Design for Internet of Things
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Lecture - 14
Energy Harvesting - 02

Before we do the demonstration, you must know the critical component that is used in the harvesting part of the chain. You have an energy source you get vibrations there is a device an energy harvesting source which takes that and gives you some electrical output, and that electrical output is fed to the electronics and the output of the electronics gives you DC voltage, some power with which you can connect your loads.

Most important critical part is also the fact that when you harvest the energy the voltage and the power, basically the voltage is in small ranges - 20 millivolt, 30 millivolt 40 millivolt, 50 100 kind, of very small voltages. No active device IoT device can actually work in that kinds of very extremely low voltages. So, you take these low voltages and boost them to reasonable voltages 1.8 to 3.3 any one of the settings are should be possible.

Then your electronics controller sensors everything will work. So, which is that chip which does that magic of trying to take input low DC voltage and gives you a higher DC voltage is the boost converter. These boost converters that we are referring to are switching regulators they give you very high efficiency. Efficiency can be as high as even 95% and these regulators themselves the DC-DC converters themselves should not consume a lot of current.

Because they are supposed to give you give the power at the output voltage into current is the power. So, if itself consuming current then the output power delivered will be low. So, it should be under extremely low quiescent currents, number one. Number two it should you should be able to configure the output to 1.8 upto 3.3 any one of those settings are possible. Then it should have supply voltage supervisor I mentioned.

Quite like that it should have something called a signal some sort of a signal, which says that the voltage is not all that good and therefore the load should try to go to ultra-low power or should go to some sleep state and so on. So, some feedback should come from the from the electronic power management DC-DC boost converter which will tell the load electronics what it should do based on the status of that signal.

So, that is something that should be there. Next is input is changing all the time output loads are changing all the time. Supposing you have a con SoC, and to that SoC you connect a sensor via the ADC now when you switch on the sensor the ADC, switches on ADC inside the SoC takes current. That means the power consumption of the embedded device goes up. So, that means load current is changing even if the load current changes the output voltage should remain solid rock solid it should not change.

Because voltage has to because several of these devices require a fixed proper voltage, in order to make to in order to function. So, it should have a good load regulation, load regulation means any changes in the output current changes in the load should not affect the output voltage. You can apply the same logic to the other side, line regulation that means at the input even if the input varies up and down which is true for any harvesting device the output should be held at the required voltage.

Then you say it is line regulated. So, line regulation, then load regulation, then the fact that you need a supply voltage supervisor, the quiescent current consumption. These are important parameters that you should look out, for any kind of a energy harvesting systems, IC s which are used for managing power harvested, power from the input to the output.
Let us look at LTC 3588 which is the chip of interest that is the chip.
(Video Starts: 05:21)

Here you can see the specifications 950 nano amperes, input quiescent current not even 1 micro about less than 1 micro. Output in regulation no load of course, it is under no load condition. 450 nano amperes input quiescent current under, what is known as the under-voltage lockout, under voltage lockout condition. If the voltage at the output changes for some reason it issues a signal called a UVLO and then it itself will shut off.

So, that the system will not malfunction under fluctuating output voltages either voltage is there, or the voltage is not there. You cannot have a brown out condition where voltage keeps changing. So, you have a under voltage lockout mode, which is a very important requirement, input can change from 2.7 to 20 volt and the chip can give you 100 milliamperes of current. You can select output voltages 1.8 to 3.6. These are the main things.

And you can see Piezo electromechanical, wireless HVAC, mobile asset, tire pressure sensors, battery replacement, remote switches, standalone nano power, all these are applications for this particular chip, and this is how typically you connect. You see that the Mide V21BL is the Piezo electric harvester, two terminals of that are directly connected to PZ-1 and PZ-2 of this chip.

The energy that is generated from the vibrations is essentially held in this Vin at this point comes to this point Vin which is typically in a few millivolts. That Vin is taken and then an output Vout is generated by using this LTC-3588, and the associated boost converter circuitry which essentially comprise of an output inductor and the corresponding storage capacitor which is 47 microfarads in this case.

Here you get DC which is reasonably good useful for driving the electronics. Now what should be the output 1.8 or 3.6 or anything in between that will be dependent on this output voltage select switch. So, this is the most important requirement. There are some things that you may want to look out in terms of these view graphs. This is regulator start-up profile, when it is doing a cold start.

