Lappeenranta University of Technology
School of Energy system
Electrical engineering
Master's Program in Electrical Engineering

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High-power ultrasonic enhanced de-watering (HUED)

Examiners: Professor Pertti Silventoinen
Professor Aki Mikkola

Supervisors: D.Sc. (Tech), R Scott Semken

“Unconditional, Unlimited, Pure love is the highest frequency in the Universe!”
— Gunjan Bugde

ABSTRACT

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Continual improvement to the worldwide standard of living has led to an extraordinary and rapid increase in the levels of sludge being produced in several industrial sectors. How these sludge materials are managed or disposed of affects both the environment and industry balance sheets. In addition, environmental standards that are increasingly more restrictive are making the treatment and disposal of wastewater sludge more and more expensive for municipal treatment plants. With total solids contents typically below 15%, municipal and industrial sludges are mostly water. Economically removing as much water as possible from these sludges makes their disposition both easier and less expensive. This thesis describes work that explores the potential of enhancing traditional sludge dewatering processes by applying high-power ultrasound or a combination of ultrasound and electrokinetics.

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Arup Ratan Dey
Lappeenranta 30.09.2019

Dedicated to my parents

ABSTRACT

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LIST OF SYMBOLS AND ABBREVIATIONS

f_{dr}	Driving Frequency
f_r	Resonance frequency
i	Initial
G	Conductance
B	Susceptance
$\omega_\circ$	mechanical resonance
C	Capacitance
L	Inductance
R	Resistance
VS	Volatile Solid
BNR	Biological Nutrient removal
WAS	Waste Activated Sludge
DAQ	Data acquisition
HUED	High-powered Ultrasonic Enhanced Dewatering
TSC	Total solid content
GAO	General Accounting Office
ACL	Access Control List
EPA	Environmental Protection Agency
WWTP	Wastewater Treatment Plant
SEM	Scanning Electron Microscope
DDcod	Degree of Disintegration
E. coli	Escherichia coli
PSP	Primary sludge particulates
SSA	Sewage sludge ashes
FET	Field effecting transistor
CCD	Central Composite Design

1. SLUDGE DISPOSAL ISSUES AND A POSSIBLE SOLUTION

Sludge is composed of organic and inorganic materials with a huge fixate of plant nutrients, a small number of different trace elements, organic chemicals, and pathogens. One of the extensive sources of sludge is considered sludges from the wastewater plant and the solids from the septage. Waste from human, residential, industrial, hospital, run-off streets, and farmland are the sources of sludge. The countries around the Baltic Sea annually generated 3.5 million tons of dry solids, which expected to increase to 4 million tons by 2020. The sludge is highly classified for use as a fertilizer, because of the inorganic chemicals in the sludge, which can be very dangerous for the human body. [1]

1.1 The importance of sludge management in keeping the environment and human health safe

Sludge contains many pathogens, radioactive contaminants, and heavy metals that are dangerous for human health. The US General Accounting Office (GAO) reported that this radioactive contamination of sewage needed to be controlled. E.P.A and US Department of Agriculture research on risk assessment has found a person, an animal, or plant that is highly and chronically in the worst situation due to sludge pollutants. Reduction of landing degradation causes five to seven million hectares of fertile land is being lost every year worldwide. [2]

Landfilling of sludge is the most cost-effective sludge disposal method. Landfilling sludge's contains heavy metal and chemical substance, which can leach into the soil and ecosystem, food contaminants and water. The wastewater industry has limited control of the volume of sludge produced, but it is clear sludge is not going anywhere.

Continual population growth for the next 50 years with an increasing infrastructure growth sludge management become a big challenge for the UK. According to UK water report, 80.3% sludge of UK after recycling going to the land and 18% of dispose with the thermal destruction method. Around 0.7% of sludge directly disposed to landfill without any filtration. [3]

1.2 Reducing weight and volume, reducing disposal costs, and mitigating environmental and health issues by dewatering sludge

Separating liquid and solid contents from sludge for waste minimization is known sludge dewatering. Sludge dewatering is necessary to keep the environment safe and increase cost efficiency in sludge disposal. Sludge management creates potential savings of economic resources destined for public health, especially to treat waterborne diseases also reduction of chemical use of fertilizer for crop production. Public and private sectors need to dispose of sludge in a manner that approved by regulatory agency. In many wastewater treatments plants, sludge management systems are not available. Sludge is just air dried, disposed of or discharged without any treatment, which is harmful to the human body, plant, air, and soil.

Today, energy production from dried becomes a common interest in many countries. London is an ideal example of producing energy from sewage sludge as a renewable and environment friendly source of energy. Because of having the economic and environmental benefit of energy production from sludge is becoming an identical source of energy production.

Wastewater treatment plant transports sludge in different places to dumb under the ground or land spreading which have legal restriction and causing excessive cost of transportation. According to EPA (American Environmental Protection Agency) WWTP send 40-60% of spend their total budget on handling sludge. [4]

According to [5] coagulation chemicals used to enhance the efficiency flocculants aids. Chemicals such as iron or aluminum salts is added to reduce the consumption of them sludge dewatering. Various research project is going on for developing the dewatering techniques avoiding chemicals, however improving the mechanical and electrical operation. Dry solid content is around 19% and 30% after applying dewatering techniques. Using different techniques for dewatering this percentage of dry solid content is possible to raise to 40%. Considering the chamber filter press technology can provide higher solid content by conditioning with lime. Two another most popular dewatering method is centrifuge and belt filter press used for dewatering municipal waste due to their efficient operation and cheaper option.

1.2.1 **Parameters influences dewatering**

Different types of parameters influence sludge dewatering to make the dewatering process easier.

Concentration (g/l)

The concentration of sludge measured in (g/l). The concentration of sludge is in cooperation with the flocculent. Mixing sludge in a viscous solution of flocculent will be harder if the concentration of sludge is higher. To make the mixing process easier, post-dilution of flocculent, injecting the flocculent upstream, multiple injections of the flocculent, use an online mixer used. [6]

The organic matter content (%)

Percentage of Volatile solid content (VS) in sludge is the organic matter content. Sludge containing higher organic matter content is more difficult to dewater. As a result, the dryness of sludge will be minimum same as mechanical properties. On the other hand, flocculent consumption will be high. Thickening step is done when the VS is higher in the sludge. [6]

The colloidal nature of the sludge

Colloidal nature of sludge makes dewatering of sludge more difficult. Higher colloidal nature of sludge is more difficult to dewater. Four factors will affect the colloidal nature of sludge. [6]

- The origin of sludge

- The freshness of sludge: Freshness of sludge of is measured by colloidal nature of the sludge, which increases with the level of fermentation.

- The origin of wastewater: Sludge coming from dairy and brewery helps to increase the colloidal nature of sludge.
- The sludge returns: Because of the failure of the control system by sludge management sludge coming from that system increases colloidal nature.

1.3 Dewatering enhancement using a combination of high-power Ultrasound and Electrokinetics

The main idea of this thesis is to enhanced sludge dewatering using frequency control high-power ultrasonic transducer with electrokinetics. Modifying a conventional dewatering process by developing new technologies to decrease energy needs, increase yields also improve dryness.

The ultrasonic transducer is a generator, which creates higher frequency vibration from the source of energy. From the three main types of transducer of we have used piezoelectric transducer for dewatering.

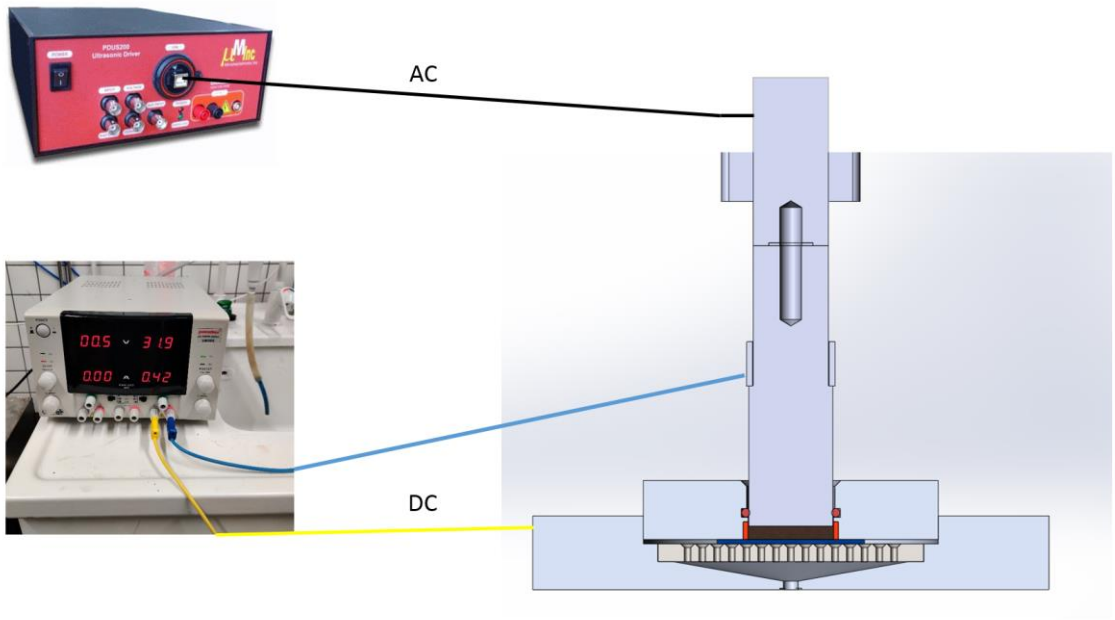


Fig 1: The combination of Ultrasonic and electrokinetics

To enhance the dewatering technology, we have designed a system that combines ultrasonic with electrokinetics. See figure 1. In our designed system, we will apply ultrasonic and electrokinetics at the same time. Different range of transducer will be operated here for certain period with the electrokinetics. Later we will compare the result which transducer provided better dewatering result. The transducer will be running at the resonance frequency by a power amplifier. DC source will relate to the ultrasonic system for electrokinetics. To minimize energy expenditure basic theories of dewatering and drying related methods are discussed. To introduce ultrasonic transducer theories and types of different transducer also their effectiveness in drying and dewatering are discussed.

1.4 An experiment plan designed to answer seven questions about the commercial practicality of Ultrasound- and Electrokinetics-enhanced dewatering.

In our thesis, we will answer seven question to determine the practicality of our designed dewatering system. The seven question are given below:

- Is it possible to dramatically enhance dewatering by adding ultrasound and/or electrokinetics?
- Can this method of enhanced dewatering be practically applied and scaled up to industrial sizes?
- How dry will the sludge be after applying this enhanced dewatering approach?
- What is the estimated cost per kg per %TS of this enhanced dewatering?
- What would be the estimated relative cost of an enhanced dewatering system?
- Which option will be more efficient using transducer in before dewatering, during dewatering or after dewatering?
- What is the percentage of dryness of different types of sludge after experiment?

1.5 The structural roadmap of the thesis

Section 1 contains a short description of the thesis. This section contains information about sludge, parameters that effect in sludge dewatering with the achievement and goals of this thesis. Different types of technologies are used in dewatering and most popular technologies are being discussed in section 2. In subsection, various types of the transducer that have been used in dewatering are discussed. Section 3 is about the control system for the ultrasonic transducer. Traditional control system with the control system we have chosen for our experiment with reason is available in subsections. Phase-locked loop control system is used in our experiment and what is the working principle of every section of the control system is discussed here. Designing of that control system and the equipment is used to run the control system with all related information is being discussed in section 4. Section 5 and 6 is about the whole setup of the experiment and result we have got in our experiment. Lastly, in summary is brief about the outcome of this thesis and future improvement.

2 SLUDGE TYPES, CONVENTIONAL DEWATERING, AND THE WORKING PRINCIPLES OF ULTRASOUND- AND ELECTROKINETICS-ENHANCED DEWATERING

2.1 Six sludge types

2.1.1 Wastewater sludge

The source of the primary sludge is the primary treatment process results in suspended solids and organics that can't be solved with the water. This type of sludge has a huge percentage of organic matters, like faces, vegetables, fruits, textiles, paper, etc. with 93% and 97% of water behaves like a thick fluid. Dewatering ability of primary sludge is excellent because it has very low level of solid content, which is 55% to 60%. [7]
Escherichia coli (E. coli) was investigated in primary sludge particulates (PSP) according to [8]. Primary sludge is regularly coming from household waste and toilets which is collected from the primary sedimentation tanks. [9] According to [10] in cropland, strip mines and public parks in some areas in united states processed primary sludge is widely used. Sludge's from organic source increase the primary sludge (PS) disinfection.

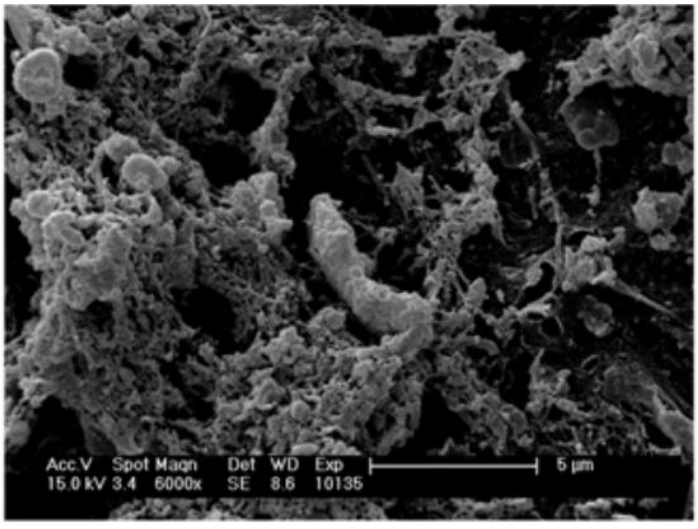


Fig 2: Ultrasonic disinfection of E. coli-PSP complex for 35 minutes [11]

According to [11] E. coli presented in PSP protected from ultrasonic disinfection while the unentrapped cells were not, which is presented in figure 2. Using the energy of the ultrasonic disinfection protection of unentrapped cells can be minimized. From their research, they

found that the ultra-sonication (20 kHz) can overcome the entrapping PSP. In addition to by competing disinfection of entrapped E. coli complex has been completely shattered.

2.1.2 **Biological sludge**

The mixture of the microorganism from the biological treatment plant is known as the biological sludge. Different types of microorganisms are available in biological sludge such as bacteria, amalgamate in bacterial flocs through the synthesis of exopolymer. This microorganism can separate very easily from the sludge by simple decantation. [6]

Parameters	Biological sludge
pH	6.9
EC (electrical conductivity) (μS/cm)	7.2
TS (%)	1.51
OM (%)	53.40
SS (%)	9600
VSS (%)	7170
TN in sludge's supernatant (mg/L)	40
TP in sludge's supernatant (mg/L)	64
Capillary suction time (s)	49.8
Particle size (μm)	
Surface weighted mean D [3,2]	21.32
Volume weighted mean D [4,3]	67.21
d (0.1)	12.87
d (0.5)	52.01
d (0.9)	144.3

Table 1: Characteristics of biological sludge [12]

From research [13] found that an extensive volume of biological sludge originate from the plant where the wastewater being treated, which contains such parameters presented in Table 1. To minimize the consumption of organic pollutants of wastewater and concomitant microbial growth biological wastewater treatment process is being used. The excessive amount of sludge needs to be disposed of in a feasible way and which brings a serious

problem. To solve this problem the excessive sludge is mainly used in soil application, landfill, combustion and ocean dumping which cost 50% of totals cost of the wastewater treatment plant. Bio sludge contains microorganism, organic and inorganic. In microorganism there are macromolecules compounds such as polysaccharide, protein cellulose, lipid acids, esters etc. [14] According to [15] to prepare bio flocculants this excessive biological can be used. From their research, they found that from biological sludge 99.5% for 4 g/L kaolin clay can be acquired with a bio flocculants concentration of 3.0% (v/v) at pH 10.5. Here the main component is polysaccharide found from the analysis.
Biological sludge has different properties such as

- Extensive volatile solid content (VS is 70% to 80%)
- Less dry solid content (7 g/l to 10 g/l) mostly needed to use step by gravity belt dynamic thickening
- Medium dewatering ability (Higher the solid content harder to separate water from the sludge).

2.1.3 **Mixed sludge**

Combination of primary and biological sludge results mixed sludge. Waste activated sludge is produced from the system of biological nutrient removal and activated sludge which contains high nitrogen and phosphorus. Series of steps are being used to dewater the sludge such as anaerobic and anoxic sludge tanks, sludge holding tank, centrifuge, and belt filter press or dewatering tanks which are then dried and disposed.

Metal contents (mg/kg, dry basis)	Range	Median
Arsenic	1.1–230	10
Cadmium	1–3410	10
Chromium	10–99 000	500
Copper	84–17 000	800
Lead	13–26 000	500
Mercury	0.6–56	6
Molybdenum	0.1–214	4
Nickel	2–5300	80
Selenium	1.7–17.2	5
Zinc	101–49 000	1700
Iron	1000–154 000	17 000
Cobalt	11.3–2490	30
Tin	2.6–329	14
Manganese	32–9870	260

Table 2: Metal content in municipal sludge [16]

Mixed sludge contains several metal contents like as presented in Table 2. Sludge is mixed to increase the efficiency of the sludge dewatering process. Mixed sludge always required conditional chemicals contaminants which play big role in thickening or dewatering because mixed sludge behaves like secondary sludge. The conditioning amount depends on the equipment used and the percentage of primary versus secondary sludge. [17]
Mixing ratio of sludge is often as follows:

- Mixed sludge contains primary sludge around 35% to 45%
- Biological sludge percentage in mixed sludge 65% to 55%

2.1.4 **Digested sludge**

After biological stabilization sludges comes is known as digested sludge. Digested sludge from sewage is just dumped on land or sea which added more cost for transportation to remove it.

