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Resonance Acoustic Concentration of Suspended Particles for Optical Discrimination of Aerosols

GREGORY KADUCHAK AND DIPEN N. SINHA
LOS ALAMOS NATIONAL LABORATORY

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ABSTRACT

Acoustic concentration of aerosols has received much attention over the past several decades. Typical concentration devices rely on acoustic levitation techniques to localize particles near the nodal planes of an acoustic standing wave. The standing wave field is typically very dependent upon spatial alignment of the system components and often requires moderate to high input drive power levels. The present research describes an extremely simple acoustic levitation device for use in optical discrimination of aerosols in air. It is constructed from a hollow, cylindrical piezoelectric which has been slightly modified to increase the amplitude of the radial surface displacements. An acoustic standing wave is created on the interior cavity of the shell where particle concentration takes place at the nodal planes of the field. This levitation device is extremely useful since it requires no alignment, power consumption is small (< 1 Watt), and hollow PZT cylinders are commercial-off-the-shelf items.

TRANSCRIPT

DR. KADUCHAK: A few weeks ago, when we got the first agendas out, I was sitting in a pretty nice position, speaking a bit earlier in the afternoon, but a little bit of shuffling went on, a little bit of jockeying, the dust cleared, and here I am. I figured I would kind of take this to my advantage. I started thinking I am at the end, it is two long days, you look out in the audience, what are you going to see? Probably glassy eyes and a lot of coffee and things like that.

I figured probably the best thing to do is actually make a talk that is simple, colorful, no equations, just something that is fun, just some fun physics and some fun things to look at it, and that is really what this is about.

[Transparency]

First we will start with the motivation. Unfortunately, if you look at the first thing on here, it is not really that fun a topic. The application for what we are doing is we are actually looking at biological and chemical aerosol detection.

In light of the recent political events and just the current activities in the world, this is actually a very serious question, and I will probably spend one or two transparencies on this, then we will just jump out of that and go to the applications, where the actual neat stuff is coming out.

The "what" is low power -- I am going to have it underlined here, because this is what we are really after, acoustic concentrator. We are going to use an acoustic resonator to give us some type of particle positioning inside a chamber.

It is going to be extremely low power, much lower power than I have actually ever seen done, and we will give reasons as to why this is necessary. The main point, as I said, is this is going to be simple, there is a very simple main point to get out of this.

We are going to get a low-cost, low-power, off-the-shelf acoustic levitator, acoustic concentrator, et cetera. We are going to give you the ability to concentrate and levitate drops, et cetera, for about a hundred bucks, no alignment, no nothing, very simple.

[Transparency]

The actual application we are looking at is a rapid early-detection system. You have some kind of biological release. Unfortunately, they do not look like this, because then we would not need a detection system, but you have something released over the horizon, it is coming, you are over here, you want something between the release and yourself. You want something to tell you, hey, something is coming, you need to go through counter measures, you need to stop this thing, you need to take cover, one of the above.

If you think of typical systems, for example, one of the typical systems today is what do you do when you sample the air. You take a large sample, take the particles out, the aerosols, et cetera, put it in solution and do a mass spec on this. It is very time-consuming, very cost-consuming.

In the battlefield it is probably a feasible thing that you could do. You could have somebody taking samples continuously, doing mass spec, et cetera, but in situations, say, like federal buildings, things along these lines, if you are looking in the future, this really is not a feasible system.

What we are working on is a trigger system. It is not going to classify what is coming at us, it is going to say, hey, it is time to start looking, it is time to open up all the bags or to start looking in other directions, or start doing these types of time-consuming events.

[Transparency]

I do not really want to dwell too long on this one. This is a project that brings several divisions of Los Alamos together. Obviously the life sciences people are going to be looking at the biological particles and how these things interact, what types of things we can see. There is us. We are going to be doing an acoustics part on here. There are people doing the laser work and the optical classification.

The actual device that we are looking at, the sizing, or the actual classification of the particles or detection is going to be done optically. Here is a cartoon of a laser cavity. For the device that we are looking at it is going to have a UV intercavity laser. We are going to be sending particles or aerosols straight down through the laser cavity.

Through there we are going to look at the light scattering. You are going to get sizing information. Typical biological particles range anywhere from 1 to 2 to 3 microns, so you start rejecting dust and things like that just from those lines.

When you start looking at scattering intensities, if you look relative to the forward direction at the intensity of 135° to the intensity of 90° coming off of these particles you can actually see that there is a separation due to the indices of refraction of these things. Here is typical dust -- this is a silica -- and these are some typical spores that you see, so we have separation there.

Another way of trying to detect these things is from fluorescence. With the UV excitation of these things, there is a group of __________ acids and proteins that fluoresce in the 200-400-nm range. Typical biotoxins are typically proteins, so we have that working for us in that direction.