If these are the values as mentioned in c-storage cout and so on how does the system behave is what he is actually telling us and you can see that Vin is shown Vout is shown and power good is also shown. You can go up to as I said maximum of upto about 20 volts or so. So, these 20 volts is appearing here you can see that this is appearing here and all the voltages down from here are being shown.

Voutput continues to remain beautifully held at that same point. And P good signal is available soon after the output is stable, and the input is sufficiently high then it knows that it can support the output voltage for a significant amount of time. All during this jagged stage P good continue to remain low, only if it finds that it is stable then it will issue a P good signal. Once the P good is issued the electronics can switch on and then start working.

So, that is what this chip is actually doing. Let me show you some important parameters. All the numbers now are I am sure will be very easy for you to understand Vin, Vin quiescent current you can see everything is in nano and when it is buck enabled sleeping it is in micro 1.7 micro buck enable not sleeping is 150 micro. That means if the chip is active, it is actually taking 150 micro amps.

Vin under voltage lock out threshold as I mentioned to you that for different voltages you have different lock out thresholds. As I said this chip can work from 1.8 to 3.6 settable using those pins and for that 1.8, he has given the typical values here, which is max is 4.3 typical is 4 and then minimum is 3.77 and so on. So, all these are nicely indicated here. Now you have to learn to understand these data sheets as much as possible.

Because they are the ones that will tell you give you valuable information on whether this chip is suitable for your application or not. Look at the very first one on the left side. The left side is about load regulation. You see the x-axis is current the y-axis is the output voltage. You are holding this output voltage to a point, and you are saying that irrespective of the current being drawn at the load the voltage is held exactly there except at this point where it dipped a little bit.

But then it stabilized but then we already see that slowly it is deteriorating more and more. This is the kind of region over which you want to work from here to about this point. For sure you want to work till here after this it is ok, up to this point at least or maybe this point here, but after that it is really bad because you really do not you it is not in regulation anymore. So, that the point here.

This is with respect to the load current varying from one extreme a small value to the other extreme which is in the right-side value. Look at the line regulation. Line regulation is saying irrespective of the changes in the input voltage 4, 6, 8, 12, and so on. My output will continue to remain at two points little less than 2.5 and I will try to maintain that as much as possible, and I will try to keep it as straight as possible.

Ideally it should be a straight line, but this is not bad either right it is gone a little above a little bit on the left side it has gone down, and on the right side has gone up if you take this as the reference line. But it is not bad it is not so badly tilted, and he has made this measurement the manufacturer for this setting 100 milliamperes of load current then L value at the output L value is this much.

So, these are some important parameters that you may want to look up and then start using them for in your circuits. Then there is one more important parameter which is related to efficiency. I mentioned that switching regulators are very efficient. Now look at this you have load current going from 1 micro to 100 milliamperes perhaps because that is what the chip can support.

Efficiency is down from starting from 30% going up to about 90%. If you want to maintain very high efficiency obviously your, the load current should be reasonably high which means the harvesting opportunity also should be good. If you are able to draw so much power out from that system, that means input also should be giving you that kind of power. Therefore, under extremely low input power essentially means low load currents efficiencies are poor. Once it goes above a certain range you are maintaining 90% efficiency.

Again, this is with respect to different voltage settings that you have, and the inductor which is set to 10 micro henry efficiencies versus load. See this is how you should be able to connect different points. Similarly, you can look at efficiency with respect to the input voltage it is mentioned here. You can look at efficiency versus input for Vout of a certain value, if you fix the Vout to 3.3 you put an inductor which is 10 micro henry.

How does the efficiency vary? That is also something that you want to study. These charts have to be looked up based on your requirement and your own personal settings and this is very important. Now having got this background on this chip 3588, let us now shift to the demonstration.

(Video Ends: 14:45)

But demo is just a one-minute clip that we can show you. You need a lot of preparatory information before you actually see a demonstration, what I am going to show you is I need to show you vibration energy harvesting, but for that you should know the harvesting opportunity you must know what are all the frequencies that the vibration platform is offering you. For that you need a sensor to do that measurement.

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What I have here is this? You cannot see this well, no problem but I will show you the data sheet of this. This device is called a slam stick and this device that I have in my hand is what I am going to apply on the vibrating platform to characterize the platform and to see what is the harvesting opportunity that is available from the platform. So, let us see what this device is?