Properties of digested sludge:

- Less Volatile Solids content is around 50%. During digestion, mineralization occurs.
- Around 20 g/l to 40 g/l dry solid material in digested sludge.
- Dewater ability is much better compared to others.

2.1.5 **Physio-chemical sludge**

Physiochemical sludge results from the physio-chemical treatment. By doing physiochemical treatment primarily separates colloidal particles. This type of solids is visible in the naked eye which can be separated by the influence of gravity, flotation depends on the relative densities of solids and water. The size of colloidal particles is less them 1µm have high stability. [18]

Physio-chemical treatment mainly removed a primarily the colloidal particles which are done by adding an additional chemical.

2.1.6 **Mineral sludge**

Sludge containing a minimum level of associated water (sand, silt, slag, scales, crystallized salts…). The reason behind the name is this type of sludge produced during the mineral process. In mineral sludge, it also includes hydrophobic matter that has enough hydrophilic matter ensuring the predominance of the latter has an adverse effect during dewatering. According to [19] from various research project found that sewage sludge ashes (SSA) contain calcium, silica, and an alumina rich mineral which can possess Pozzolanic properties. Because produce clinker of cement pozzolanic material from sewage sludge will be the best option to use. The way to minimize the negative impact on the concrete industry using supplementary cementitious materials by avoiding explosive materials [20]. Sewage sludge in the construction industry might be the best alternative of cement [21]. In addition to as a filler to produce asphalt concrete, bricks, and tiles said by [22]. Adding lime in the mixture of the Pozzolanic material can increase the mechanical properties according to [23]. Based on [24] adding several pozzolanic minerals (such as BFS, metakaolin, fly ash, and lime, etc.) and alkali activator helps to improve the property of sewage sludge ashes based concrete. Enhancing the pozzolanic properties of sewage sludge ashes by mixing sludge

admixtures where different types of several minerals composed with the general Portland cement and Portland Pozzolanic cement describes in their research work [25].

2.2 Conventional dewatering technologies

2.2.1 Screw press technology

From various industrial application to material handling like dewatering sludge's screw press technology used. Sludge is fed into the overhead screw which turns pushes between the screw and a strainer and the water is drained out. Solid waste has collected another side of which later dried to produce briquettes. The briquettes become a source of solid fuel and its calorific value is comparable or better than that of any other solid fuel like coal, wood, etc. In India screw press technology is quite common for oil crashing. Low-cost screw press technology is used for separation of solid waste from the sludge of the biogas plants to produce briskets as a source of fire, which considered as good substitute firewood. The horizontal continuous operation design of screw press technology is used for dewatering or solid separation of a wide range of products. [26]

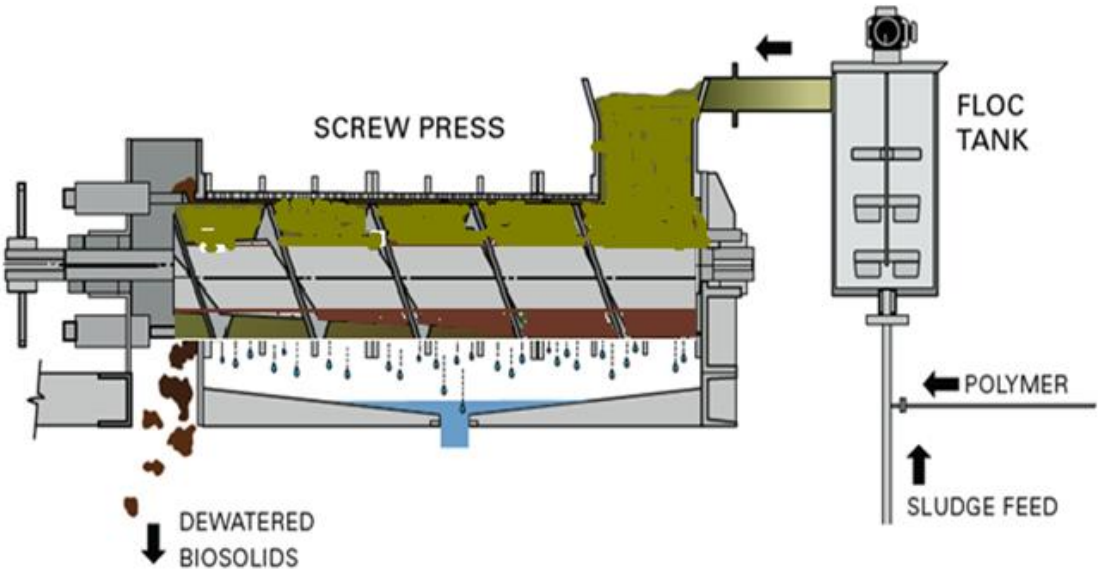


Fig 3: Screw press Machine [24]

According to [26] screw press machine is designed to separate the solid for producing briquettes from the slurry by extracting water from it represented by figure 3. The parameters here are 2 tones/hr. with 8 rpm, with a factor of safety of 2.5. To get the 40% of total solids the diameter of the hole is tested here is 3.00 mm.

In screw press dewatering machines flocculated sludge pumped into a cylindrical screen where auger is rotating in slow speed. The diameter of the auger shaft increases towards the end of the basket and the gap between its flight's decreases. Auger forwards the thicker sludge to annular clearance which has a circular opening with adjustable discharge cone therein. To maintain the sludge pressure in discharge and a pneumatic cylinder is pressed against the opening of the cone. Separated sludge water came out through the filter. The filter is cleaned by the scrapers of the screw. Stationary spray bar backwashes the filter periodically without interpreting the dewatering process. [27]

2.2.2 **Rotary fan press technology**

Rotary fan press dewatering technology presented in figure 4 is best for municipal and industrial sludge dewatering because of its continuous improvement and R&D. This technology requires less supervision compared to other dewatering technology due to its reliability and simplicity. It is one of the safest technologies for the stand-alone automatic operation which can be monitored and operated by remote control. The reason behind the wide using of this technology is its low operating cost, easy operation, minimum power consumption, and low maintenance. [28]

To operate the dewatering from biosolids and sludge's rotary press technology is considered a very simple option. Because of using a rotating screen or filter plate water get extracted from the sludge with least resistance. After that stage dewatered sludge travels through the pneumatically adjusted restrictor. Due to the restrictor, it creates back pressure on the solids forming a plug of dewatered solids. For different type sludge dewatering require different pressure and time profiles to get optimum dewatering efficiency. Rotary fan press technology is considered the most effective for dewatering because it gives us the option to maximize of production capacity. Having various advantages of operation, it's had some negative sides also. Such as dewatering raw material have foreign materials like plastics,

hair, rocks, etc. In that case, we need to extract those by adding a filter before the dewatering unit.

According to [29] parameter, which are responsible for the performance of the rotary press

- Selection of polymer
- The rate of polymer dosing
- Sludge with the mix of polymer
- Sludge age
- The thought put speed and pressure of the sludge pumped into the system
- The rotation speed of the filter plates (screen); and
- The restriction applied to the cake solid

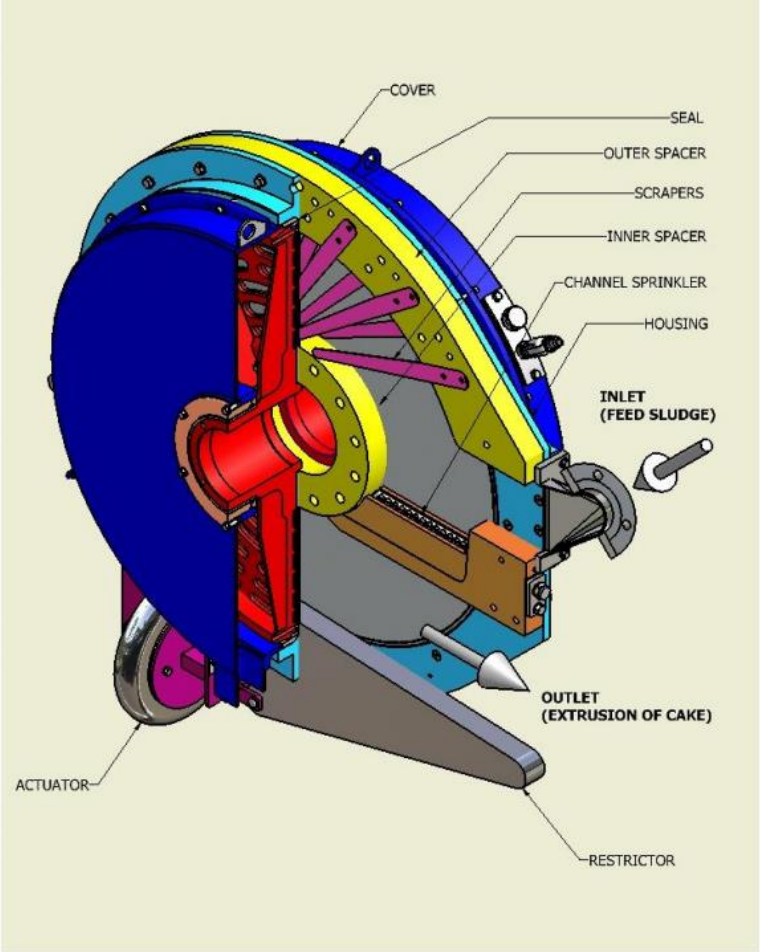


Fig 4: Rotary Press dewatering machine [30]

2.2.3 **Centrifuge Technology**

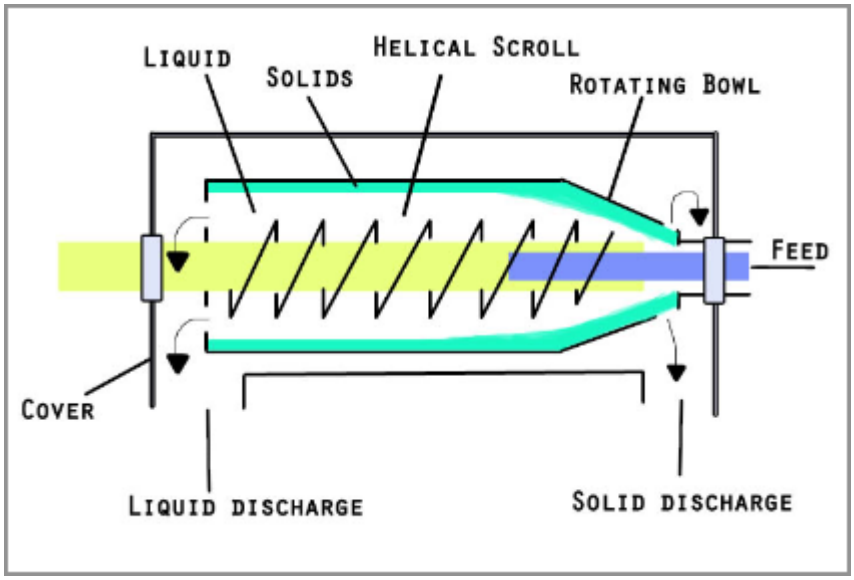


Fig 5: Schematic of decanter centrifuge [31]

For sludge dewatering centrifuge dewatering method is considered very common dewatering technology. Running the centrifuge is considered very expensive dewatering approach because of its high energy consumption. The reason of using that technology very often because of its high productivity. The mechanism of its high productivity is its high centrifugal force on sludge. The applied pressure on sludge is from 2000 to 3000 G. The centrifuge dewatering method used to separate two substances with different densities such as solid-liquid, liquid-liquid, solid-solid. The biggest advantage of using the centrifuge dewatering method is its simplest installation process. Figure 5 shown the schematic diagram of centrifuge dewatering process. Centrifuge dewatering system chamber large liquid capacity which allows to work it with more concentrated slurry. The problems with this system require high maintenance mostly the rotating part. Centrifuge system creates very high noise and vibration when running at high forces.

2.2.4 **Belt filter press Technology**

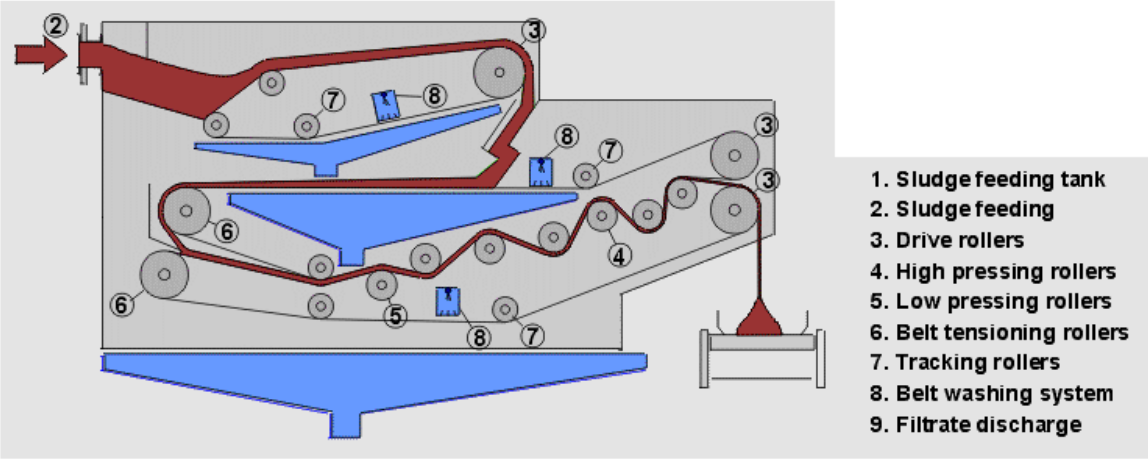


Fig 6: Belt filter press dewatering machine [32]

Another most commonly used dewatering technology is the belt filter press technology presented in figure 6. In belt filter press machine, there is a tank for sludge feeding to the machine. From tank sludge is fed into the belt. Belt is rolled by the driver motor. There are three main rollers which used to applied pressure and tensile of belt. There a one high and low-pressure belt for application pressure to the sludge. For cleaning the belt there is a washing system. After sludge passing through the belt the water got released from the sludge and the dry solid is came out from the outlet. To get better dewatering result the flocculent is added to the sludge to avoid the accumulation of the solid particles. Gravitational drainage of the sludge can be improved by adding flocculants on the sludge. For dewatering sludge content which inserted into the belt filter press should be 3-4% of Total solid.

2.2.5 **Filter press technology**

For treatment of the municipal and industrial sludge filter press dewatering technology become very reliable and efficient dewatering method. The basic mechanical design of the filter press machine is consisting of several filter plates. In filter press there is pressure of 16 bar on the sludge by filter plates. This filter plates are placed vertically on and between two sidebars or in the overhead support beam. The filter press name differs according to the mounted of filter plates. If the filter plates mounted inside bar known as sidebar filter press and filter plates mounted with overhead support beam is known as overhead filter press presented in figure 7. In filter press machine they used around 60 to 80 filter plates which dimension is about 1.5 m * 1.5 m to 2 m * 2 m. [33]

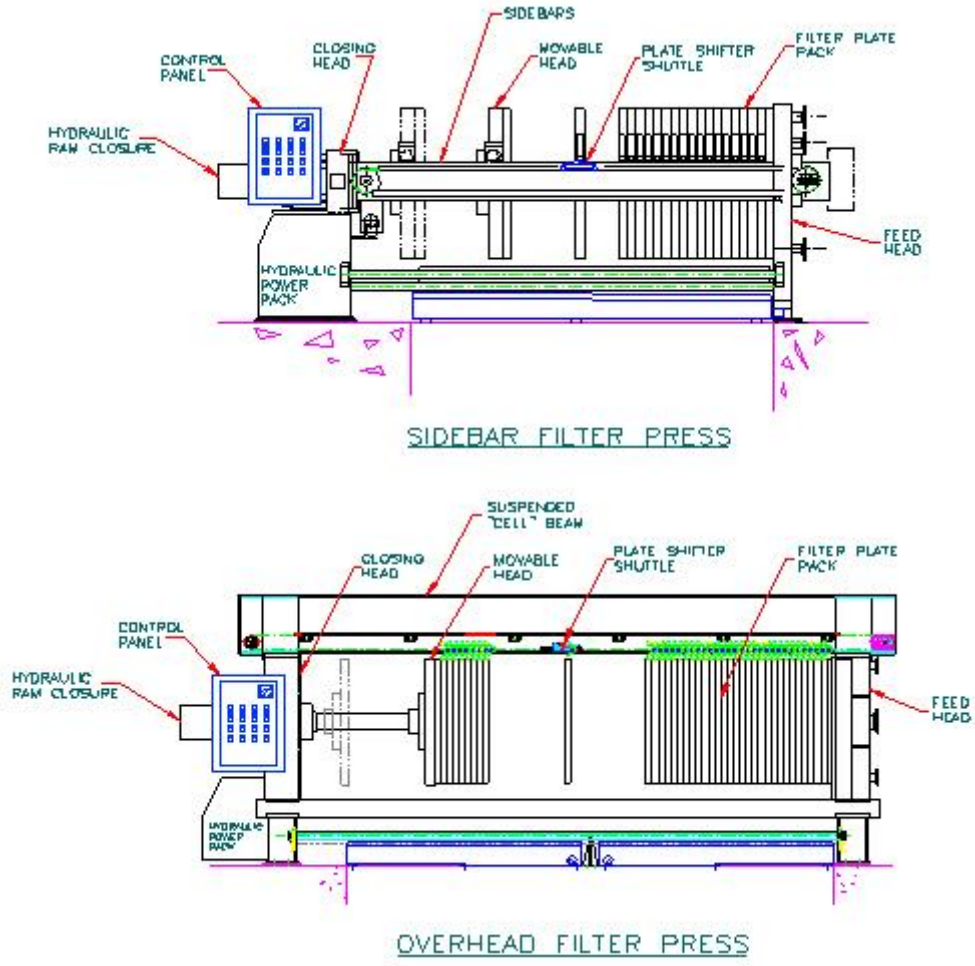


Fig 7: Schematic diagram of Filter press [34]