Typical viable cells, or live cells, or cells that have been living at one time have things contained within the fluorescent to visible, so there is another piece of information that you can throw in and start separating things out. This is really how the optical discrimination is going to start looking at things, telling you what is about to happen or telling you that you do have an aerosol in the air.

[Transparency]

This is a cartoon of the apparatus. As I said before, you are going to have some kind of laser cavity, it is going to do some type of sorting by refractive index, sizing, fluorescence, several things like that.

What we are going to do, we are going to try to concentrate the particles before they enter the laser cavity. You might ask why, and it is this second bullet down here. Typically, in an aerosol release, you are looking at about one bioagent particle per liter of air.

You are looking at driving air through a very small cavity. The quantity of air it would take to get just one bioparticle, or the flows that you need to get good statistics on these particles you cannot blow through there.

What we are working on right is trying to acoustically concentrate these particles and actually have the air flowing into some device, concentrate the particles to one region of that chamber, run only that portion of particles through the laser cavity, and then all the extra air can go out, so now we can start getting flow rates where we can start getting sizable statistics with these bioparticles.

That is where the low power comes in. The vision for this type of device, when you start thinking about it, is a smoke detector for biological agents. You need something lightweight, you need something portable, and you need something battery-operated, hopefully, in the end, something that you can put in the air-duct systems of a federal building, for instance.

[Transparency]

Now we can put all that stuff aside and just talk about what we have done here. This is our first prototype concentrator here, or resonator. It is a simple piece of PZT. I believe it is a 5400, 3/4" diameter, 3/4" length. Notice we have gone through no pain in mounting this thing. You have typical pins here, you do not want to interrupt any moments, or anything, but we just threw in a typical ring stand and we are just holding it there.

[Transparency]

If you plot what the cavity should look like, these are plots for the n = 3 axisymmetric mode of cavity, where we have 3 nodal lines for the pressure going out from the center. Here is the center of the cavity, with the exterior cavities here. This is the absolute value of the pressure within the cavity and you can see we have 3 dark blue lines here that correspond to the pressure nodes of the resonant field within the cavity.

If you look at the force, positive numbers here correspond to forces going outward radially. Negative numbers are forces coming in. If you really look at this, you end up with 3 stable equilibrium positions within the cavity. They form 3 concentric rings that correspond to the pressure nodes of the cavity.

This is all well and good, levitation, concentration -- I dare not even guess how long that has been around. If you were to just drive it at this frequency, the odds are you are going to get nothing. I know we cannot, we cannot just drive it at some radium over the cavity and actually be able to concentrate or levitate particles.

[Transparency]

The kicker, or the simple physics, or the thing that, in hindsight, looks really simple is if you look at the electrical impedance of the cylinder that I just showed you (and this especially we picked out), the breathing-mode resonance is here, 66.7 kHz. What you have to do is match that resonance to the resonance in the cavity. Once you do that, then we can start coupling energy in the cavity in accomplishing this feat.

[Transparency]

Here it is. Here is this thing, a little 3/4", $100.00, non-alignable, perfectly aligned cavity resonator. We have 2 drops levitated.

[Transparency]

If you go back to this plot right here, gravity is playing a role in this, going in a downward direction. Here are your 3 stable equilibrium positions, here are your lowest potential energy places.

[Transparency]

This corresponds to a drop at the bottom of the center ring and here is the middle ring right here. If you look at the drop diameter, it is a little less than a meter. Gravitational force they were counteracting is about 1.59 dynes and the drive power is a minimum of 115 mW.

For typical resonators or concentrators you are talking at least watts, possibly 10 W or one or two orders of magnitude below that, and we do not even have to align the thing. The drive level on this is about 1.9 V to do this, so this is extremely efficient.

There are actually 3 drops levitating in the chamber. Due to anti-symmetries and stuff, when we get water in the machine, we can levitate as many as 6 drops from those different positions.

[Transparency]

Now, the thing to wake you up is the video. We have this resonator going -- I am going to explain the video before I show it and you will get a lot more out of it -- we have the cylinder, and we have modified this cylinder, we have put a crack in it. The question is, why is that?

If we put a drop of water down here, we have the pumping action of the crack, it is sucking water in and pumping it out. In the outward pump we are atomizing that into an aerosol. What you are going to see in the video is an aerosol being pumped up to the cavity and out of the cavity and that is what we are going to be trying to concentrate or show that we can get concentration going on with this.

The photography is going to be a simple Schlieren setup, so we are going to be taking something low contrast and making it high contrast. It is going to be a simple thing with mirrors, camera, light source, et cetera.

DR. SMITH: Will the fluid be flowing into the cylinder from the crack or being held in the cylinder?

DR. KADUCHAK: Both. It is going to be symmetric about the pump point.

DR. SMITH: And where is the fluid going to come from?

