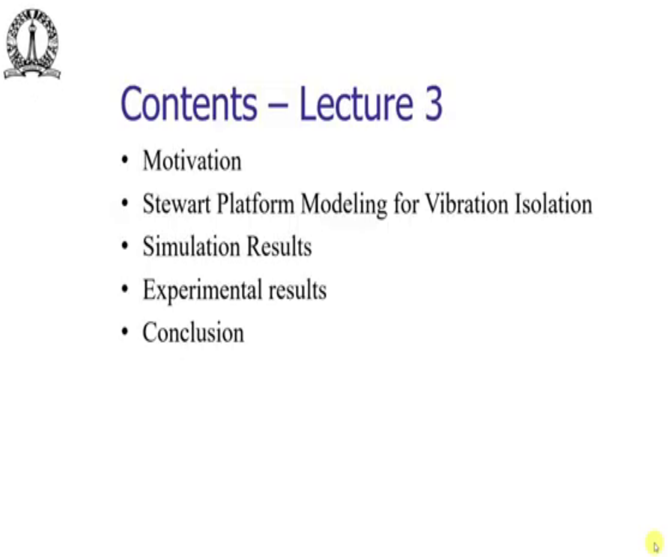
Robotics: Basics and Selected Advanced Concepts
Prof. Ashitava Ghosal
Department of Mechanical Engineering
Indian Institute of Science, Bengaluru

Application of Parallel Robots
Lecture - 18
Vibration isolation using a Stewart-Gough platform

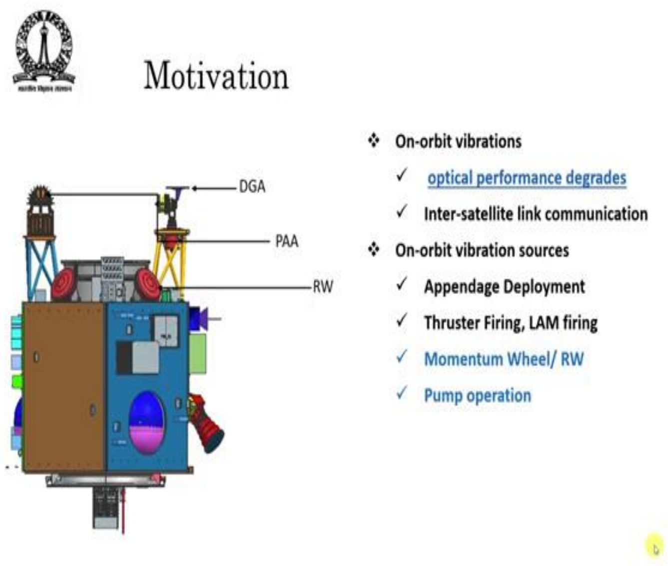
Welcome to this NPTEL lectures on Robotics Basics and Advanced Concepts, in this week we have been looking at Application of Parallel Robots. In this last lecture or example this week we will look at the use of a Stewart platform for vibration isolation, ok. So, a quick acknowledgement this is the work and thesis research of Nazeer Ahmad, he is a student from ISRO.

(Refer Slide Time: 00:50)



So, the contents of this lecture is to start with will be a motivation why we want to use Stewart platform for vibration isolation. Then the modeling of the Stewart platform for vibration isolation, then I will show you some simulation results and some initial experimental results and then conclude this lecture.

(Refer Slide Time: 01:14)



So, one of the main motivation of a Stewart platform or vibration isolation device any other vibration isolation device is that in a spacecraft there are on orbit vibrations, ok. So, we have things like reaction wheels, which are RW and then there are other devices, which generate small micro vibrations in a spacecraft and once this micro vibrations are generated it takes a long time to die out.