2.2.6 **Rotary drum vacuum filters**

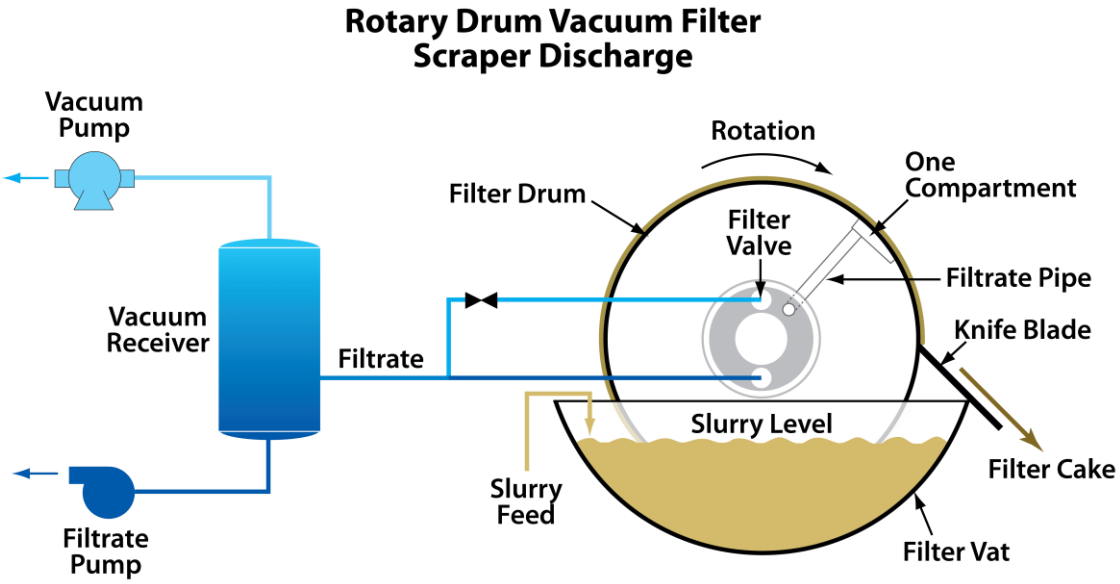


Fig 8: Rotary drum vacuum filter [35]

For industrial sludge dewatering the rotary drum vacuum filter mostly used. The rotary drum vacuum filter shown in the figure 8 has a tank where the sludge fed into it. The quarter area of the drum is into the sludge tank. The drum rotated continuously by a driver. When the drum rotates it particularly submerged in the feed slurry. A vacuum pump is connected to the drum to apply vacuum. Drum surface is used to retain the solids. The vacuum system removes the moisture from the sludge when the drum rotates. At the end the slurry cake is removed from the drum to next step. [35]

2.3 **The working principles of Electrokinetics**

To enhance the performance of dewatering with conventional pressure filtration using an electric filed to become an emerging technology. This technology has the potential to improve the percentage of dewatering from sludge. Smolen, M., Kaffar, A. [36] Says that the interfacial electrokinetics phenomenon can enhance the dewatering performance of solid-liquid mixture sludge, which is known as electro-osmosis. An external DC current is applied to the sludge. The electric double layer passes through particles of solid surface also the liquid in the material. Several advantages of electrokinetics dewatering make it an effective dewatering method compared to the other conventional mechanical dewatering

method. Electrokinetics dewatering method particularly very effective for fine particle sludge, bio-sludge and chemical sludge, which is very hard to dewater using mechanical dewatering method.

According to, [37] electrokinetics dewatering method can dewater more water from the sludge. The reason behind the high potential of electro-kinetic dewatering because it has higher dewatering rate and minimum water content into the sludge. [38]

2.3.1 **Working Principle of Electrokinetics**

When an electrical potential difference applied to the sludge cathode and anode creates a reaction, which allows the sludge to release water from it. The direction of the pore water movement depends on the net transfer of momentum by both cation and anions within the pore water. Due to the nature of clay formation, which results negatively charged clay particle. Here the figure 9 shows the water behaves cationic results the water moves from the anode to cathode.

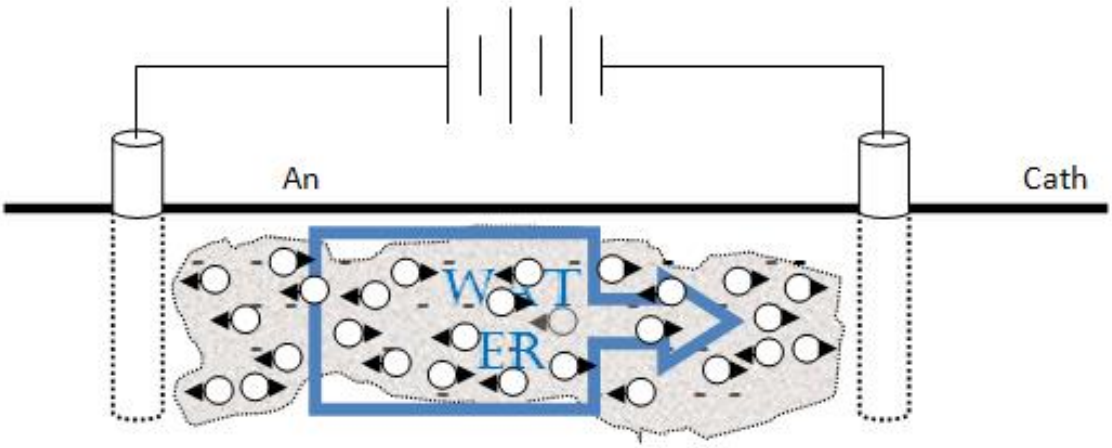


Fig 9: Sludge dewatering using electrokinetics [39]

2.4 Ultrasonic mechanisms that pertain to dewatering

2.4.1 Ultrasonic sponge effect

Ultrasonic transducer used to enhance the mass transfer of the unit operation by different sound technology such as direct and indirect effect. The direct effect of ultrasonic transducer is known as the sponge effect. Continuous compression and expansion happen in the tissue of the material causes phenomenon called sponge squeezed and release. This phenomenon helps to keeps the micro channels and pores easy to break which facilities the mass transformer. The indirect effect of the transducer in sludge is the formation of micro channel by acoustic cavitation.

Sponge effect allows to break the water from the sludge and suck the water from sludge. In order to get better sponge effect and drying we must drive the transducer matching with impedance.

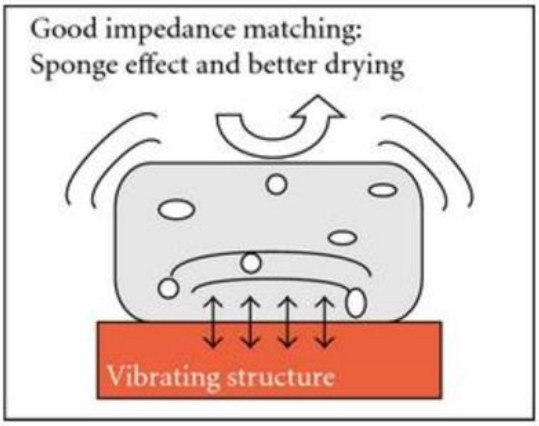


Fig 10: The sponge effect by ultrasonic transducer [40]

2.4.2 **Ultrasonic Cavitation**

The active reaction of ultrasound in the wet sludge results ultrasound cavitation presented in 11. Due to ultrasonic cavitation the pressure on sludge increases and the ultrasonic waves. There are some factors, which ultrasonic cavitation depends such as temperature, tension on the surface, viscosity medium, pressure, etc. The cavitation results the elimination of the gas bubbles in the sludge. The susceptibility of the liquid to the process increases because gas bubbles elimination by cavitation. [41] The production, development, and breaking of microscopic bubbles by ultrasonic cavitation results high heat energy with shock waves. The high heat energy, shock waves and micro jets creates turbulence and forces on the sludge results mass transfer. The resultant pressure and heat by the cavitation are can be up to several thousand bar and kelvin. [42]

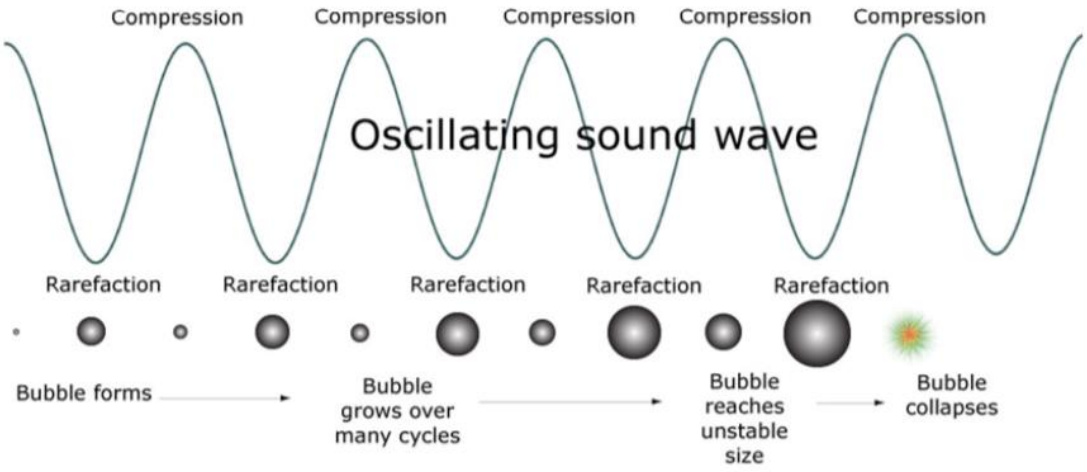


Fig 11: Ultrasonic cavitation [42]

At first stage the bubbles started to form at lower frequency such as 20 kHz. This size frequency has large resonance with power full burst and shockwaves. On the other hand, the frequency size from 1000-1000 kHz has smaller resonance but can produce large heat. That's why 1000 kHz frequency is has lower cavitation and normally use for sophisticated electronics equipment cleaning. [42]

2.4.3 **Ultrasonic atomization**

Ultrasonic atomization is the phenomenon where liquid breaks into fine droplets presented in figure 12 due to the vibrating surface of the ultrasonic transducer. There are two hypotheses proposed to define the ultrasonic atomization which is known as capillary wave hypothesis and cavitation hypothesis. The effect of ultrasonic wavelength on the size of droplet is basic theory of capillary wave hypothesis. Cavitation hypotheses is mostly applied to liquid where the liquid bubbles are produced. [44]

Ultrasonic atomization occurs when the vibrating plate vibrate at resonance frequency and proper amplitude. When the transducer running at resonance condition the capillary waves generates on the shell of the droplets. To increase the faster injection process, we need to increase the resonance frequency of the water particle. The figure 12 used to describe the atomization process. Here a drop of water with 8 mm thickness is vibrating on fixed frequency. The amplitude is increased to induce the resonance condition.

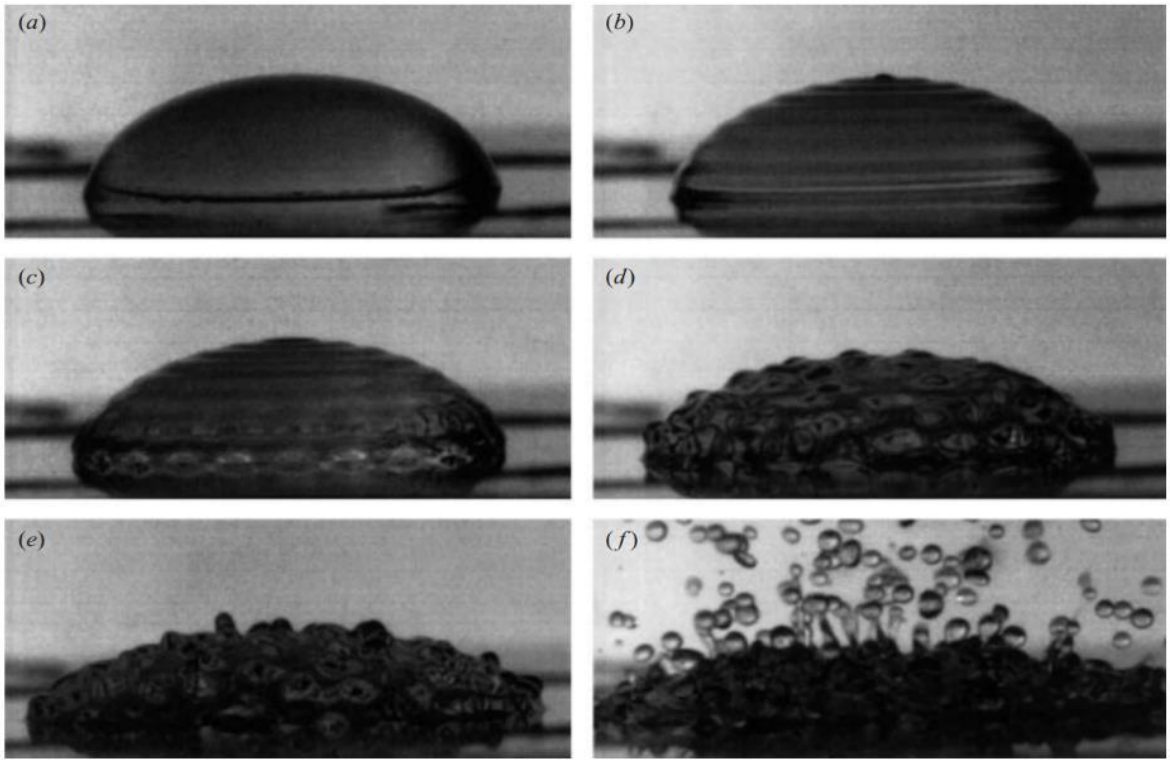


Fig 12: (a) Drop of water, (b) wave effect on drop of water, (c) stationary and azimuthal wave impact on the drop, (d) wave transformation after long time, (e) more effect of ultrasonic wave, (f) atomization

2.4.4 **Disintegration effect**

Sludge disintegration process the cell walls by breaking them to enhance the microbial decomposition also for biogas recovery. Sludge disintegration influences the amount of content in the dewatered sludge cake by liberating water from cellular material. Disintegration by ultrasonic is considered a reliable method for sludge disintegration. Ultrasound waves create compression in period with the sludge rarefaction.

Description of ultrasonic disintegration taken by *DD*cod taken as the dependent variable. Due to the sonication time or density of ultrasonic responsible to the sludge disintegration. Power function model according to the shown in Eq. 1

$$DD_{\mathrm{COD}} = 1 - \frac{1}{(1+\mathrm{k}\mathrm{C}^{\mathrm{l}}\mathrm{E}^{\mathrm{m}}\mathrm{t}^{\mathrm{n}})} \quad (1)$$

Here from the equation 2

C = Sludge concentration in g/l

E = Ultrasonic Density Wm/l

t = the sonication time in minute

l = sludge concentration

m = ultrasonic density

n = sonication time

k = reaction rate constant

$$ln\left[\frac{DD_{\mathrm{COD}}}{(1-DD_{\mathrm{COD}}}\right] = ln\,\mathrm{k} + \mathrm{l}\,ln\,\mathrm{C} + \mathrm{m}\,ln\,\mathrm{E} + \mathrm{n}\,ln\,\mathrm{t} \quad (2)$$

Ultrasound frequency is most effective in waste activated sludge (WAS) at lower frequency, i.e. 20 kHz. Comparing the degree of disintegration with the frequency range from 41 to 3217 kHz it is found that the disintegration is more efficient is lower frequency. Figure 13 demonstrate that the degree of disintegration (*DD*cod) is highest at 41 kHz. By breaking the microbial cell release the intercellular material which increases the degree of disintegration. On the other hand, increase of ultrasonic frequency decrease the efficiency of sludge disintegration.

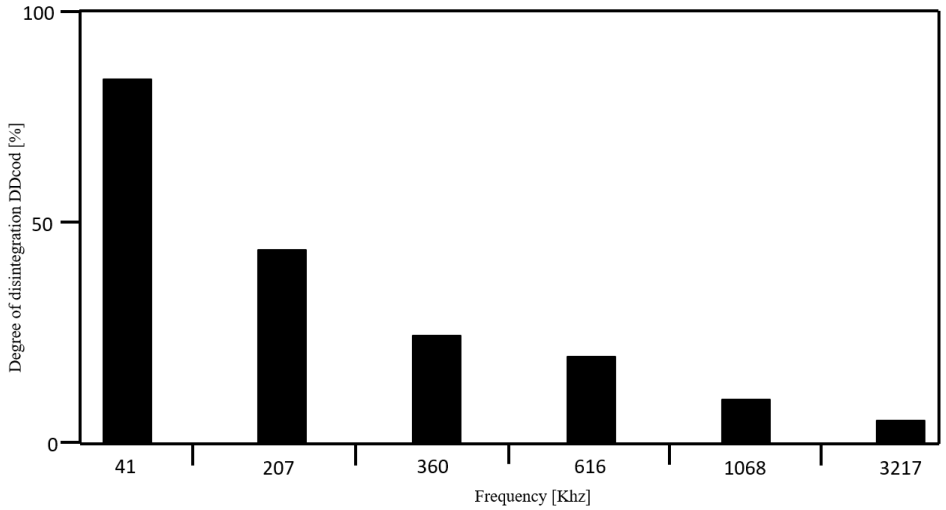


Fig 13: Degree of disintegration sludge with the frequency response [45]

In addition to by varying sonication time will help to get better result from the experiment. Changing the sonication time to 30, 60, 150 minutes will improve the microbial activity. Microbial growth occurred due to the dispersing the agglomerates into smaller units. Fig 14 represents the changing of results of volatile solids and biogas due to change of sonication time with constant sonication frequency 41 kHz. [45]

Figure 17 presents the how ultrasonic disintegration enhance the results of anaerobic degradation of the waste activated sludge. After doing the disintegration on waste activated sludge fig 17 (a) shows what percentage of volatile solids removed from there. In addition to fig 17 (b) represents the production of biogas from waste activated sludge and how it is rising.

