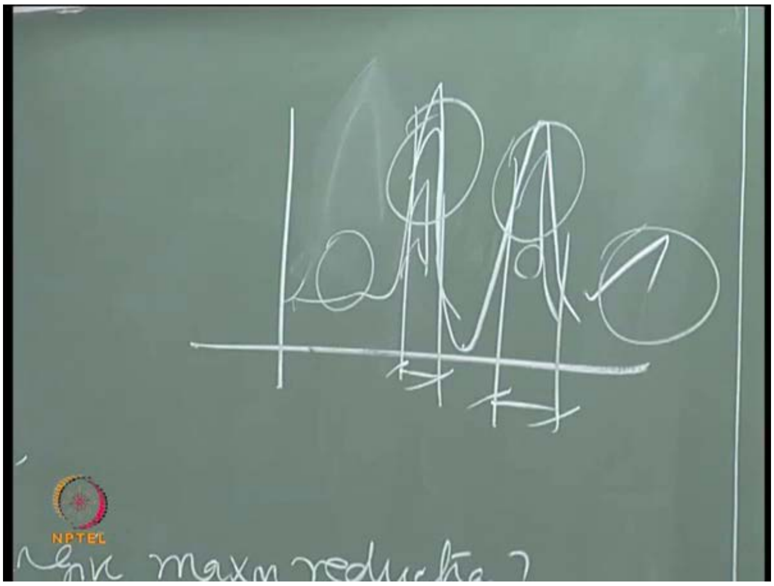

So, only in these bandwidths the chosen ratios of mu will remain effective. Lower than this and higher than this T M D will play no role in contriving the response. That is very important to understand; you cannot actually plan a passive system of control mechanism for a wide range of frequency. So, generally it is an engineering attempt to try, and then let us try to control the response at the resonance. Because it is expected that the response will remain maximum at near resonance case for the tower, let us save or reduce the stresses in the tower legs and the response in the tower deck at least resonating frequency. So, we can pick up that kind of decision and design the secondary mass system to achieve this.

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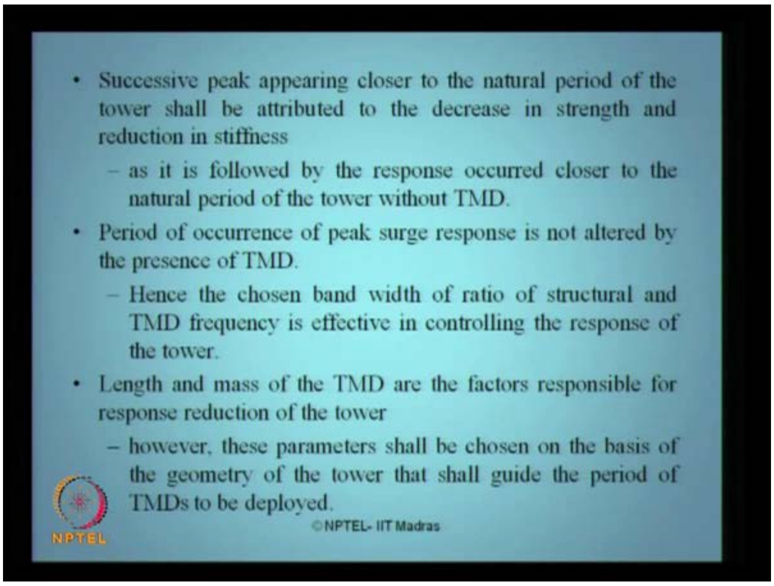

So, the length and mass of T M D are the factors as we saw in the case, masses in grams as far as the exponential is concern, length is in centimeters. So, these are the two factors we have been tried and attempted iteratively to see which is the maximum reduction possible? However, these parameters are very important to know that they will be chosen on the base of the geometry of the tower. So, however selected these 50 100 150 and 200 grams or how these mu ratios of 0.1 to 10 percent I have been selected, it all depends upon what is the mass ratio with respect to the tower, that is very important., They cannot be generally applied to all kinds of platforms, so you have got to see that is why the whole exercises attempted to tuning the secondary mass for damping the response of the primary system. That is one of the passive techniques deployed in this study.

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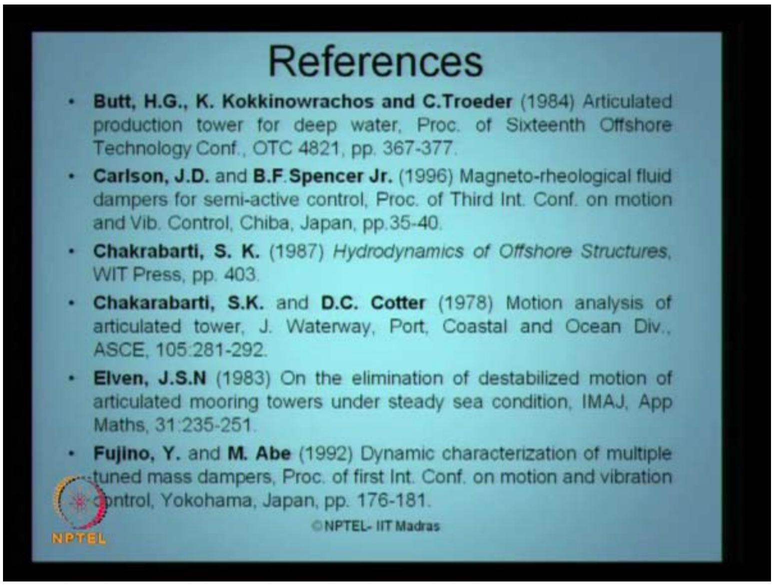

So, this is got interesting reference we have to acknowledge the authors for working on these references. Since 1984 people have been working on this, of course some of the studies have been borrowed from Chakrabarti and cotter.