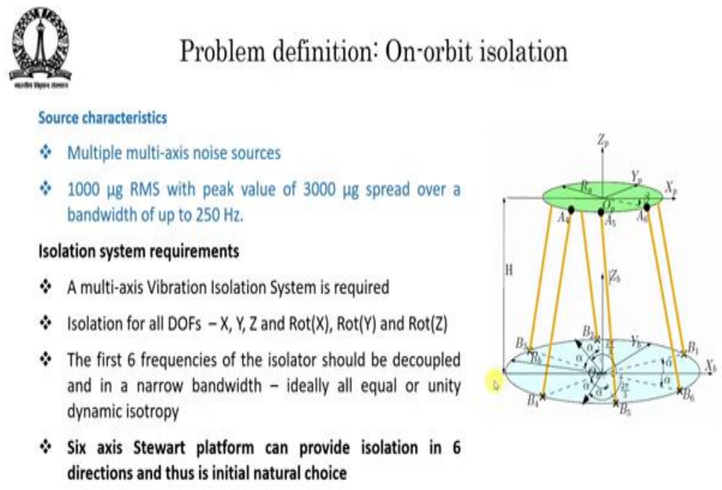
Basically because the spacecraft is made out of aluminum with very little damping, ok; and any sensor which is attached to the spacecraft so, for example, the camera or any other optical device, which can be used to take images of the earth or for inter satellite link communications. These devices performance will degrade because they are vibrating.

So, they will not be looking at the same place or they will not be sending the signal in the same direction all the time. So, most of the time, these on orbit vibrations are there ok, so, basically it starts when you deploy an appendage. So, for example, if you want to deploy a solar panel there will be some vibrations which will be set up and which will take some time. We also have firing of thrusters to change the orbit or change the attitude of a spacecraft once in a while, ok.

So, these thruster firing or LAM firing will again introduce some vibration. One of the major sources of vibration is this momentum wheel and reaction wheels, ok. So, basically you have this momentum and reaction wheels, to make sure that you do not waste energy in trying to correct the small errors ok, this is like a gyroscope.

So, it will try to maintain the orientation of the spacecraft or the camera or whatever else you have on the spacecraft. The spacecraft also has some pumps to circulate some liquid for cooling and so on. So, all this causes vibration when it is in orbit.

(Refer Slide Time: 03:33)



So, most of the time, we need to have some isolation device between the spacecraft body and the sensor, ok. We have multiple sources of noise multi-axis sources of noise. So, this noise could be in the X, Y, Z or even rotation directions, typically it is of the order of 1000 μg RMS with a peak value of 3000 μg spread over a bandwidth up to 250 Hertz, ok.

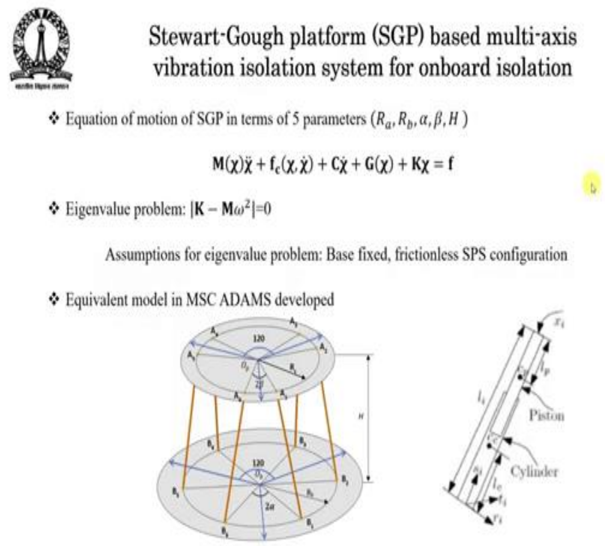
So, what we need is a multi-axis vibration isolation system; meaning what? That we need to isolate vibrations from in coming from different directions and different sources; we need to isolate all the degrees of freedom that is the bottom line. So, we want to find vibrations happening along X, Y, Z and also the rotation directions and we want to isolate.