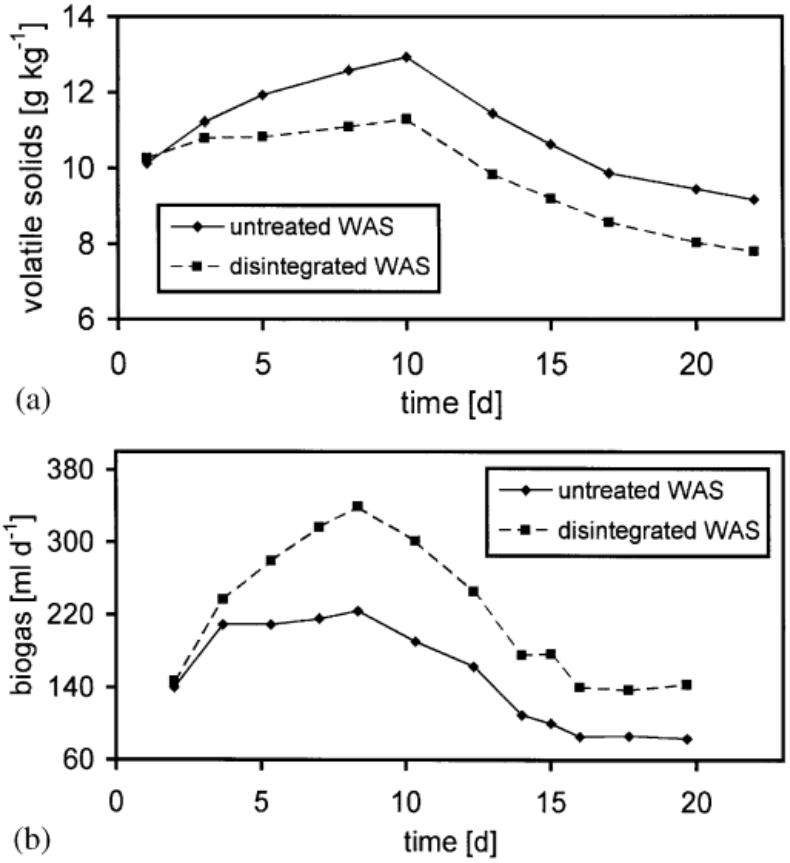


Fig 14: Disintegrated sludge (a) volatile solid reduction (b) Improving Biogas Production [45]

When the sludge sonicated for 7.5 min it causes floc DE agglomeration and not cell disintegration. From the table 3 shows that the biogas production was slightly reduced because sludge sonication for only 7.5 minutes. When DD increased results the percentage of methane gas increase in the biogas. Analyzing the data from the table 1 is cleared the methane in biogas is constant of the disintegrated sludge which means the methane production is constant.

	Disintegration time (min)				
	Control	7.5	30	60	150
Disintegration					
Degree of disintegration DD_{COD} (%)	0.0	0.0	4.7	13.1	23.7
Oxygen utilization rate (%)	100	110	80	65	23
Volatile solids degraded (%)	21.5	22.7	27.3	31.4	33.7
Gas production					
Total biogas (l)	2.93	2.79	3.39	3.83	4.15
Biogas/VS degraded ($l\,kg^{-1}$)	483	434	441	433	436
CH_4 (%)	62.8	63.5	65.9	67.3	68.9
CH_4/VS degraded ($l\,kg^{-1}$)	303	276	291	291	300
Digester effluent supernatant					
COD ($mg\,l^{-1}$)	215	202	240	250	622
Acetic acid ($mg\,l^{-1}$)	11	21	9	11	11
C_3–C_6 VFA ($mg\,l^{-1}$)	nd[a]	nd	nd	nd	nd
NH_4-N ($mg\,l^{-1}$)	516	471	558	560	638
P total ($mg\,l^{-1}$)	19.0	19.0	19.3	24.7	20.7

ND = Not detectable

Table 3: Waste activated sludge disintegration and subsequent anaerobic digestion [45]

2.4.5 **Ultrasonic waves impact on pH and temperature**

Time of sonification and density of ultrasound are the main factor of ph. If the sonification time is longer with higher density results higher pH reduction shown in figure 15. When the sonification time is 30 minutes which results more pH, subtraction compared to time of sonification 1 minute. In addition to, temperature increase in due to ultrasonic wave causes less pH reduction. PH of sludge decreases due to ultrasonic wave 0.375 W/ml to 2.5w/ml and after 30 minutes of operation it decreased to the minimum level 6.92 w/ml. Figure 8 represents the pH behaves with the sonication time.

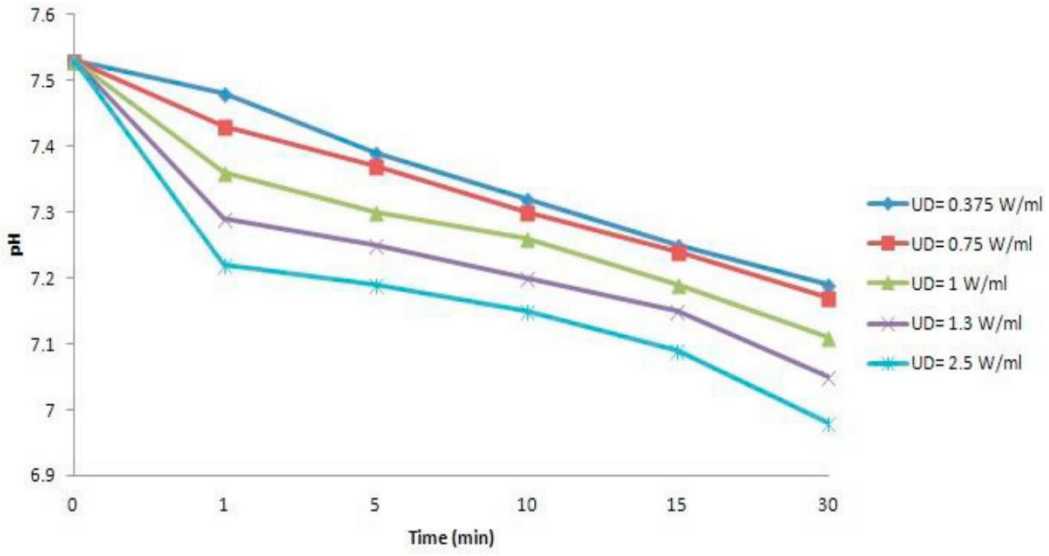


Fig 15: Due to time of sonification time and density of ultrasonic pH variation [46]

Ultrasonic process causes cavitation and implodes of Nano bubbles results increase of temperature and it increase with the duration of time intensity of ultrasound sonification time. Temperature was highest when the sonification time is 30 minutes and least in 1minute. Temperature was 31.8 C in 30 minutes during ultrasonic density moves to 0.375 W/ml to 2.5 W/ml. How the temperature varies with the sonication time represented by figure 16. This characteristic of sonification time and ultrasonic density is confirmed by another research done by Augustina in 2011 and Feng in 2009. [46]

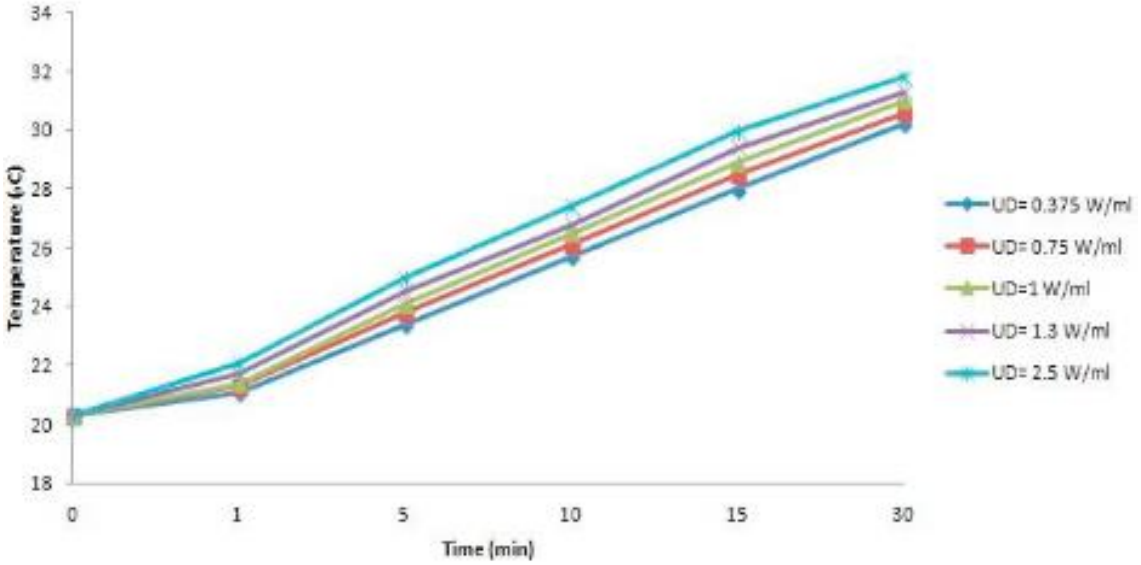


Fig 16: Variation of temperature respect to time of sonification time and density of ultrasonic [46]

Dry-solid content percentage in sludge is responsible to increase of temperature. Long time treatment is also another effective reason to rise the temperature. Huge quantity of sludge absorbed great amount of energy which results enhancement of cavitation. Cavitation creates obstacle of movement into the sludge guaranteeing results increase of temperature to ultrasonic transducer. Sludge temperature raised significantly with the ultrasonic vessel because of not having cooling system. In addition to long treatment time allows the temperature increase from 5° C to 60° C. [47]

2.4.6 **Particle size distribution**

Ultrasonic treatment results decrease of sludge particle size. Distribution of sizes of the particle of sludge's measured after the ultrasound experiment the effectiveness of ultrasound on sludge particle measured. Major part of untreated sludge floc particle size is range from 400 to 700 µm which decrease due to ultrasonic effect shift towards 100 µm. Ultrasonication time is an important factor of particle size reduction. Ultrasonication time lengthened to 30 minutes where peak at around 100 µm and lower peak at around 500 µm. on the other hand, after 60 minutes of sonification time the result is better than the previous result. Now there are two peaks at around 100 µm and around 300-350 µm. longer sonication time results re flocculate of the particles makes them so small which not detected by measurement status. Figure 17 shows the how particle size effected by the ultrasound with the different period.

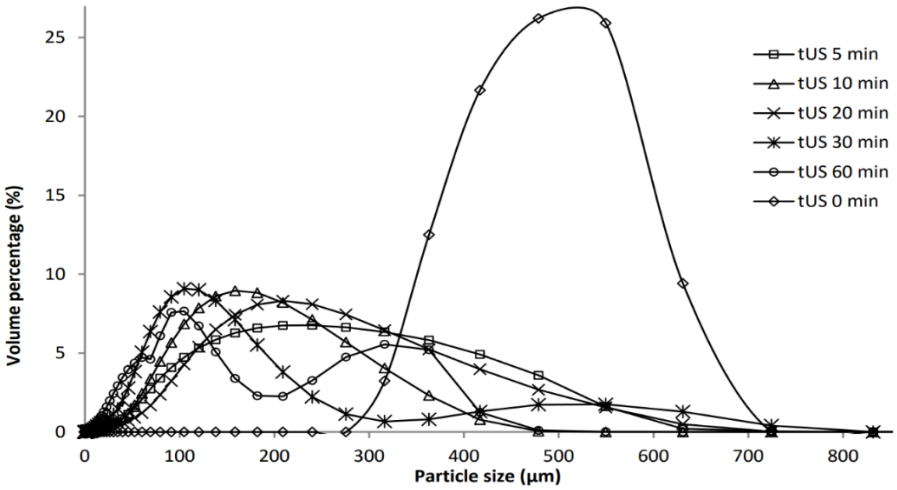


Fig 17: Particle size effected by the ultrasound with the different period [47]

Sludge particle size decreased as Ultrasonication time is increased which also state by some other research like (Chu et al. 2001; Mao et al. 2004; Dewil et al. 2006; Feng et al. 2009b). in first few minutes ultrasonic transducer is more effective on particle size. According to Gonze et al. (2003) and Mao et al. (2004) sludge particle size were most effected in first 5 minutes of sonication time. [47]

3 EXPERIMENT PLAN TO INVESTIGATE THE PRACTICALITY OF ENHANCED DEWATERING USING ELECTROKINETICS AND ULTRASOUND

3.1 Answering the previously mentioned seven questions

To determine the practicality of our designed dewatering method evaluated by using the seven questions. The questions are designed in a way that can evaluate the combination of ultrasonic and electrokinetics practicality in industry. We have designed an experiment plan to determine the possibility of enhancement dewatering dramatically from the combination ultrasound and electrokinetics. After getting the result from experiment we analysis the cost and relative things of our designed dewatering method to know the can we applied in industrial scale. The resulted data from the experiment will tell us the dryness of the sludge after applying ultrasonic and electrokinetics separately and then together. The analysis of the running system cost to achieve per kg per % TS of this enhanced dewatering method will also help to get idea cost effectiveness of this system compared to conventional dewatering technologies. Different types of sludge will be used during the experiment to compare the efficiency of the system. From analyzing the resulted data from the experiment, we can find out which sludge provide better dryness.

3.2 The execution of the experiment plan

To answer these questions, we have designed our design of experiment in way which can help us to answer this question. We have divided our experiment into three phases. First phase of experiment will be done by using chia seeds as a sample. We will be doing 12 experiments in the first phase of our experiment with three variables. The next phase of experiment will be continued with the industrial sludge and varying the thickness of the sludge.

The first phase of design of experiment is give below:

Three variables were selected to be studied in these first phase of experiments

- Transducer frequency: variable with 2 levels, note "midpoint" [15, 20, 30] kHz
- Pressure: variable with 3 levels [1 bar, 2 bar and 3 bar]
- Voltage: variable with 2 levels [15 V, 30 V and 45 V]

Design

The plan is based on 2k, with three repeated measurements at the midpoint of variables. The plan is as follow in Table 4. The last experiment (highlighted) is added so it can be performed if time allows. As four repeats is better than three, but for this kind of initial plan three is enough.

Experimental time will be decided from the first experiment which will be let to run for so long that water extraction ends totally.

Test Cast No.	**Transducer frequency, kHz**	**Pressure, bar**	**Voltage, V**
1	15	1	15
2	15	3	15
3	15	1	45
4	15	3	45
5	30	1	15
6	30	3	15
7	30	1	45
8	30	3	45
9	20	2	30
10	20	2	30
11	20	2	30
12	20	2	30

Table 4: The test plan

With this plan it is possible to evaluate the combined effect of these variables. From the center point repetitions the repeatability of the measurements can be evaluated. It should be

noted that the transducer frequency is not exactly in the midpoint, but it shouldn't affect optimization that much.

Response variables

From the equipment, quite a few responses can be recorded. Main one being the water content of sludge after experiment.

- Water content of sludge, sample of sludge is dried in the oven
- On-line scale measurement, how much water leaves the sludge during process
- Voltage and Current of the equipment
- Frequency of transducer during operation, measured by an oscilloscope

3.3 Three experiment phases

The design of experiments in three phases to optimize the number of experiments. In first phase we used chia seeds alternative of sludge. Phase 1 experiments are designed using 2k method to optimize the number of experiments. We will be doing 12 experiments in first phase with considering three variables. In second phase we will be conducting more complex Central Composite Design (CCD) plan. The CCD plan will be designed after finishing the first phase experiments. From the result of the first phase experiments we will do analysis on it and make some changes with our variable to get better result. The third phase of experiments we will be conducting more optimized experiments with different types of sludge.

3.4 The experiment plan and hardware

3.4.1 The designed list of experiments with three variables

We have designed an experiment plan based on the three variables. Experiments are designed in a way that we will try highest and lowest values of variables at first and later we will try with mid-level values. Which helps us to get an idea that which values of these three variables are more efficient. By comparing the resulted data from the experiment, we can find out which variable is more efficient for different types of sludge.

Variables			
NO.	Pressure	Frequency	Voltage
1	1	15	15
2	2	20	30
3	3	30	45

Table 5: Testing variables

The table 5 is contains the list of experiments. We have designed 12 experiments for the first phase of test. We will do the four experiment with each transducer. At first, we will use 15 kHz transducer with lowest values of pressure and Electrokinetics which is 1bar and 15 V. In fourth no of experiments we will try the highest values of pressure and Electrokinetics which is 3 bar and 45 V. After finishing the four experiments with the 15 kHz transducer we will start testing with highest frequency 30 kHz transducer. The testing parameters for the 30 kHz transducer is same as 15 kHz. We also do the four tests with the 30kHz transducer. At the end we will do the testing with the 20 kHz transducer with all the mid-range values. We will apply 2 bar pressure and 30 V for electrokinetics. By varying the parameters, we will do the four experiments with 20 kHz transducers.

3.4.2 **The procedure of tuning the transducer to run the transducer at resonance**

Introduction

If any test requirements or steps are unclear, or if there is an issue with meeting any requirements or carrying out any steps, please contact arup.dey@lut.fi or andrei.nekrasevits@lut.fi as appropriate.