(Video Starts: 15:42)

Look at the data sheet. This is referring to from a company called MIDE this is called a slam stick, and the slam stick essentially will let you make a measurement. So, you can see it is a data logger. You can see here it is a data logger and it actually has a triaxial accelerometer and basically what we are using is this slam stick C which is DC response MEMS, it can measure up to 16g from what we see here and it has a sampling rate which is configurable and so on and so forth.

And it is basically a recorder, and it is available in sort of a portable manner it has a battery inside and it has a micro-USB receptacle so that you can connect to a computer and pull out the vibrations from that system. This is the slam stick C of interest, triaxial accelerometer DC response plus minus 16g it can basically use for general purpose testing and low frequency vibration apart from vibration it can also measure the pressure and the temperature.

Now let us look at what do you get from that from that slam stick, what you get is this? On the x-axis you get the time samples, you get the time samples on the-x axis. On the y-axis you get the g-value, you get the g-value. This is a triaxial accelerometer that means there should be x, y and z axis. You can see that z is the most dominant frequency that z-axis is the one that is giving you a lot of vibrations and in fact quite high amplitudes as compared to the x and y.

But this is just a just x-axis is sampled, and y axis is the g, you do not know really what is the frequencies of the associated vibrations which is the most dominating frequency and associated amplitude of that frequency. Therefore, you are forced to do a simple FFT to find out what exactly is happening. So, now you see this is the FFT of that signal what you have is x-axis is frequency y-axis is the acceleration.

So, you can see that these lines are thick the band is thicker here band is thicker here as compared to the others. If you are able to fine tune to a spot frequency, then you can even harvest up to 1.6g and in this case if you are able to fine tune this frequency this particular spot frequency, it can be even more higher. Well, that is all that you can try and improve on great.

So, now you see you started from one point and then you started making measurements and went on to look at all these pictures. Now let us actually go and put this on to a platform.
(Video Ends: 18:55)

And see a live demo of everything that we have been talking of including getting the harvested output giving it to the electronic chip which is the LTC-3588 getting an output from that and then showing you an output voltage. We will restrict our demonstration to open circuit voltage, but you may want to experiment by connecting different loads to see actually what is the power output that you may that you get from that system.
(Video Starts: 19:25)

One last thing which we need to know before we move on is this system related to go back to this data sheet. Now you went you came from here you said that let us say you chose in this particular picture you chose a given spot frequency or you chose some frequency in this range. For this particular frequency you must go back and see supposing you chose in this picture supposing you chose 100 hertz as an example you chose 100 hertz.

So, for these 100 hertz if you look at 100 hertz here you will know what should be the tipping mass that should be applied on the harvester. So, that harvester will start vibrating with this particular that particular frequency and you will continue to get. How much g value? At 100 hertz if you take 100 hertz if you apply 100 hertz you will get 0.2 around 0.2 anywhere between upto about 0.3.

Maybe you may get on a continuous basis you will get 0.3g you know vibrations values which you can use for the higher the g obviously is higher the power output. So, for this particular let us say 100 or 120 that we may want to apply we will again get back for that, you can see the range is not so bad you will get a tipping mass of some value and amplitudes typically are fractional of a g.

You can see here you get 1 otherwise it is by and large a fraction of the g value that you will be getting. And for that fractional value of g value, you will get an open circuit voltage which is ranging from 4.1, 5.9 and so on. And this voltage will now be taken out given to the rectifier, bridge rectifier which is inside and then this is still AC. This is still not giving you it is not usable voltage directly.

This will have to be fed into the rectifier and then you will get some useful DC which ultimately can be used to power the embedded node. Let us turn our attention to actual platform.