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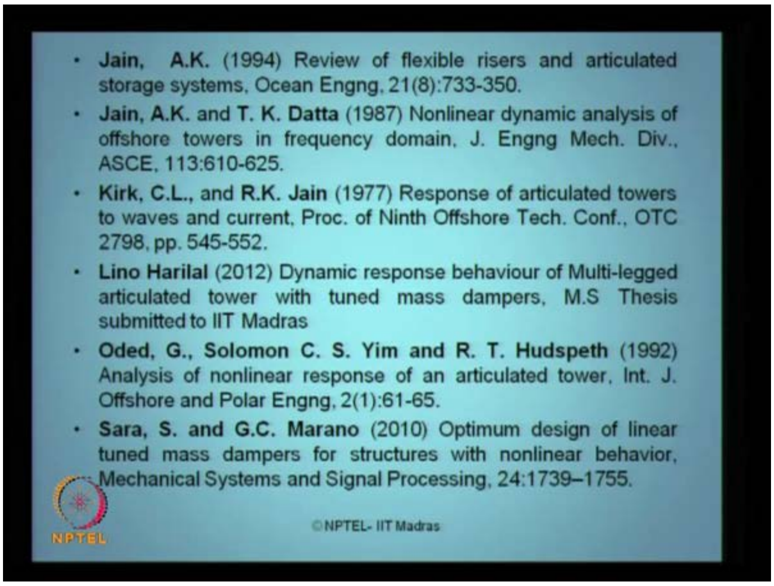

Of course, we already referred to Jain and Datta, Kirk and Jain in earlier lectures of articulated towers under waves and current. There is one of the M.S Thesis output which we had from my IIT M, which is being attempted on this particular study. The response control has been also attempted by Sara and Marano in 2010 very recent attempt for finding out optimum design of linear tuned mass dampers for structures with nonlinear behavior. So, it has been a recent method of research where people are now focusing on response control of chaotic system or nonlinear behavior systems. So, we see here one of the classical example applied to this problem and so on, so any question?

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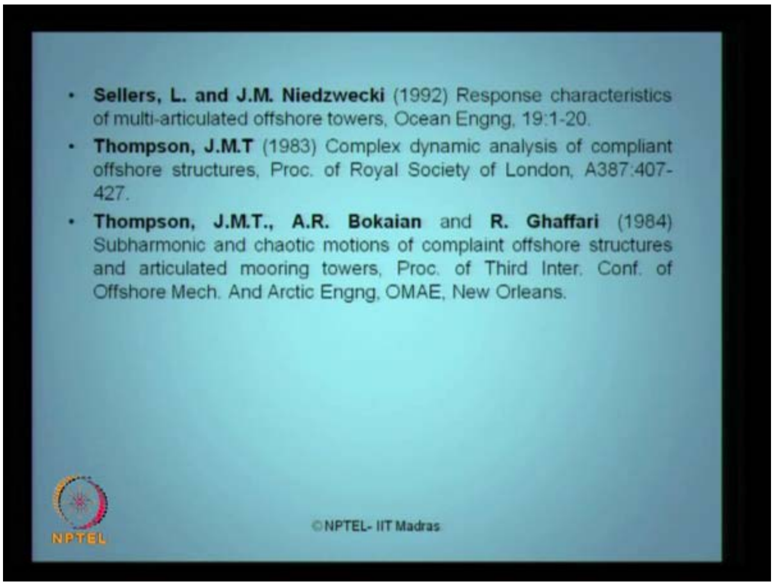

Inthe next class we will talk about (( )), the dynamic analysis of T L P; we will pick geometric design of a T L P, we will alter the shape of T L P from square to triangular form, we see what are the advantages and they derive the mass matrix, stiffness matrix and damping matrices, for a new innovative triangular form of T L P from the research paper. We will form the equation of motion, solve the equation of motion and time domain using new mass beta iteration scheme, and then get the results. Then one can also see if the new geometric form is stable? How to check the stability?

So, we have a Matthew's method stability study on a triangular T L P and showed that this is much more stable on a specific degree of freedom compare to square T L P, whereas the cost saving of the new geometric is more than about 40 percent. So, once you have a cost saving, you et a stability also and the response are much lower this form is acceptable, that is how new geometric forms evolve in offshore engineering to go for deeper waters. We shall understand this mechanism in two three lectures down the line, followed by which we look at a new form, which is completely non available in the literature, which has been started hinter on 1995.

Then experimental works are carried out only in our place in a IIT M, which has been published in wide literatures about two three papers we have in journals and conferences it is a new form will talk about the geometric form design, then derivation of mass stiffness and damping matrices. Again experimental analytical study is detail conducted using star C C M and exponential study here in wave basis, we will compare them validation. Then we will explain you how dynamics can be applied to this kind of practical problems that will be the target of the second module complete lectures.

Of course, we understand the principles and applications, we move on to advance application of model response characteristics and sarcastic response in dynamics in the third module, we will talk about application of this. We will open up the research topic in the third module, which one can carry out forward for doing sarcastic response of dynamic analysis for structure in the chaotic behavior. We will talk about that in the third module that is the target.