On the day of testing, suitably qualified technical personnel are required on site to assist in undertaking the tests. The personnel shall have the ability to:

A. Set up and disconnect the control system and instrumentation as required;

B. Ability to collect data from the experiment using data acquisition box;

C. Mitigate issues arising during the test and report on system incidents.

Equipment

List of equipment

Name	Description
Power amplifier	PDUS 200
Oscilloscope	Agilent 54622D
Signal generator	Agilent 33250A
DAQ box	USB 6341
BNC probe	
Multimeter	Ifluke 117
Thermocouple	
Laptop	DELL E7250
Transducer	Three transducers for each frequency (15kHz, 20kHz, 30kHz)
Horn	Three different horn for each frequency (15kHz, 20kHz, 30kHz)
Pneumatic cylinder	
Vortex tube	
Scales	
Experimental stand	
Enclosure	

Table 6: List of equipment

Site Safety requirement

The following is required for test procedure:
Ear protection (earplugs and earmuffs)
Enclosure for the apparatus

Transducer Tuning

Procedure

At first, we must polish the top surface of the horn by the polishing paper, which relates to the transducer. Then using the torque wrench, we must clamp the horn with the transducer. Following the circuit diagram, we have connected power amplifier with the signal generator to amplify the current supplied to transducer. A 100-ohm resistor relates to the transducer to measure the current flow through the transducer shown in the figure 18. To measure the current, we have connected oscilloscope channel 2 with the resistor. To measure the voltage from the table 6, channel 1 of oscilloscope relates to the signal generator. By changing frequency though the signal generator at the same time comparing the phase difference of voltage and current signal we can tune the transducer. Example. If a 15 kHz transducer relates to the horn and transducer is resonating at 12 kHz, we must reduce the length of horn and again clamping it with the transducer. In that case, we must start supply frequency from low and increase it gradually in the same time we must check the phase difference of voltage and current signal. If the phase shift is nearly zero at 14 kHz frequency, we can say that transducer is properly tuned.

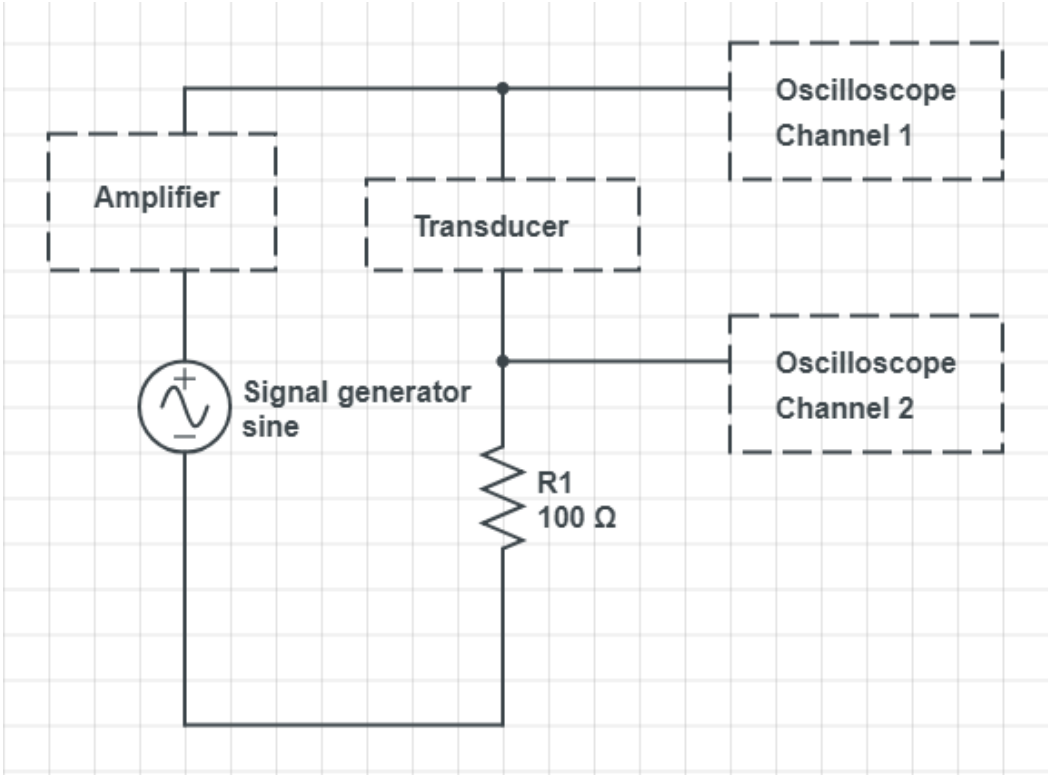


Fig 18: Circuit diagram

3.4.3 **The preparation of chia seeds with three different thickness**

Chia seeds preparation

Test samples used in the experiments are Chia seeds. To prepare samples to simulate industrial sludge following preparation is followed to achieve 20% TSC. The samples are made following the table 7.

For 12mm thickness:

No.	**Conditions**
1	Plastic cup is placed on the scales and the scale is set to zero.
2	Using scales 24 grams of Chia seeds are placed in the cup.
3	Water is poured into cup to get 112.8g total net weight.
4	Sample is stirred in a cup and then covered with lid.

5	After 50 minutes has passed the sample is ready for testing.

For 9mm thickness:

No.	Conditions
1	Plastic cup is placed on the scales and the scale is set to zero.
2	Using scales 18 grams of Chia seeds are placed in the cup.
3	Water is poured into cup to get 84.6g total net weight.
4	Sample is stirred in a cup and then covered with lid.
5	After 50 minutes has passed the sample is ready for testing.

For 6mm thickness:

No.	Conditions
1	Plastic cup is placed on the scales and the scale is set to zero.
2	Using scales 12 grams of Chia seeds are placed in the cup.
3	Water is poured into cup to get 56.4g total net weight.
4	Sample is stirred in a cup and then covered with lid.
5	After 50 minutes has passed the sample is ready for testing.

3.4.4 **The data collection procedure for the experiments**

Data Collection

Temperature

To measure the temperature of ultrasonic transducer we will use the DAQ box. By this we can collect temperature for every second. DAQ box will save the data in excel file. Using excel we can analyze the data after experiment.

Extracted water

A digital scale is used to measure the water extracted from sludge. We can store the data which we have got from scale.

Amplifier, Phase and Frequency

Resonance frequency will be measured by a software which is coming with the piezo driver PDUS 200. It has several options to control amplifier, phase and frequency. It has a status panel for amplifier which shows the amplifier is on or off. For phase and frequency measurement it has a plot window where its shows the value of phase and frequency graphically. Voltage and current can also be measured using the same software. There is also a plot window for that which show the measured value graphically. To measure resonance frequency, it has an option in setting that can track the resonance frequency automatically. Control of frequency can be done also manually. In that case in setting window we can set the maximum frequency, current frequency, minimum frequency and power.

Electrokinetics

For electrokinetics we will supply the power using a power supply. The supplying power will be constant for fixed time. So, we will note that manually. Following our test plan, we will supply dc 15 V constant for 1^{st} phase of testing.

Test Tips

Chia seeds dewatering testing done by following the table 7.

Step	Action	Comment
1	Using sandpaper polish horn and transducer ends with threaded hole until any roughness is eliminated	Horn and transducer frequency type used is dependent on the test number
2	On test platform put horn through the ring and assembly it with the transducer using strap wrench until tight fit is achieved	
3	Adjust pneumatic cylinder position so that when the piston is at zero stroke the distance between flat end of horn and filter support plate is 45mm	
4	Put test samples in the filter ring and center it on the filter support plate.	Number of samples put is dependent on the required cake thickness for the specified test number.
5	Place the filler on top and center the base to the horn	Make sure the filter ring has been inserted in the filler upon placement
6	Open valves for pressured air for cylinder and vortex tube	Pressure in cylinder is regulated dependent on the test number
7	Turn on electronics and begin data recording of signals as set out in section 8	Parameters are adjusted according to the test number
8	Lower the horn into position and put enclosure around the test setup	

Table 7: Experiment step

Data collection

Step	Action	Comment
1	After the test is overturn off the horn, remove the enclosure and remove the filter ring with samples	Experiment time is dependent on test number
2	Put the contents of the filter ring into foil basket and measure the weight	Place the foil basket on scales and set weigh to zero before putting samples for measure
3	Mark the test number on foil basket and put it in the oven	
4	After all tests for the day are done set the oven temperature to 105°C and leave overnight	
5	Measure dried mass of the samples when the drying is done in the morning	

Comments:

3.4.5 **The test apparatus described.**

Fig 19: Testing setup

Figure 19 is the mechanical part of the dewatering testing setup. Where pneumatic cylinder is attached with the transducer to vary the pressure following the figure 22. Vortex cooler from figure 26 is connected the right side of the transducer. A measurement scale is set up under the draining plate figure 21 to measure the extracted water. Under the transducer there is a draining plate to let the water passes to the measurement scale. A connection box used to make the all electrical connection safely. Where we connected our transducer with an electricity supply.

Coupler

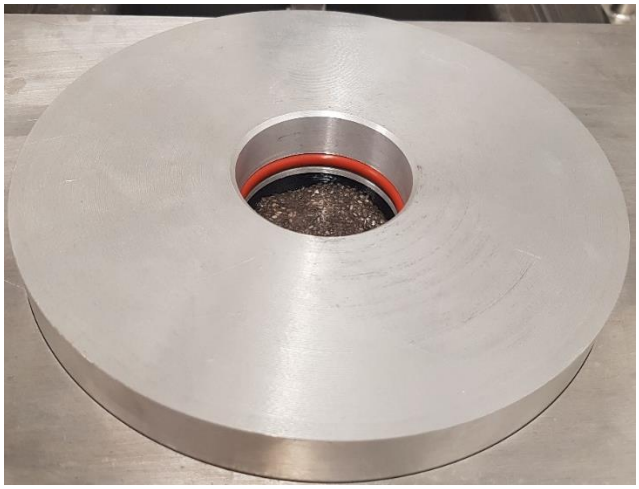


Fig 20: Coupler

The coupler used to fit the horn on the draining plate. It helps the horn to hold onto the draining plate. Coupler is made of aluminum. There is an O-ring set into the coupler, which separated the horn with the coupler. Another benefit of using O-ring is to absorb the vibration from horn and protect the coupler from vibration. For our experiment, our designed coupler is looks like figure 20.

Draining plate

Fig 21: Draining plate

This draining plate is designed to let the extracted water from the sludge to measurement scale, which is situated under the draining plate. Draining plate made from aluminum

contains several holes to let the go through the hole. Figure 21 presented how the draining plate looks like in our experiment.

Pneumatics Cylinder

Fig 22: Pneumatic cylinder

The pneumatic cylinder is used to pressure to put pressure on sludge by with the ultrasonic transducer. With this pneumatic cylinder, we can apply pressure with different values. For our experiment, we tried different values of pressure and compared the result with the presented pneumatic cylinder in figure 22.

Horn

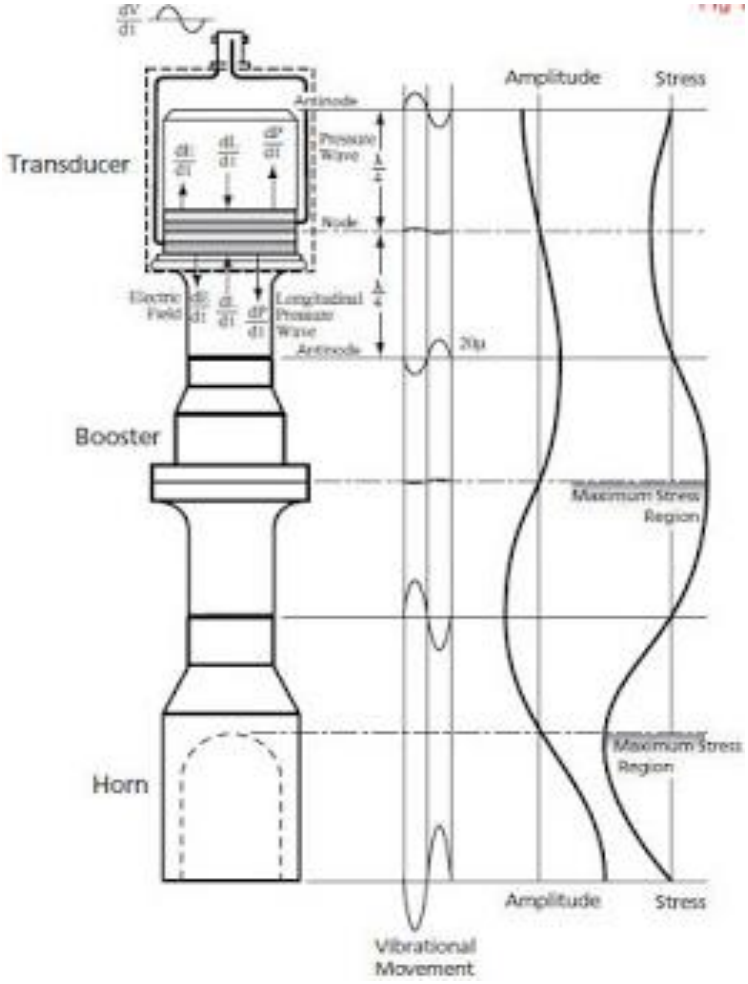


Fig 23: Horn connected with transducer [48]

In figure 19 a horn is clamped with the ultrasonic transducer. For getting better result of dewatering we have a horn with the ultrasonic transducer. We have designed different sizes of horn according to the ultrasonic transducer requirement. Length of the horn designed according to the frequency of transducer, which is presented in figure 17. According to the figure 24 the length of horn increases with the transducer frequency decreases. How stress and amplitude of ultrasonic is become effected by connecting a transducer can be easily read from figure 23.

Fig 24: Length of horn for transducer [48]

Transducers

(a) 15 kHz (b) 20 kHz (c) 30 kHz

Fig 25: Ultrasonic transducers [49]

Ultrasonic transducers convert electric signals to ultrasound. This kind of device known as a critical component of an ultrasonic system. Piezoelectric transducer converts electrical energy to ultrasound, which results in moving fluid. Piezoelectric transducer mostly used in the field of ultrasound. Piezoelectric transducer changes its length according to the voltage across though the material. If stress is applied across the length of the material it changes the applied voltage across the length. Ultrasonic transducers presented in figure 25 are used to during the experiment. [50]

Piezoelectric transducer

Piezoelectric material consists of crystal and ceramics this two main types of material. This kind of material used in different kind safety protection. In the car airbag and in a piezoelectric detector sensor this type of material being used. This material worked as a piezoelectric effect when it is set up in a solid material with the electrical and mechanical connection. High power ultrasonic transducer is used to dewater the municipal sludge by high-frequency vibration. High-frequency vibration is used to get 60% of dryness. Different parameters are also encountered during the experiment such as a vibrating plate transducer is designed and constructed.

Cooler

Fig 26: Vortex cooler [51]

Figure 26 presented a vortex cooler is used for cooling the transducers. Because if the transducers temperature goes above the 40 degrees is considered harmful for transducers. We have set up a knob in the air supply pipe, which allows controlling the supply air into the vortex cooler. The knob will help us to control the temperature of the air.

Filter plate

Fig 27: Filter plate

This filter plate used to put the sample on it. It is made from steel have a very small hole that allows only to pass through it. The steel filter plate presented in figure 27 is used to do the experiment

Piezo Driver

Fig 28: Piezo Driver [49]

Figure 28 is the picture of the PDUS 200 piezo driver operates the ultrasonic transducer on resonance frequency. It has various option to run these transducers. The driver can be run

manually where we must set driving amplitude, maximum frequency, current frequency, minimum frequency, and power manually. Here the amplifier generates sine wave according to the amplitude and frequency. In resonance tracking mode the amplifier will find the resonance by its own marinating the constant phase between voltage and current.

DAQ Box (USB 6341)

Fig 29: DAQ box (USB 6341) [52]

LabVIEW software used to operate this DAQ box presented in the figure. Figure 29 is the DAQ box (USB 6341) used to measure the temperature of the ultrasonic transducer to protect it from excessive heat. We also develop a control system to operate the whole dewatering system with this device. Control system to find the resonance frequency of the ultrasonic transducer. To measure the extracted water of sludge we will also use this DAQ box.

4 THE CONTROL AND DATA ACQUISITION SYSTEM

4.1 The overall electrical system

To continue the experiments according the experiment plan we have designed a control system for the electronics. The control system is mainly for the controlling the ultrasonic transducers. To drive the transducer at resonance frequency the control system used to find that resonance frequency. The phase difference of the voltage and current of the transducer is observed to find out the resonance frequency. At what frequency the phase difference of the voltage of the current is minimum considered the resonance frequency. A phase locked loop control method considered a better control system compared to the other control system after studying. The control system designed by using the LabVIEW operating system. A DAQ box used to run the control system. Some other features also included with the control system such as dynamic tuning procedure. Dynamic tuning method can be used to tuning the transducer. The control system used for the ultrasonic cleaning is also being discussed here. The temperature measurement of the transducer is done by the designed system in LabVIEW. The system for the measurement of the temperature is also being discussed here.

4.2 The system developed to operate the transducer at resonance

4.2.1 The importance of operating the transducer and horn at resonance

To get the best performance from the transducer it's must need to drive at the resonance frequency. Driving the transducer at resonance frequency is provides better dewatering result at minimum electric impedance, which become a cost saving option. The amplitude of the transducer will be higher when the transducer s running at resonance frequency. Transducer is designed in a way that if the transducer is 15 kHz then it will resonate at nearly 15kHz. In our designed system we have attached a horn with the transducer. we have designed a horn for every transducer which will at the resonance frequency of the transducer. To drive the transducer at resonance frequency a control system being designed. The control system can find the resonance frequency of the transducer.