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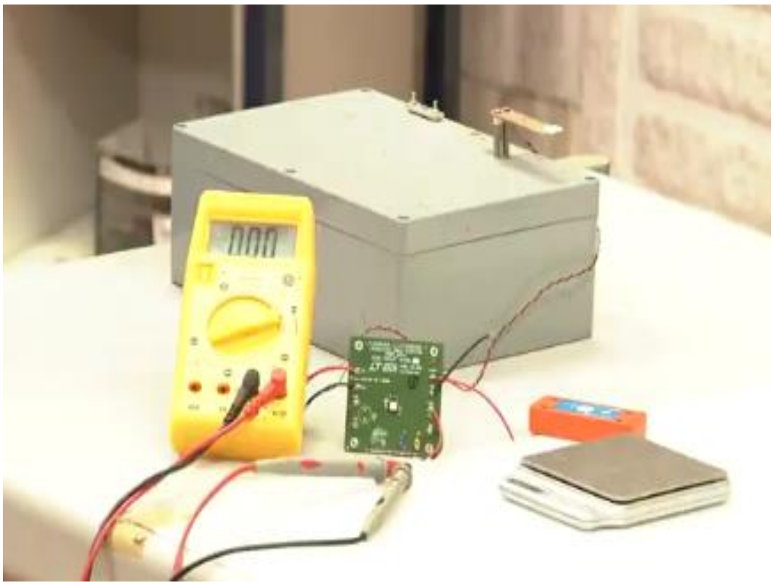

So, first step is Abhishek takes this and applies this to the platform. Here what we have is a platform this platform is the one that is vibrating here. You see this is the vibration energy harvester, which is sort of coupled to this platform when this platform vibrates this the vibration harvester also vibrates. Now you are getting 0 volts here and this is the board of interest, this is the electronics of interest I mentioned to you about 3588, LTC-3588.

We got this chip from there and this you see here is the weight balance and then these are two simple weights that we have. So, let us start the demonstration. We will start this vibrating platform and apply the tipping mass, no first of all I have already shown you that the complete time series with respect to the time samples I have shown you the view graphs. So, we will quickly jump into applying the weights on to the harvesting device.

So, you can see that Abhishek has applied the two weights and now this vibration harvester is tuned to 120 hertz. We said that we will get a fractional of some g value 0.2 or maybe a little more than 0.2 g and that should give you some basically some AC output, which in turn is fed to the controller here and then we should get some DC output. You can see that sound you can hear that sound that it is vibrating, and you will see that the multi meter continues to shows 3.6.

(Video Starts: 23:41)

Demonstration is just one part of it folks absolutely critical for you to do a simulation study first. Take the hold of the data sheet of the vibration harvester that you have located, put it into an electronic circuit simulation like spice, test out your circuit and then build the whole system on the board. Because often you buy components and you do not know it works or not. So, a first cut understanding of how the whole system works is very, very critical.

It is not going to be easy even for you to do simulation. That is the best thing in this course for you actually you can sit back, download models, understand the different components that are there, and I will actually show you something that you will be able to use back in your homes in the comfort of your homes, you can do some energy harvesting based simulations very important.

Whether you are a serious system builder or whatever system the simulation is a must. Let me direct you to a paper that you can actually download and that is related to piezoelectric energy harvesting solutions review. You can actually download this article now and it is a beautiful article, and it tells you something very important which I will direct you to what it says is, it not only provides you the theory it also tells you that you can do SPICE simulation of the energy harvesting source like a vibration harvester.

The authors go on to show a very close model of MIDE V22BL, this is a company which you can find, and you can buy this device MIDE V22BL. They take a very practical case. They talk about the Mide Piezo Electric Device vibrating at 41 hertz. Because you have applied a tip mass of one gram on it and this is the circuit that they are referring to. So, you can see that it is a sine.

So, sine wave source 24 volts and 41 hertz it has a parasitic resistance of roughly 119 k, this is what this MIDE V22BL actually has. Now remember we did not use MIDE V22BL, we use something else. So, we have to you know accordingly substitute those numbers and create our own source number one. Number two you also need to know the parasitic resistance associated with the source.

That is actually not shown here although he mentions here it is 119 k and he replaces with a load resistance where you can measure the AC output voltage here. In our case we do not use r1 but we actually connect it to directly to the electrical circuit which is the LTC-3588 chip which is used for connecting the output of the vibration harvester directly to give you something useful.

Now see how we should translate this into our simulation so that more or less we should get the same output that we saw in our physical demonstration that we did. We used in our circuit V21B, which is a typical thickness of 0.031 inches, and this is the one of interest. So, let us look at some of the dimensions and the electrical parameters associated with V21B. So, to look up the electrical parameters let us go down and look up a specific setting there.