DR. KADUCHAK: We put a drop in the bottom of the cavity. [The video is shown]

What you can see here, here are the mounting brackets. We have the cylinder right here, it is the same one you see in the pictures. We have 3 nodal lines. You can see one out here toward the center. We have the middle one and then we have the center one. You can see these 2 here, that is where the actual aerosol is agglomerating, falling down to the lowest energy position and we are levitating drops there.

As you see, this is a drive voltage of about 2 V on here. If you look at the transient time, this is real time that you are seeing. Just as soon as the aerosol is pumping up into the cavity we are concentrating to the nodes. As you were asking, this is the pump action coming out of the bottom of the crack, and then we have the pump action going up to the top.

You will see occasionally these things will get too big, fall out, and then they will be re-emitted back into the cavity. The frequency is a little bit over 66 kHz.

[Transparency]

One question that should be really bothering you at the moment is temperature. What we have done is we have taken this crystal and we have matched its resonance to some cavity resonance at some temperature. If we change the temperature, both frequencies are going to change, both of the cavity due to the change of the sound speed in air and the crystal itself.

So we devised a little experiment. We popped the crystal in an oven. We are going to measure the voltage and currents across the crystal. We have taken a standard sample. We are going to levitate that sample, start dropping the voltage and wait for this thing to fall out and then say that is the minimum voltage or power required to levitate that sample at a certain position and record that as a function of temperature.

[Transparency]

If you plot these things out, it is not quite as wide as we want to go, but you see pretty well over 30° C we are driving these things -- this is a 2.5 dyne sample (I do not know the exact number, it is tens of milligrams) -- under 200 mW, which is extremely efficient for a device like this.

As you can see, as we change the temperature, we actually do have to change the driving frequency for the crystal to be able to do this, as you would expect.

[Transparency]

Finally, what are we working on right now? I do not have any results from this for the moment, but I will just give you the spiel on it. Okay, everything was fine and dandy, we got 3 rings, we got low power -- that was the big thing -- so we have accomplished a lot already.

The question is, now that you have 3 rings, how do you get the stuff into a laser cavity? We want something, possibly axially. From the 3 rings right now you can envision you are going to have to come up with some type of flow tubing or something to channel things into the cavity and filter what is flowing through that tube.

One thing that we are working on to try to alleviate that is if we can get an axial node or drive things to the axis of this cylinder and match it up this way. There is only one mode for the cylindrical cavity where we do this, and that is the M = 1 mode; that would be to say that where we have 2 halves of the cylinder going out of phase.

If you look at the time-averaged force for that, you do have a restoring force to the center all 360° around the axis. This is the only mode you can do it in. Currently we are working on getting crystals to match up with this mode.

[Transparency]

In summary, as I said, we are going to keep it simple. You can make a low-powered, low-cost, off-the-shelf, air-coupled acoustic levitation device from a simple PZT cylindrical resonator for about a hundred bucks.

Thank you.

DR. GAITAN: What is the actual dependence of the 3 ring modes? What is the dependence of the sound field? Are these cylindrical in shape?

DR. KADUCHAK: They are cylindrical in shape, it is a Bessel function, it is symmetric.

DR. GAITAN: Bessel function radially?

DR. KADUCHAK: Radially, correct.

DR. SMITH: And they are constant?

DR. KADUCHAK: We do see effects from the end, we do have a restoring force back toward the center.

DR. SMITH: _________

DR. KADUCHAK: Right, there is a stable position. If you look halfway down the diameter of the cylinder, that is the stable position in the axial direction.

DR. LEVY: You concentrate a bubble right in the center of a cylinder. Is it different, water from air, and that is why you are having difficulty getting it --

DR. KADUCHAK: One thing is the huge impedance mismatch between water and air. It is extremely hard to couple energy into the air medium. That would probably be the most basic thing that you are looking at. The other thing is the power limitations to do that.

DR. LEVY: You need a lot more power to just get the axial mode as opposed to the 3 modes?

DR. KADUCHAK: It depends. It is almost a different problem with what you want to drive. Yes, I am not sure exactly how to go on the axial modes in water versus these 3 modes in air. The reason why we are able to do this is we take advantage of the focusing effect of the cylindrical cavity to give us those rings.

DR. LEVY: I remember _________ giving us demonstrations where he would smoke a cigar and then put some sound waves on it and the whole thing would drop down. That is not what you want to do. You can coalesce smoke from --

DR. KADUCHAK: Right, yes. The particle concentrations we are looking at are very low. As far as something like that, I do not think that is a problem.

DR. ISAAK: In your demonstration, what kind of aerosol were you using and how did you create the aerosol?

DR. KADUCHAK: It was water.

[Transparency]

As I showed, the cylinder itself, if you look at the bottom of the cylinder, we had a crack going axially down it and it served as a pump, so we put a drop of water right in the bottom of the cylinder and the pumping action sucked it in and then it atomized it and popped it out. It was the vibration of the cylinder itself that gave us the aerosol.

Thank you.