4.2.2 **The control system used to operate the transducer at resonance**

A control system for ultrasonic transducer is a control of high frequency by automatic equipment for command. Frequency control system operate by getting feedback after estimated the movement of current passes through the ultrasonic transducer. Higher frequency conversation and stabilization of frequency is assured by control system. An ultrasonic system consists of piezoelectric transducer, a power amplifier, Magneto astrictive and a control. Driving an ultrasonic may face some problems. 1. Because of its high ratio of reactance to resistance of resonant circuit transducer must drive in resonant frequency for its good efficiency and large amplitude. 2. Resonance frequency varied then the desired one. 3. Because of changes of temperature results various resonant frequency. A proper control system requires operating the transducer in a resonant frequency. [53]

We designed a control system presented in the figure 30 for controlling the transducer at resonance. For calculating the phase difference of voltage and current signal are observed and tune it to minimizes the phase difference. The control system designed based on the working principle of phase locked modulator. Here we supply frequency using a signal generator. The formula to calculate the phase created here to measure the phase difference. To measure the phase difference and RMS output displayed by the spectral measurement.

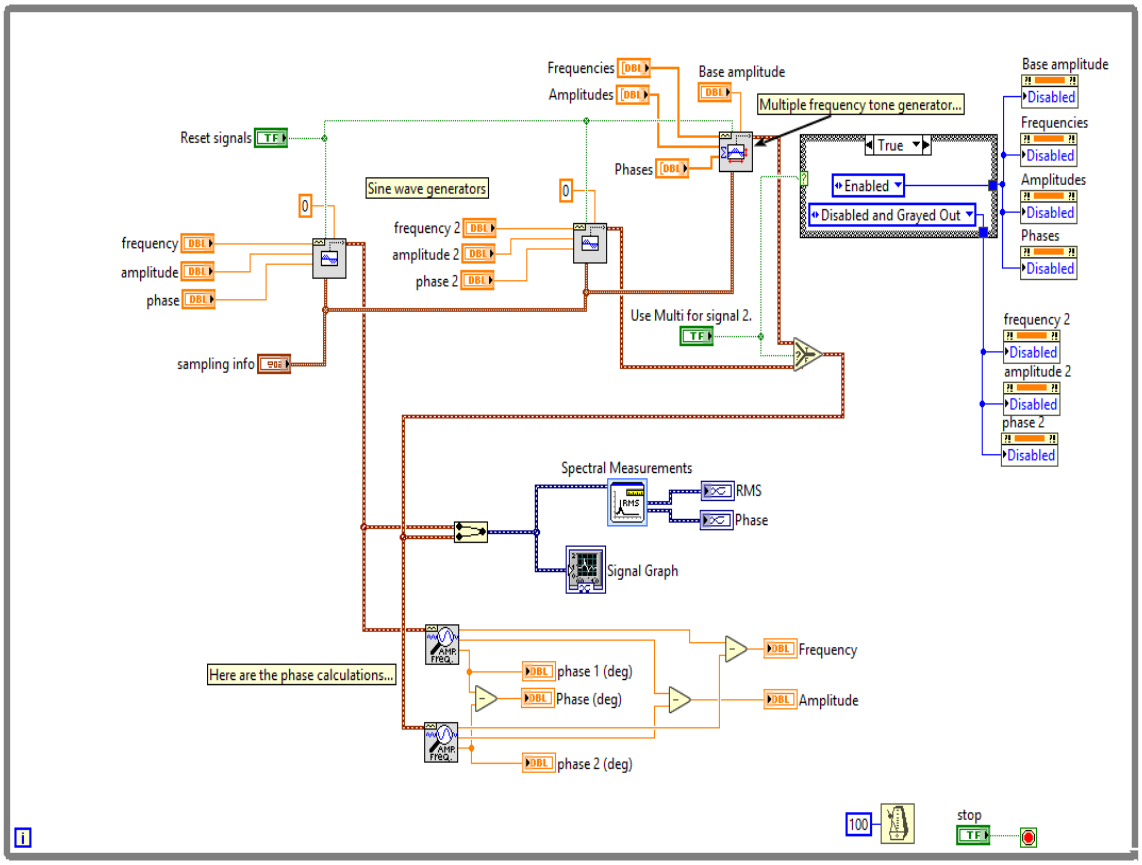
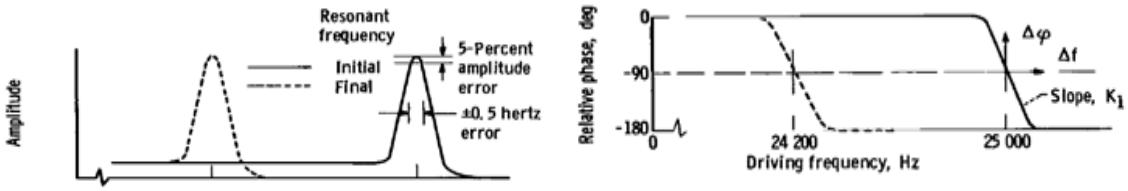


Fig 30: The control system for ultrasonic transducer

Phase locked loop of ultrasonic transducer



(a) (b)

Fig 31: (a) Resonance frequency response with time (b) Ultrasonic driver characteristics [54]

Phase locked loop method of ultrasonic transducer control system is the control system of frequency of ultrasonic transducer. This method of control system is compatibly better than the previous control system methods. Figure 31 (a) represents the mechanical oscillation driving frequencies closes to the design frequency. To maintain the amplitude peak value within 5 percent of it, sharpness of the control frequency accuracy needs to be ± 0.5 hertz.

By Dashed line on the graph is the changes of the resonance frequency after 20 minutes from its starting result of 25 to 24.2 kHz. Figure 31 (b) used to show the phase difference between the mechanical output and the electrical input oscillation.

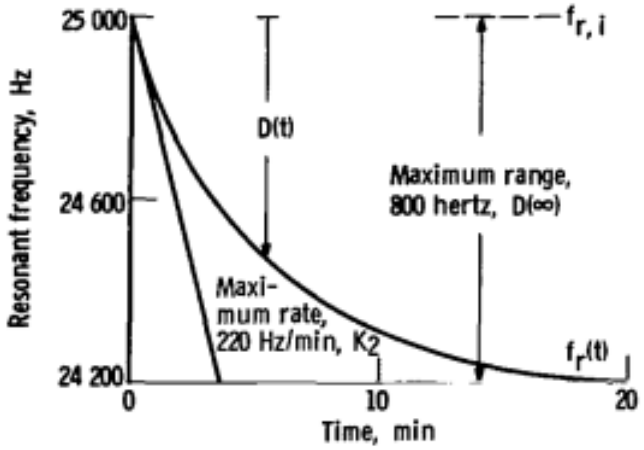


Fig 25: resonance frequency variation [54]

The resonance frequency variation with time presented by a test result in this figure 25. A maximum range of 800 hertz with the minimum rate of 220 hertz changes per minute. Here the time intervals 20 minutes.

From the figure 32 block diagram it shows that that the transducer is driven by the power amplifier. This power amplifier adjusts the proper power level for the ultrasonic transducer by controlling the gain. Voltage control oscillator relates to the power amplifier which supply voltage to power amplifier. Output frequency of the oscillator where the voltage is controlled is proportional to the input of the direct current voltage. The voltage-controlled input is obtained from the phase demodulator with low pass filter, which input is two electrical signals. To maintain the resonance of the electrical signal the relative phase of the two signals must be controlled to -90 degree. The filtered output of the phase demodulator is a direct current voltage proportional to the deviation of the phase difference between the signals from the -90' point. The error between the two signals driving frequency and resonance frequency is proportional to the direct current voltage which applied to the voltage-controlled oscillator which found the resonance from driving frequency.
The error can be calculated from two equation and defining the range.

$$f_{dr} = f_{\mathrm{ri}} - K \tag{3}$$

Equation for characteristics of transducer from fig

$$\Delta_{\varphi} = K_1(f_{\mathrm{dr}} - f_{\mathrm{r}}) \tag{4}$$

The equation for resonant frequency

$$D(\mathrm{t}) = f_{\mathrm{r}}(\mathrm{t}) - f_{\mathrm{ri}} \tag{5}$$

After having the solution of these three equations is the closed loop error

$$f_{dr} - f_r = \frac{-\mathrm{D}}{1+\mathrm{K_1K}} \tag{6}$$

The integrator inside of low pass filter and voltage control oscillator in the phase locked loop control system make it possible to have a voltage in the input to the voltage-controlled oscillator without any error.

The error in phase locked loop can be calculated from the transducer characteristics equation and the resonant frequency.

$$f_{dr} = f_{ri} - k \int \Delta\varphi dt \tag{7}$$

If input range is

$$D(\mathrm{t}) = K_2\mathrm{t} \tag{8}$$

By taking input range in count the error will be

$$f_{\mathrm{dr}} - f_{\mathrm{r}} = \frac{\mathrm{K_2}}{1+\mathrm{K_1K'}}(1 - \mathrm{e}^{-\mathrm{K'K_1t}}) \tag{9}$$

The error must be less than 0.5 hertz that's why the open loop control gain must K' must be

$$\lfloor K' \rfloor \geq \frac{\lfloor K_2 \rfloor}{0{,}5\lfloor \mathrm{K_1} \rfloor} \tag{10}$$

The phase locked loop control error is not function of variation of resonant frequency only the rate of variation. The major advantage of phase locked loop method because resonance frequency variation K_2 was relatively small, and D was large.

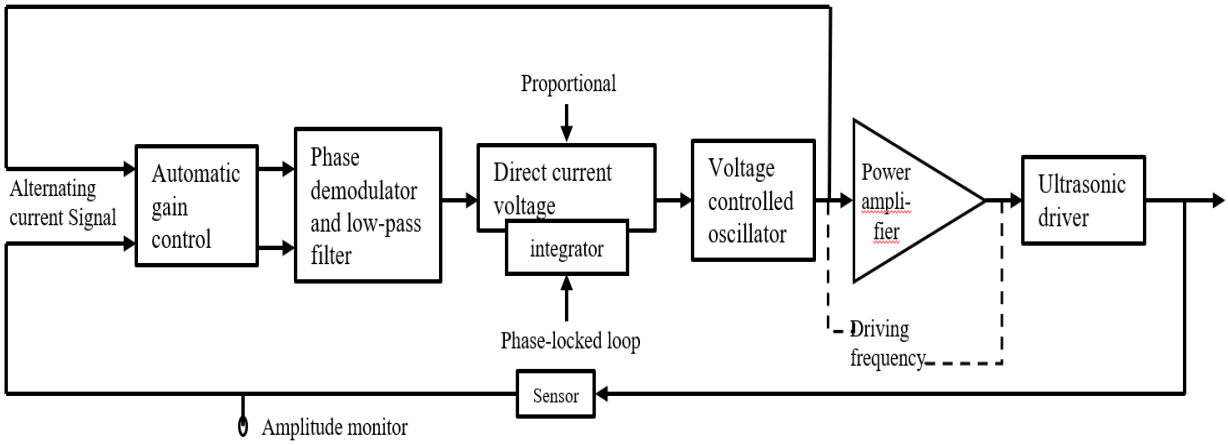


Fig 32: Phase locked loop control system [54]

Phase locked loop error is less than the function of resonant frequency range variation in conventional proportional control system. This control system can be setup commercially available equipment's. In this control system the automatic gain controls are the Schmidt triggers that convert input sine wave to signals of constant amplitude. [54]

Dynamic Tuning

Dynamic tuning method for ultrasonic transducer resonance is founded on retaining the resonance constant at zero value presented in figure 33. On the other hand, the frequency driving signal from the voltage-controlled oscillator adjust by the phase of motional admittance of transducer. The process of adjusting the frequency done automatically and instantaneously.

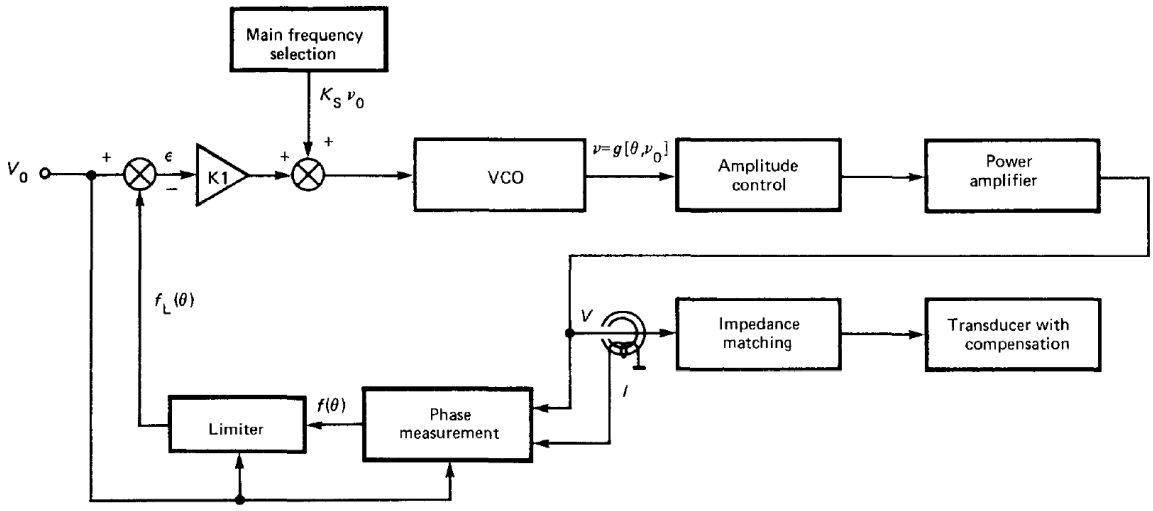


Fig 33: Circuit diagram for dynamic tuning ultrasonic transducer [55]

By assuming mechanical resonance ω_0

Where $\omega_0 \boldsymbol{L} = 1/\ \omega_0 \boldsymbol{C}$, Here the inductance is denoted by the L and capacitance by C of the electrical circuit for ultrasonic transducer operating near the resonance frequency.

From that electrical conductance denoted by G and susceptance B,

$$G = \frac{1}{R} \tag{11}$$

$$B = \omega_0 C_0 \tag{12}$$

Here if we do the tuning of capacitance C_0 by an inductance L_0 parallel connected with the transducer in the circuit. In that case impedance of total driving point will behave like resistive component

The center frequencies of the band of electrical and resonance ω_r and mechanical resonance ω_0 merge into one when the capacitance is compensated to C_0. Which is characterized by the peculiarity of annulling the value of B and therefore the phase of the admittance of the transducer.

Reactive component started working if the transducer started to operate out of resonance frequency. Because of that the only phase difference between voltages passing through the current in the transducer is zero. This is the only phase difference happens only at the center frequency at the resonance band. There is a phase difference in the frequency which is not

at the resonance. When the operating frequency varies from ±50 degrees in the extreme of the band, the finite value of phase difference started to rise.

To drive the ultrasonic transducer at resonance frequency the operating frequency of transducer need to be adjusted continuously to keep the phase difference zero. The system shown in the figure 33 have a voltage-controlled oscillator (VCO) to drive the transducer at resonance frequency. Frequency is controlled by a voltage dependent magnitude of the mentioned phase difference. [55]

Electronic system description

Figure 28 is the design of the circuits which describes the electronic configuration results quite good results from the experiment by supplying various power amplifier and ultrasonic transducers operating at high Q air. For the voltage and current measurement and processing of the transducer there is two circuits for that. The limiter connected with the two signals which phase difference measured. Output of the VCO relates to the power amplifier by means of an emitter-follower preamplifier. [55]

Measuring phase difference:

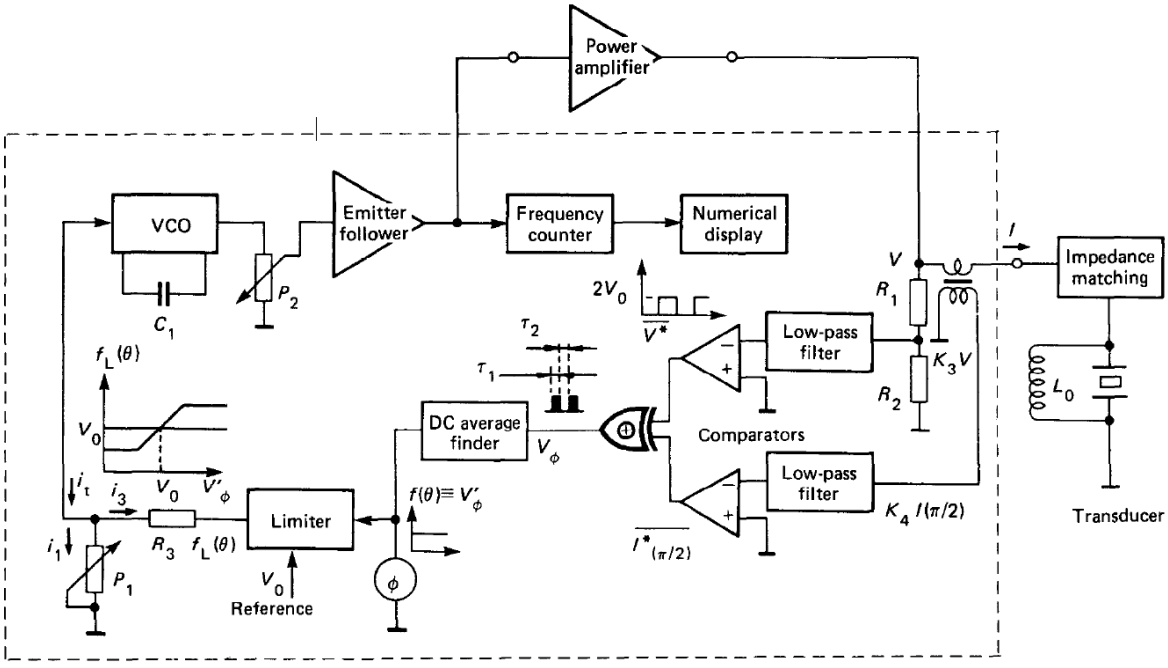


Fig 34: Electronic system Block diagram [55]

Output of the pulsed signals of exclusive OR gate and DC average calculator of the gate is used to measure the phase difference between the voltage and current signals. Two level comparators relate to the output of this exclusive OR gate in a way that it obtained below output logic function.

$$V_{\emptyset} = \overline{V*} \oplus \overline{I*(\pi/2)} = \overline{V*} \cdot I*(\pi/2) + V* \cdot \overline{I*(\pi/2)} \quad (13)$$

The figure 35 shows the plot of $V_{\emptyset}$ in opposition of the time as a function of the signals V and I for phase differences. From the figure 35 it's easily visible that the resonance of voltage and current are in phase, $V_{\emptyset}$ results in square wave ($\tau_1 = \tau_2$) which by means of the DC average finder gives rise to an analogous signal $V'_{\emptyset}$ of the value $V_{\emptyset}$.