Now if you look at V21B single wafer series capacitance. Look at this Single Wafer Series Capacitance at 100 hertz is 26 nano-farad. This should be part of the model and single wafer series resistance should be 950 ohms. Now if you are talking of the 950-ohm series resistance since we have two wafers which are connected in series you will have 950 into 2 which will give you some value of r.

But the same thing if you look at the series capacitance this will become half because series capacitance will reduce by half. So, you can more or less think of this as a very small value something like 13 nano-farad very small value. You may want to put it for accurate simulations but for this demonstration purpose I may not have included it, but it is important you must put it in the format in the circuit equivalent circuit that I had actually shown you.

So, these are the two parameters. So, now let us shift to demonstration but before we shift to the demonstration let me also run through the electrical circuit that we have here. The chip also is a very interesting thing I provide you something called P good.

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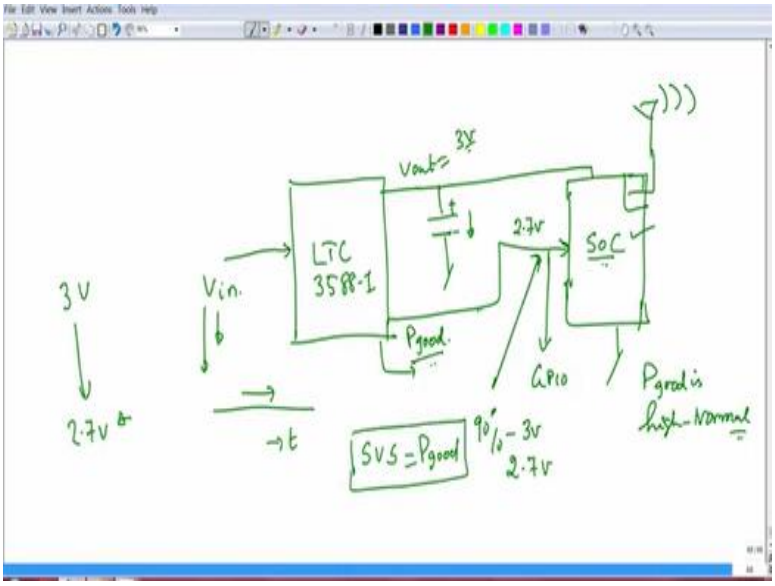

And P good can be continued to be used in a very challenging and very interesting way by the SOC. It can program by saying that as long as P good is high. I will do normal operation, what this simply means is assume that Vin drops for some reason vin drops for some reason but P good continues to be high. This removes it filters out the fact that the Vout will drop drastically.

See typically what they do they take Vout into a capacitor; they use this put this as a capacitor and you are storing energy this is your P good so let me connect it back here this is P good. This is telling this P good signal is telling the SoC do not worry I am insulating you I am insulating you from any changes in Vin dropping but then if Vin drops for a significant amount of time.

If it drops for a significant amount of time the capacitance here the charge on this capacitance also starts falling significantly. This P good is a very clever pin, it says if the fall is 90% of let us say 3 volts, that means it is 2.7 volts. If the output was set to 3 volts 90% of 3 volts is 2.7 volts. P good will go down when it comes to 2.7 volts. Any change from 3 volts to 2.7 it will not down the signal.

In other words, you have a nice way of insulating any changes in Vin up to the point where the Vin drops so significantly that the capacitance starts discharging and the voltage across the capacitance comes down to 90% of the programmed Vout. And I for an example I took 3 and I am explaining this. So, this P good is a very useful pin which you must use. Well, LTC calls it P good, TI calls it supply voltage supervisor SVS.

So, P good and supply voltage supervisors more or less are one and the same. Each company has its own notion of what a good signal is. So, one can use that in an effective way. So, that is about what LTC can do for us.

(Video Starts: 32:07)

So, now let us shift to the simulation study and we will demonstrate the simulation straight away. Now if you look carefully the top one is essentially the energy harvester let us expand it a little bit you will see that we have used in our experimental results this is just working backwards. We have taken a sine wave we are getting AC output of 15 volts, and our frequency is 100 hertz.

Since the data sheet mentioned about series resistance for a single wafer as 950 ohms. We multiplied and put this value there and the tip mass that we have put is also shown there it is about 4.2 grams. So, this is the tip mass, so it is and our piezo harvester is MIDE V21B. So, now that is directly interfaced to the two inputs of the electronic chip. So, let us go down now you can see that it is exactly constructed from whatever is available on LT spice, you can see that P good is.