It is nice if the first 6 frequency of isolator are decoupled in a narrow bandwidth, ok. So, the X frequency, Y and Z frequency and similarly the rotation frequencies are if very close to each other. Then we can use a tuned mass damper, which can effectively isolate all the frequencies in the same way, ok. Remember if you go back and remember your vibration curve so, it is horizontal and then peaks and then again it decays.

Now, the peak is the natural frequency of the vibration. So, if these natural frequencies are very close to each other then I can design a damper which will work for all the 6 degrees of freedom. A six axis toward platform can provide isolation in 6 direction and is thus initial natural choice, ok.

Stewart platform is 6 degrees of freedom, I can somehow cook up something in each one of the legs; such that the forces and moments, which are coming on the base or on the top platform or maybe let us say at the base from the spacecraft does not get transmitted to the top platform that is what we want to do.

(Refer Slide Time: 05:54)



So, we want to design a Stewart-Gough platform based multi-axis vibration isolation system for on board isolation, ok that is our goal. So, we can define the equations of motion of a Stewart platform in terms of 5 parameters, ok. So, what are these 5 parameters? It is the radius of the top platform, the radius of the base platform, the angle α between two points.

So, between B_1 and B_6 we have 2α so, this α is one such parameter because, I can place this connection points on the periphery of the circle in different ways, I can choose this angle α. Similarly, this β is the angle in the top platform between two connection points searching 2β is the angle between two connection points.

And then we have this height H of the top platform with respect to the bottom platform. So, these are the geometrical parameters, which are natural in a Stewart platform and we can derive the equations of motion of a Stewart platform in Cartesian coordinates that, this is what $\boldsymbol{\chi}$ means; $\boldsymbol{\chi}$ means x, y, z and orientation.

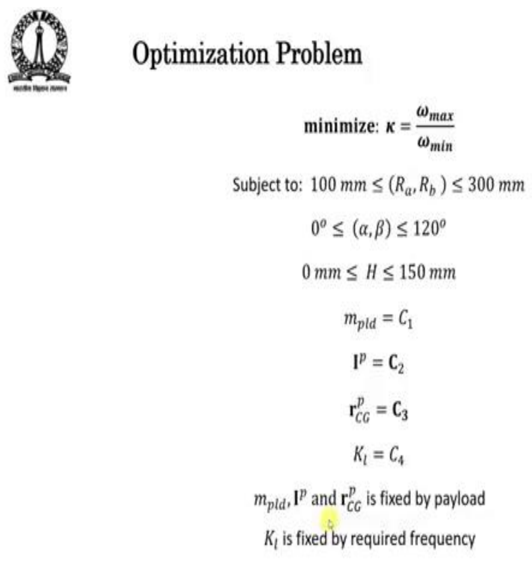
Remember, we have discussed equations of motion in joint space or in Cartesian space, ok. So, we can derive it as in Cartesian space. So, then we can find the eigenvalues of this function, which is $|\boldsymbol{K} - \boldsymbol{M}\omega^2| = 0$. So, this $C_{\dot{\chi}}$, G_{χ} and Coriolis term and all these terms are not very important when you are considering vibration because it is not moving much, ok.

So, for the eigenvalue problem we have assumed that the base is fixed there are these joints are all frictionless ok, and hence only in some sense $\omega = \sqrt{\boldsymbol{K}/\boldsymbol{M}}$, ok. $\boldsymbol{K}$ is coming from the stiffness matrix and $\boldsymbol{M}$ is coming from the mass matrix. So, we have developed this model of this Stewart platform also in ADAMS.

So, not only can we solve these equations of motion with appropriate assumptions and find the eigenvalue of this matrix $\boldsymbol{K}$ by $\boldsymbol{M}$ ok or this eigenvalue problem we can solve and obtain the eigen frequencies, but we can also go to ADAMS and obtain the frequencies.