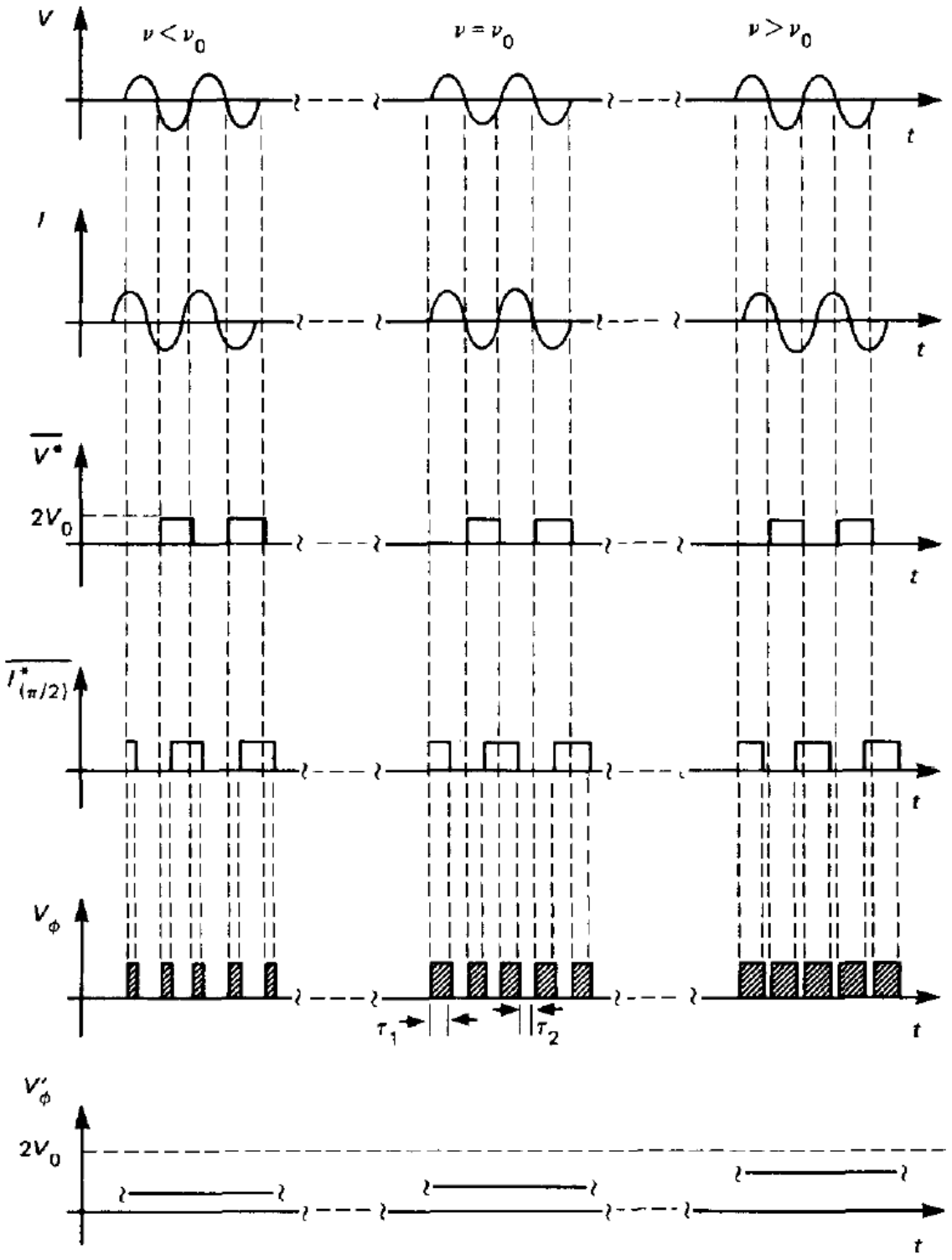


Fig 35: phase measurement of the using the plot diagram against time [55]

There will be the finite phase difference of the voltage and current if the ultrasonic transducer is not running at resonance frequency. Here if the currents lag the voltage then the frequency

will be higher than the resonance or if the current leads voltage then the frequency will be lower than the resonance frequency. At first when the signal frequency is higher than the resonance the exclusive OP gate will be asymmetric where the pulsed signal $V_{\emptyset}$ in the gate. Here $\tau_1 > \tau_2$ which causes the rise of voltage $V'_{\emptyset}$ higher compared to the magnitude proportional of V_0 to the phase difference where the value $2V_0$. When the phase difference is $\pi/2$ the magnitude is $2V_0$. The $\tau_1$will be lower than the τ_2 also the voltage $V'_{\emptyset}$ is less than if the frequency will be lower than the resonance.
[55]

Ultrasonic cleaning system

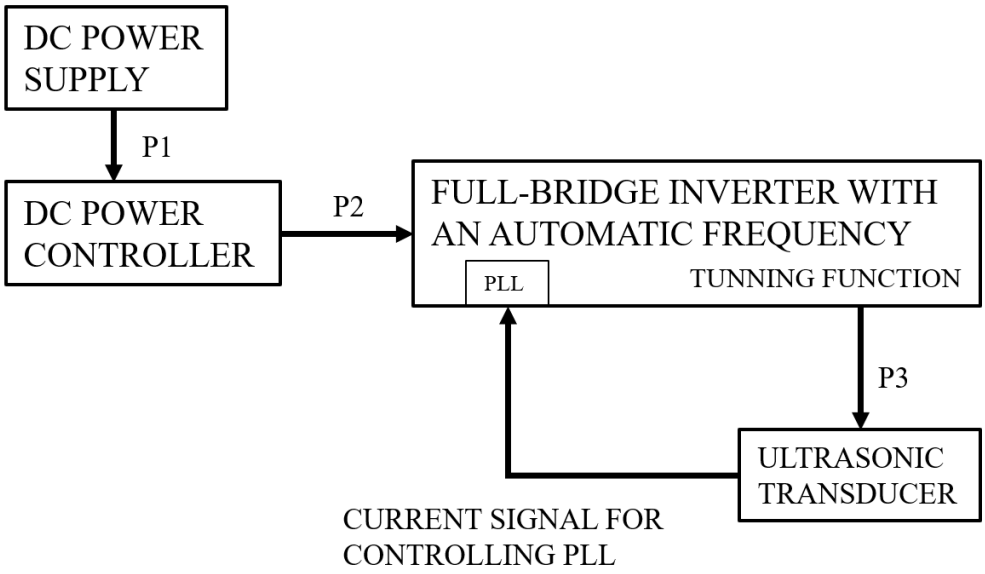


Fig 36: schematic diagram of cleaning system using ultrasonic [56]

The cleaning system using ultrasonic designed in way that a direct current power controller connected with the DC power supply to control the power supply to the ultrasonic transducer. A full bridge MOS-FET DC-to-RF power inverter with an automatic tuning function relates to the power controller to control it shown in the figure 36. From the DC power supply the power input P1 is supply to the controller of DC power which is fixed DC voltage. Power output from the DC power controller P2 is fed into the full bridge MOS-FET DC-to-RF power inverter which controlled by the DC power controller. An automatic tuning function is attached with the full-bridge MOS-FET DC-to-W power inverter. Output of the DC power

controller is controlled by the pulse width of the running voltage. DC power controller can also be controlled digitally. [56]

4.2.3 **The power amplifier used to drive the transducer at high power at resonance**

Automation gain control

To adjust the power of the received signal by receive chain using analog or digital gain automation gain control (AGC) has been used from figure 37. According to [57] the lineup of the gain is manipulated “up or down” while controlling the signal to maintain the signal to noise ratio. An algorithm for the gain control may lower the gain in average if the input power is high due to the strong desired frequency. Automation gain circuit has two stage of amplification to amplify the signals. A simple transistor-based amplifier is used to amplify first then an op-amp based AGC amplifier has been used. AGC amplifier gain may vary according to the input signal level. To restrict over amplification of strong signal and enough amplification of weak signal automation gain control is used. Automation gain control apply very high gain when the signal is weak and the power of the signal falls, at the same time automatically decreases their gain. This kind of amplifier can be found in the circuits of the audio amplifier circuits, audio ICs, signal analyzers etc. [58] AGC main purpose is to suppress audio transients which can be harmful for human ear. By improving the audibility of sound AGC helps to hear in noisy environment. AGC adjusts the amplification to keep the output signal within bounds. [59]

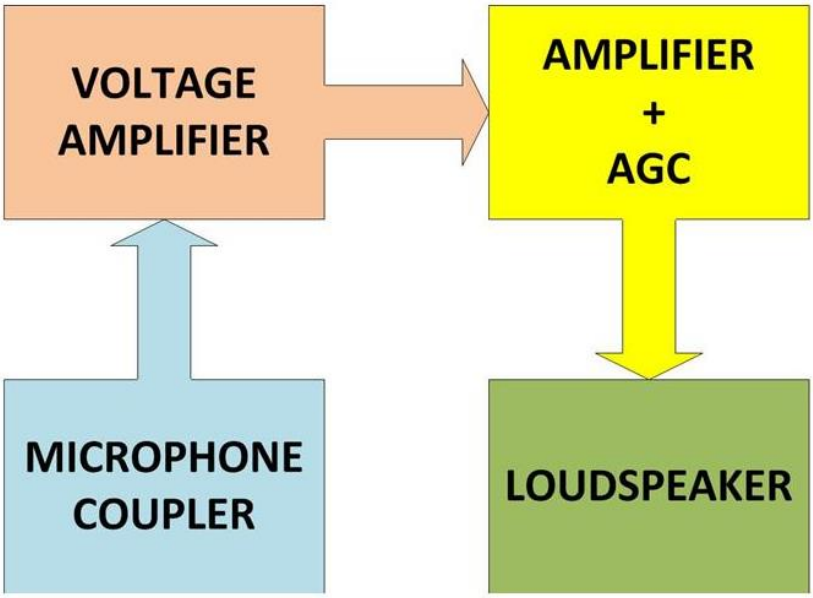


Fig 37: Schematic diagram of automation gain control system [58]

Microphone coupler

When the weak audio signals generated from the microphone coupler is used to couple out this generated weak signal. Different microphones have different kind of operating principle to do the couple out weak signals. Avoiding other things every microphone has a diaphragm which vibrates in order to the generated around signals. Due to the amplitude of the sound signals the diaphragm vibrates and because of vibration the current following through the microphone varies. [58]

Voltage amplifier

The voltage amplifier acquires the signal from the microphone coupler. This amplifier has fixed gain which amplify the audio signals of the microphone for enough level of automation gain amplifier circuit. The designed circuit have very extremely high gain to able to make proper amplification of signals.

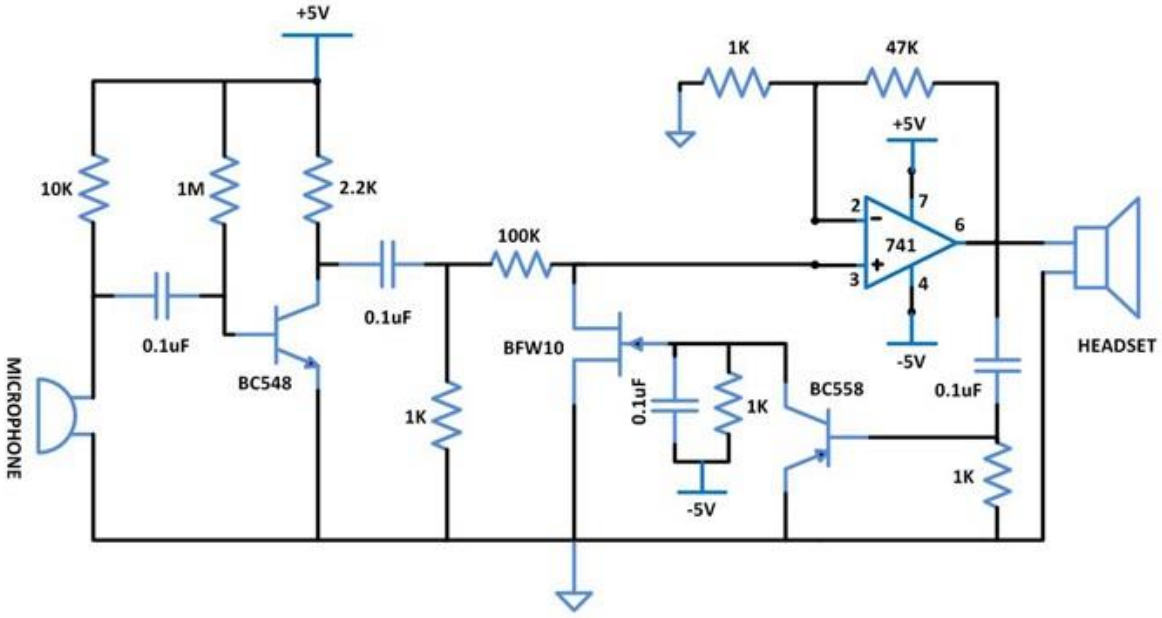


Fig 38: Voltage amplifier circuit diagram [58]

In this circuit figure 38 a 2.2 K ohm resistor was used to pass higher than the one-mile ampere current via the transistor. Series connected resistor with the transistor BC458 which creating around 2.8 volts in Vce.

$$V_{\text{ce}} = 5 - (2200 * 1\text{ mA}) = 2.8\,V \quad (14)$$

For this circuit output current is fixed at 1 mA. The output current produced by the input current can be calculated by the help of the hfe of a transistor with the input and output currents. Here hfe generally known as a current gain from the equation

$$hfe = I_c\,/I_b \quad (15)$$

Here,

I_c Current output of the collector

I_b Base current of the input

We know the maximum hfe value of a transistor 300. Now applying the value of$I_c$and hfe in the equation we can get the I_b , which is around 4uA.

Due to base resistor R_{b} voltage V_b across resistor reduced 0.7 volts. Since the supply voltage is 5V and due to base resistor obstacle, the supply voltage become 4.3 volt.

$$R_{\text{b}} = \frac{4.3\text{V}}{4.3\text{uA}} = \text{ 1M} \quad (16)$$

To couple the audio signals a 0.1 uF capacitor is used between the amplifier stage. [58]

Amplifier + AGC

The amplifier including AGC circuit figure 39 has conventional amplifier based on op-amp with the negative feedback amplifier, which have on its positive pin an additional feedback network. We know normally in negative feedback amplifier in its negative pin have fixed gain by the feedback resistance. On the other hand, this circuit has a positive feedback input pin that why the gain varies also for this.

A field effecting transistor (FET) includes in the feedback network on the positive pin which behaves same as a resistor with variable voltage facilities. A transistor that drive FET and RC filter is generate a varying gate voltage for the FET according to the varying the signal strength at the output of the op-amp.

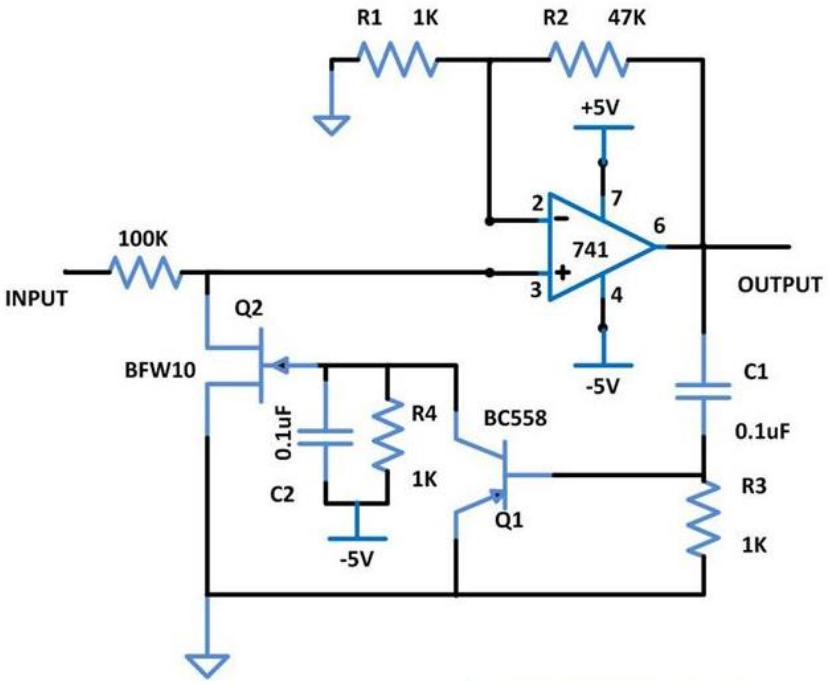


Fig 39: Circuit diagram of Amplifier with AGC [58]

A PNP transistor base received the couple of audio signals by the capacitor C1 from the output of the op-amp. By using capacitor C2 and resistor R4, the output of the op-amp and the DC equivalent voltage is couples by an AC signal. In this circuit the behavior of the Q1, C2 and R4 known as almost same kind of single diode rectifier and here C2 and R4 act like a RC filter and Q1 behaves like a rectifier.