Now kept open that means we have not connected it to any controller, but the remaining part of the circuit has been constructed based on what you find in the data sheet. So, what you see out is the Vout, we have the same circuit as I showed you 47 micro farad at the output. So, let us do a simulation it is very simple folks you just have to run the simulation and you will get the output there, you have down picture is the circuit up is the output.

Now x0axis is time and y-axis is essentially the voltage that you are getting here. Now you see Vout is shown, and it has now built to some range and let us expand a few things to see what exactly is happening. The simulation is running you can see now that the simulation is running it slowly building up exactly matching the kind of start-up profile that we had shown you earlier.

So, let us see slowly it comes at this frequency for this tipping mass and for this voltage that is generated by the piezo harvester. This is the amount of time it would typically take for you get to get a stable output voltage. Now that from here onwards the voltage has come to 3.3 maybe we can compress it once to show that it is at 3.3 and then we can also expand a small portion of it.

So, let us expand once yes let us take that part. Now that is clear now you can see that P good is in one colour, and the Vout is in the other colour. The blue colour is the P good and the other colour which you see is essentially the Vout. So, folks this is a good demonstration I suppose which will help you to build energy harvesting circuits for IoT nodes. While we showed a demonstration of vibration harvesting you can use the same tool for thermoelectric generation, you can use the same tool for solar energy harvesting and so on and so forth.
(Video Ends: 35:55)

There are some important aspects of the vibration harvester that you should know to use the vibration harvester. We did all that FFT analysis and all that. It is also useful to know the power spectral density of the vibration harvester when you apply it against some surface. You are trying to extract energy so you must also know the power spectral density. So, let me point you to this picture which is right here.
(Video Starts: 36:26)

See this picture this picture tells you the following. What it shows is on the x-axis is frequency it shows frequency on the x-axis and on the y-axis it shows g squared by hertz. This is the unit of power spectral density. So, essentially if you start looking at the different peaks that are available you will see that when the frequency in this picture when the frequency is around the 100-plus hertz, the 100 hertz region and above and these two spots actually give you quite a good amount of energy.

So, the power that is available here is perhaps the highest. So, this is one way to see how to tune the vibration harvester. Let me point you to a proper definition of power spectral density this is basically used to characterize random vibration signals you have seen that on the x-axis you found that the frequency many several frequencies are available and these are all having different amplitudes.

So, random vibrations signals are there these are PSD is basically used to characterize these random vibration signals. The PSD is computed basically by multiplying each frequency band by taking the FFT by its complex conjugate which results in the real only spectrum of amplitude in g squared you only take the real part then you get the amplitude. That is essentially the g squared actually it is not g 2 this is g squared.

The key aspect of PSD which makes it useful this is important, for random vibration analysis is that this amplitude value is then normalized to the frequency band basically the bandwidth to get the g squared by hertz this exactly what we saw there. By normalizing the result, we reduce the dependency on the number of samples in the original acquisition. So, that is the key point.

The area under the curve in a PSD represents the RMS vibration energy in that frequency range. This area can be calculated precisely by exporting the PSD into a CSV file summing the data in the desired frequency range and multiplying the frequency bandwidth by the frequency bandwidth or the space between adjacent frequencies. So, this is a formal way of understanding PSD essentially.

So, now let us go back and see one particular practical case to completely get the story right is in it. So, let us look at this picture. You have already seen this experiment. So, let us same experiment what we did was we took this vibration harvester and placed it inside an automobile. So, this basically is the story of how we can use the vibration harvesting in an automobile to let us say power a led to power up an led for some reason you want to power up that is the kind of load that we are looking at.

So, same harvester V21B piezo transducer and then some tipping mass that you can see here. This tipping mass calculation is very important. I will come to that in a second, so this is essentially for arresting on this plate and this is basically the tipping mass. This is a one-gram tipping mass. Basically, you are asked to calculate the tipping mass, but before you come to calculation of tipping mass you let us see a few pictures.

We will come to that subsequently what we did was we applied this slam stick inside a engine, place it in different parts of a car. And this is basically the slam stick which was applied placed inside the in the car engine side and we got this. What did we get? We get the PSD now which is g squared by hertz. You see that it gives you a g square PSD of 16 when you place it in the engine part and that is clearly indicated here.