So, now we want to do some kind of optimization because we have these 5 parameters $(R_a, R_b, \alpha, \beta, H)$. So, how do we choose these 5 parameters; such that we get what we want desire, what we desire is that the Eigen frequencies are very close to each other, why? Because, we can design dampers, which can then damp out all the 6 components of the force and moments or 6 components of the vibration first 6 components, ok.

(Refer Slide Time: 08:34)



So, what do we want to do in this optimization problem? We frame objective function which is minimize quantity $\boldsymbol{\kappa} = \frac{\omega_{max}}{\omega_{min}}$, ok. So, what is ω_{max} and ω_{min}? They are the eigenvalues of the $|\boldsymbol{K} - \boldsymbol{M}\omega^2| = 0$ square that eigen value problem.

And these are subject to some restrictions, ok. So, there is clearly some restriction available for R_a and R_b. So, we do not want very large or very small R_a and R_b. We also cannot have angles more than 120 degrees because then we do not have 6 points.

Likewise, there are natural restrictions on the height in this case we have assumed between 0 and 150 mm, and then this mass of the top platform is some constant, the inertia of the top platform is another constant, the location of the CG of the top platform is another vector, which is a constant this is a matrix. And then this stiffness is a constant, ok. So, this m_{pld}, inertia and the location of the CG are fixed by payload. And K_l is fixed by the required frequency.

(Refer Slide Time: 10:32)

Simulation Results

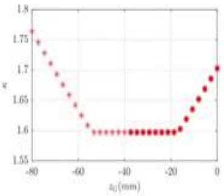
Table 2.1: Natural frequencies and mode shapes obtained after optimization with $z_{cg} = 0$

ω	51.25	39.42	39.42	32.09	30.09	30.09
(Hz)	θ_x (rad)	θ_y (rad)	θ_z (rad)	Z (m)	Y (m)	X (m)
Modal vectors	0	0.11	0	0	0	-0.14
	0	0	-0.11	0	0.14	0
	0	0	0	-1	0	0
	0	0	-0.99	0	-0.99	0
	0	-0.99	0.09	0	-0.04	-0.99
	1	0	0	0	0	0

Table 2.2: Natural frequencies and mode shapes obtained after optimization with z_{cg} as variable

ω	51.25	34.92	34.92	32.09	33.98	33.98
(Hz)	θ_x (rad)	θ_y (rad)	θ_z (rad)	Z (m)	Y (m)	X (m)
Modal vectors	0	0.19	0.07	0	0	0.05
	0	0.07	0.19	0	0.05	0.02
	0	0	0	-1	0	0
	0	-0.36	-0.92	0	0.99	0.36
	0	0.91	0.32	0	0	-0.93
	1	0	0	0	0	0

Converged results:
Table 2.1: $\mathbf{r}_{CG}^{p} = \mathbf{0}$; DII $\kappa = 1.7$
Table 2.2: $\mathbf{r}_{CG}^{p} = variable$; DII $\kappa = 1.6$



z_{cg}: −18 mm to −53 mm

So, we do this optimization problem, solve this optimization problem and then we find the natural frequencies obtained with $z_{CG} = 0$. So, z_{CG} is the location of the CG in the top platform, ok. We can also have the CG below the top platform. So, what you can see is the first 6 natural frequencies, which is $\theta_x, \theta_y, \theta_z$ rotation about rotation about X, Y and Z and motion about X, Y and Z are 51.25, 39.25 and so on and 30.09, ok.