And you also see that the frequency is typically around 77 hertz, you get the maximum say peak at around the 77 hertz. You can see that this is 76 this is 78 so this must be around the 77 hertz. These are different axis will not worry about the axis only one axis is giving the highest peak here. Then we moved it to placed it on a battery when we placed it on the battery, top of the battery, we did not get too much we got we got 0.3 g squared by hertz you can see that is indicated here with this peak and other axis components are almost 0.

Again, here x-axis is frequency y-axis is g squared by hertz. Then the third one is the same thing slam stick was placed in the trunk and you got something else this is that picture. And you place it on an air filter you got some other picture so you can go on like this. Different points you place the slam stick to see where the opportunity I s available and from there you will be able to tap the maximum amount of vibrations.

And how do you calculate this tipping mass? That is another question. The tipping mass calculation is quite straight forward. You have a very simple expression for calculating the tipping mass and that essentially is given by this.

(Video Ends: 42:29)

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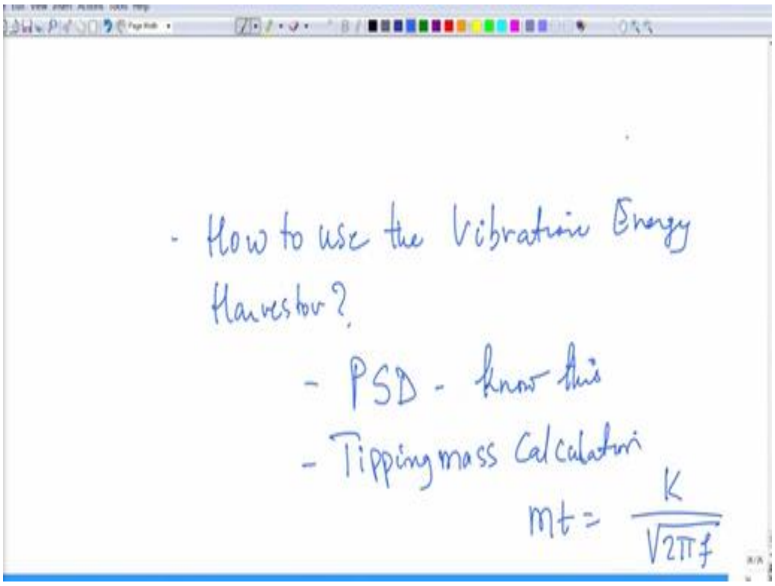

mt is equal to k divided by square root of 2 pi f, where k is the stiffness constant. That is the simple expression.

(Video Starts: 42:40)

There so let us go back. And of course, you can do all the LTC simulations and so on and you will realize that you can actually drive a led you can see that it is on here. Of course, it will not be continuously on because you are harvesting for a given frequency.

(Video Ends: 43:00)

And that is only harvesting opportunity that is available to you although there are range of frequencies you could tune the harvester to a given point and that frequency that you are able to extract energy and store it into a capacitor and then boost convert it using LTC-3588 and then take the output voltage and drive the load. So, it is not going to be continuous. But if you manage the power well then you can store that energy and maybe switch on the led for extended period of time.

Those are aspects related to power management, which we can cover subsequently. So, what is the summary? Summary is that you must keep this harvesting opportunity source which is nothing but the slam stake at different points wherever you want to extract. Analyse the FFT, analyse the PSD tune the vibration harvester to a spot frequency, to a frequency where you can extract maximum and then start harvesting from that frequency onwards.

If you want to really have an embedded system which is giving you energy all the time, then you may not be able to manage with one you may have to put many harvesters each one tuned for different frequencies. And then you harvest from that range of frequencies and then store it into the same storage buffer like a capacitor a super capacitor and then drive the embedded system.

So, that is all future work but this is just giving you an idea on how you can practically use the harvesting device and extract the maximum energy from that system.

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Here is a summary which I wanted to show you. It is not that you can harvest everything you have to do the frequency analysis understand which is the frequency at which you are getting the maximum, tune the harvester to that particular spot frequency and then extract energy from there. This is the full story of the vibration harvesting steps and this is the process. Thank you very much.

(Video Ends: 45:00)