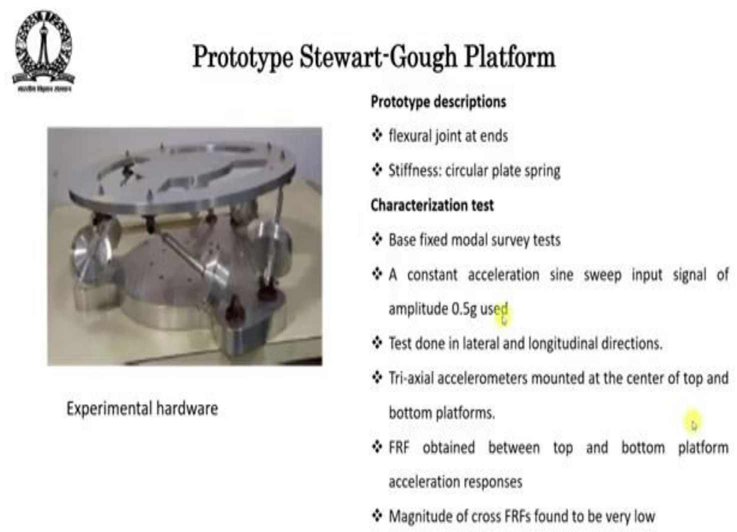
The modal vectors you can see that these are the frequencies about θ_z because these are 0, 0, 1 θ_y is not exactly model vector except that it is this there is a some small coupling, θ_x is also exactly not along the X axis, but there are some small components in the other direction and likewise along Z is exactly along the Z, but the X and Y are not exactly along the x and y, nevertheless they are very close. So, as you can see this is 0.99 this is also 0.99.

So, there is some small component ok, we can also find the natural frequencies and the mode shapes after optimization with the location of the CG below the top plate, ok. Then also you can see that it varies from 51.25 to 33.98 here it was from 51 to 30, ok. So, what is the ratio? 5 by 3, ok.

So, it is like 1.68 or 1.7 that $\boldsymbol{\kappa}$; whereas, if you let the CG fall below then this ratio is smaller we want the ratio to be close to unity as possible, ok. So, initially for table 2.1, $\boldsymbol{\kappa} = 1.7$ whereas, $\boldsymbol{\kappa} = 1.6$, if you let the CG below it, also it is very nice to see that even if you change or allow the CG to go up and down; so, from -18 to -53 ok, meaning what? It need not go down too much below the top platform we can see that the $\boldsymbol{\kappa}$ stabilizes at 1.6 ok, for a large range from about -18 mm to -53 mm.

So, this gives us a freedom to design the Stewart platform based vibration isolator, ok. So, as you reduce Z it is going down then stabilizes and then again it goes up. So, this is in some sense the optimum range or location of the weight or the payload from the top platform minus means it is below.

(Refer Slide Time: 13:50)

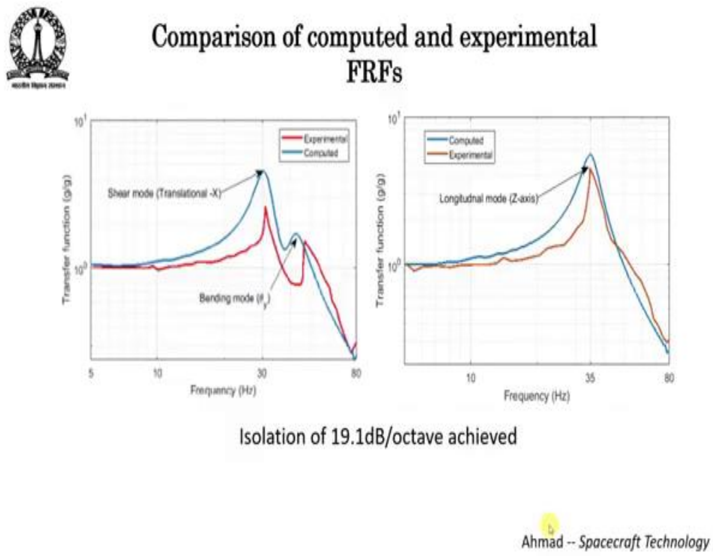


So, we built one Stewart platform. So, as you can see this is the top platform this is the bottom platform we have flexural joints at each ends. So, this is like this flexural joints, which we discussed in the last lecture also these are hinge joints, ok. The stiffness are basically circular plates ok, these are called circular plate springs.

So, in the leg we have some stiffness ok. We also did characterization test so, these are called base fixed modal survey tests, ok. So, what is done a constant acceleration sine sweep input signal of amplitude 0.5 g is used. The test is done in lateral and longitudinal directions a three axis accelerometer is mounted at the center of the top and bottom platform to find the vibration levels.

And the frequency response function is obtained between the top and bottom platform with the acceleration measurement, ok. The magnitude of the cross FRFs were found to be small ok, between the different directions of excitation.

(Refer Slide Time: 15:09)



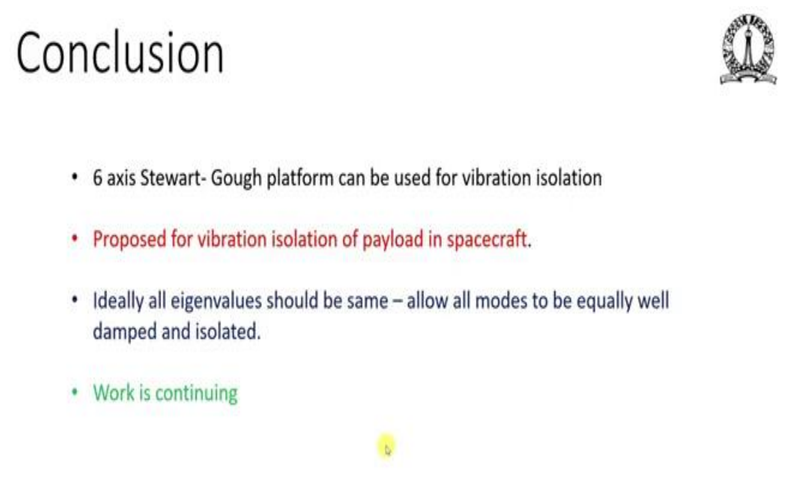
So, here is a plot of the computed and the experimental FRF, which was obtained from that Stewart platform. So, we could compute the Stewart platform because we have a CAD model we can find that the frequency FRF looks like this it will go like this. So, the resonance is around 30 hertz and then it will come down, ok; whereas, the experimental one is the red one, which looks a little bit different, but nevertheless which is of the similar shape.

So, this is at 30 this is little bit after 30 there is a dip and a rise because of another mode in this in the blue one and the similarly, there is a dip and a rise due to another mode in the red one. The longitudinal Z mode translating up and down about the Z-axis the top platform we can again compute the Z mode and also experimentally measure the Z mode.

So, these are the basic modes which you could measure in the current setup, ok. So, the Z mode the peak is a little after 35 and the experimental ones are also very similar. And what you can see is that the slope of this curve this red curve or the blue curve after the resonance is like 19.1 dB per octave, ok.

So, this is a number which tells you how much isolation you have obtained, ok. So, the larger this number the more isolation you have obtained. So, 19.1 is slightly on the lower side we would like to get something like 30 dB per octave ok, as vibration isolation.

(Refer Slide Time: 17:03)



So, in conclusion; I have showed you a 6 axis Stewart- Gough platform that can be used for vibration isolation. So, basically we have a top platform, bottom platform and in between we have these legs and whatever is the vibration, which is happening in the base or the top platform does not get transmitted because we have played around with these parameters of the top platform, bottom platform which are the two radii and the two angles, which are the connection points the height and so on.

So, there are 5 parameters which you can play around and we use an optimization problem to find out those 5 parameters which gave a ratio of the maximum natural frequency to the minimum natural frequency of 1.6, ok. Ideally we would like more ok. So, this kind of vibration isolation systems can be used in spacecraft, ok.

So, you can isolate the payload in spacecraft as I said, ideally all eigen values should be same ok, allows all modes to be equally well damped and isolated. But this is not so for this Stewart platform, which was fabricated and tested. So, this work is continuing and we hope to have different configurations toward platforms which can give a $\boldsymbol{\kappa} = 1$, where all the natural frequencies are very close to each other, ok. So, with this I will stop.

Thank you for listening.