In this circuit voltage to control trans-conductance which act like voltage varying transistor in the gate of FET voltage supplied. If the supply voltage increases to the FET, the

conduction of FET increases, and gain reduces. This operation principle to controls the gain of the op-amp based on the output of op-amp signal amplitude. [58]

Phase demodulator

The phase demodulator input is two electrical signals. Feedback signal position represents the mechanical oscillation of the however the reference signal is the electrical input driving frequency. This two-signal phase must be controlled to 90° to maintain the resonance. After filtration the output from the phase demodulator is the direct current voltage. In addition to proportional to the deviation of the phase difference between the signals from the 90° point. Phase demodulator working principle is to do the phase shift of carrier wave. We know that in the case of phase demodulator is an incidental shift in frequency when the phase of carrier wave shifted.

Phase demodulator used in another purpose like radar circuits and as well as communication circuits. Radar may find the pulse-modulated signal by using a simple circuit, which detects the presence of the RF (reflected from a target) energy.

A phase demodulator circuit analysis a modulated reference signal and from that it produces an output which is proportional to the reference phase deviation.

A phase demodulator may operate in two ways,

For the phase detector output considering a voltage

By taking the integral of the VCO input.

Phase locked loop uses first one, where the phase/frequency is used. A differential amplifier used to produce a single output voltage from the output voltage. The lowest signal frequency is should be higher than the loop bandwidth to avoid the correction of desired phase error. [60]

Power Amplifier

Many electronic systems need high output power to run the device that’s why in many electrical circuits has amplifier. To increase the magnitude of the power of the input signal basically a power amplifier is designed. Device like headphones, speaker and RF transmitters needed to increase the power of input signal to high level. To produce in output

thousands of kilowatts a radio frequency amplifier has been used. On the other hand, the DC amplifiers used to electrical control systems where high output power needed to drive the motors or actuators or different type of electrical instruments. For an audio system which way a power amplifier is used presented by fig 40.

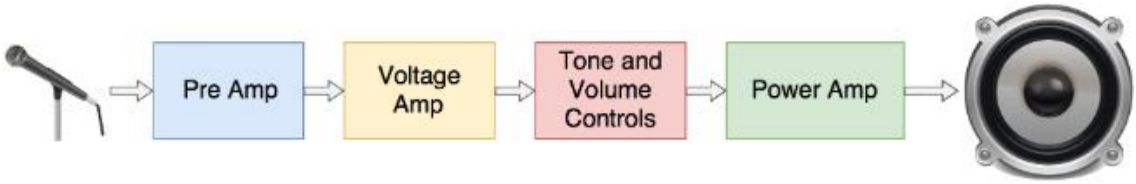


Fig 40: Operation of power amplifier

To amplify the 10 μA signal to 1mA a current amplifier is able do that job which gain has around 100 and it can be done with lower voltage output.

In first phase of experiment we have used a class D amplifier for transducer tuning. The biggest advantage of these amplifier can switch the output of the amplifier to one stage to another with the supersonic frequency. Also, the ratio of mark/space control give an average representing the momentary level of the audio signal. This kind of phenomenon is also known as pulse width modulation (PWM). In theory the efficiency of this kind of amplifier is high but in real world lots of difficulties came out, especially in world of tightening EMC legislation. Because it is no clear that for high frequency like 200 kHz might not be a good place to start. For deduction of almost all the RF an accurate cut-off low pass filter used between the speaker and amplifier. [61]

The I NUKE NU3000DSP power amplifier is an ultra-lightweight high density 3000-watt power amplifier which have the digital signal processing (DSP) control system and USB interface. To provide the ultimate signal integrity this amplifier has built-in DSP and 24-bit/96 kHz converter with extremely broad dynamic range. To protect from the overload inuke has technology called “zero attack” which offer maximum output level and able to run full-out for hour’s on-end. [62]

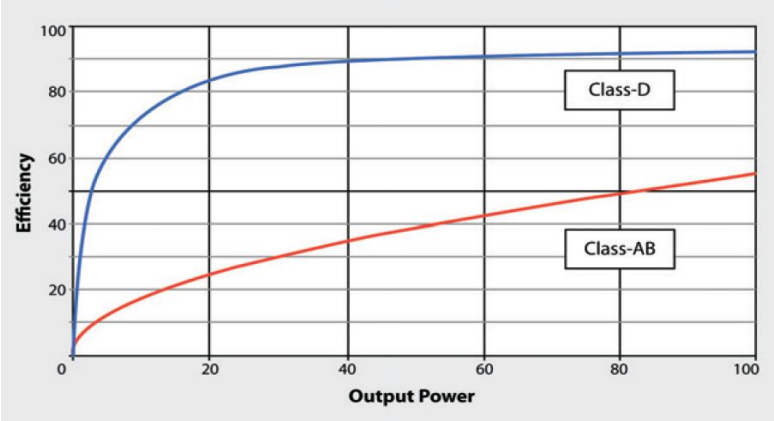


Fig 41: Inuke amplifier output [62]

The biggest advantage of this amplifier has a class D technology, which can offer enormous power and incredible sonic performance with ultra-portable and lightweight package specification presented in figure 41. Class D amplification technology is energy efficient compared to other amplification technology by eliminating the need of heavy power supplies and massive heat sinks.

Low pass filter

Filter aim is to allow such frequency to pass through the circuit. Filter is a circuit which gains varies through the circuit. Different types of filter available and used for various purpose such as Band pass filter, Low pass filter, high pass filter etc. [63] the most common and easily understood is the active low pass filter. The principle of operation of this filter and frequency response is same as the passive low pass filter. The easiest way to use low pass filter for connect an inverting or non-inverting amplifier. To supply the frequency from 0 Hz to its cut of frequency low pass filter being used. The construction of the RC low pass filter is a very simple process where a single a resistor and capacitor connected in series. [64]

To allow low frequencies to pass through the circuit, however, attenuates at high frequency a low pass filter is designed. Figure 42 represents the basic operation of low pass filter which only low to low frequency signal by blocking high frequency signal.

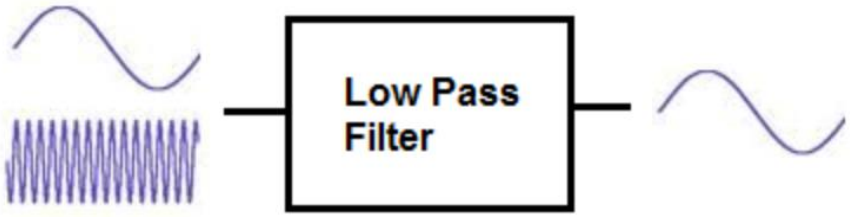


Fig 42: Low-pass filter basic operation [63]

In low pass filter low-frequency signals can go easily with lower resistance. On the other hand, high frequency signal faces higher resistance which make it harder to pass through the low pass filter. A capacitor or inductor are mostly used to construct the low pass filter. Filter called low pass RC filter composed of resistor and a capacitor. A filter having a resistor and inductor called low pass RL filter.

Low Pass RC Filter

As we know a low pass RC filter shown in figure 43 contains a resistor and a capacitor which allows to pass through the low frequency while blocking the high frequency signal that's why it's known as RC Low pass filter. In RC low pass filter a resistor placed in series to the input signal while the capacitor is placed in parallel of input signal. [63]

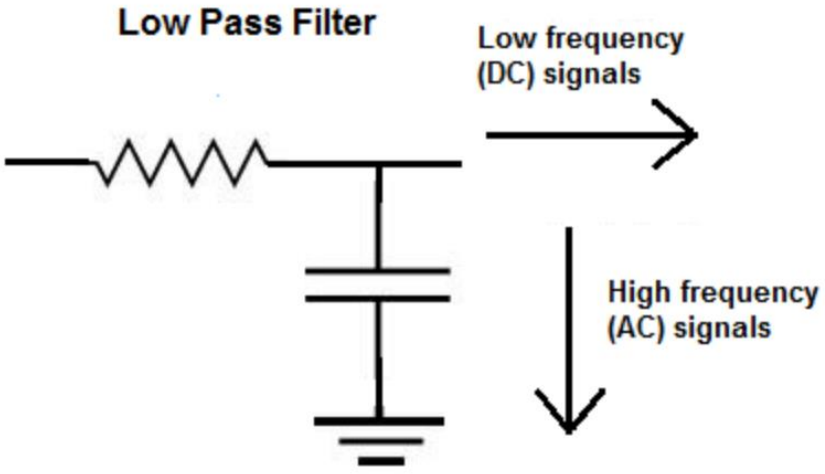


Fig 43: Low-pass RC filter [63]

The above circuit figure 37 is a low pass RC filter containing capacitor and a resistor. Due to reactive nature of capacitor it provides resistance to signals of different frequency which

entering through the capacitor. Because of reactive behaviors of capacitor, it offers high resistance to low frequency signal and opposite for the high frequency signal.

Low pass RL filter:

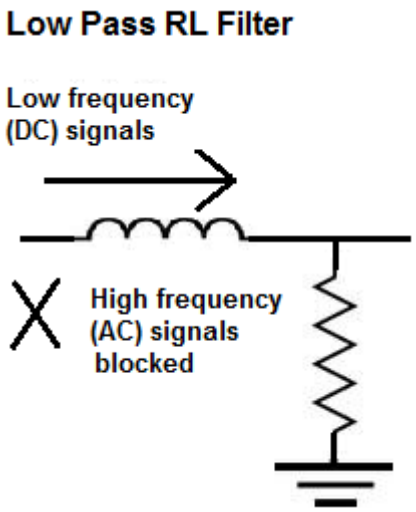


Fig 44. Low-pass RL filter [63]

A low pass RL filter is a circuit containing a resistor and inductor which allows to pass low frequency signals blocking the high frequency signals. An inductor placed in series and a resistor placed in parallel to the input signal following the fig 44.

The principle of RL circuit is operation is the inductive reactance. Based on the frequency passing through the inductor, inductor changes the inductance or the resistance of the inductor. Because of inductive reactance behavior of inductor, which allows to offer various impedance for different frequency. In addition to inductor behaves totally opposite of capacitor. Inductor to control the high frequency signal creates higher resistance and for the low frequency signal there is lower resistance. [65]

4.3 The electrokinetics system

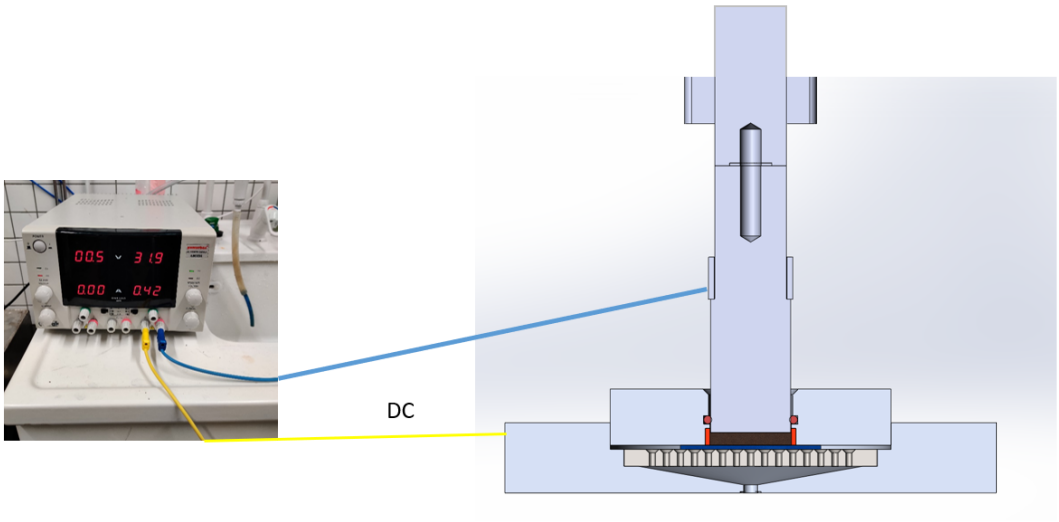


Fig 45: Electrokinetics setup

To apply electrokinetics in our designed system we used a DC power supply shown in figure 45. Here the anode and cathode connected with the horn and draining plate. We are supplying AC to drive the transducer by a power amplifier. To apply electrokinetics we are using DC. The problem here is the we can't apply two different types voltage source in the same load. A thin film used for the insulation of the horn from the ultrasonic transducer. The thickness of this insulation material 0,075mm. Using the DC power supply, we supplied three different range of voltages such as 15, 30 and 45. The electrokinetics applied to the sludge for an hour with the ultrasonic.

4.4 The control system used to measure the temperature of the transducer

The temperature of the transducer measured to avoid any critical situation of the transducer. By measuring the temperature of the transducer, we can tune our cooling system. If the transducer become very hot, we can increase the pressure of cold air from vortex cooler. This approach can save the cost of running the cooler all the time. We know that if the transducer temperature going above then 40 degree centigrade considered harmful for the lifetime of the transducer. The safest way to avoid this situation is monitoring the

temperature of the transducer. So, the designed system shown in figure 46 has the notification system which notified the user if the transducer temperature going above the critical temperature. We need to analysis the temperature of the transducer during the running to measure the effect of transducer temperature at dewatering. To do that the control system has the data saving option. Here the figure no 40 is presented the control system of temperature.

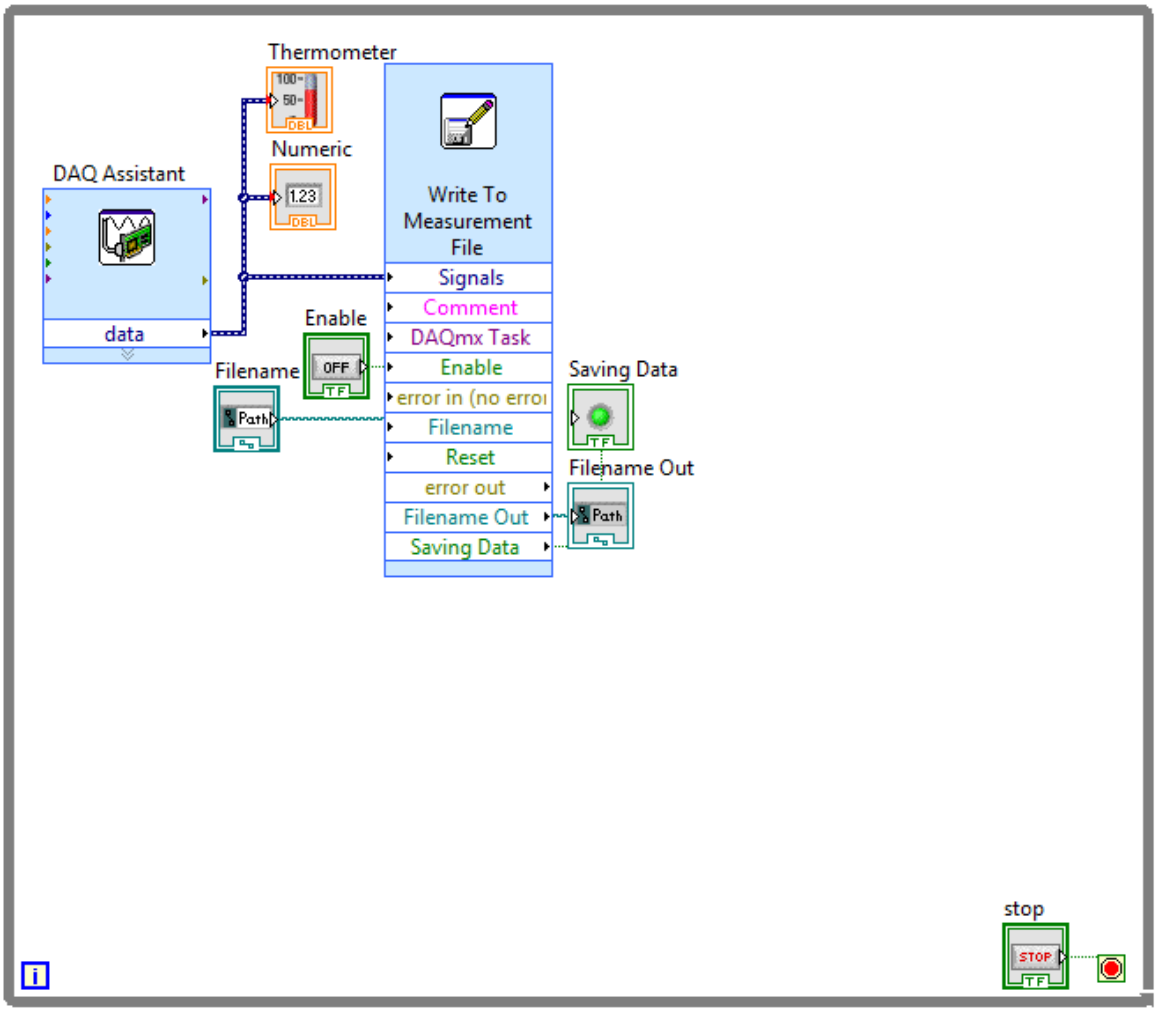


Fig 46: The temperature measurement system

5 THE POTENTIAL PRACTICALITY OF ULTRASOUND- AND ELECTROKINETICS-ENHANCED DEWATERING METHODS

5.1 Dewatering dramatically enhanced by adding ultrasound and electrokinetics

After having some experiments done in our lab, we have observed that adding electrokinetics and ultrasound together improves the dryness of dewatering result. At first, we did some experiment with different thickness of the sludge with the three different transducers. After having these experiments, we stored the resulted data. Later we done some experiments with the voltage range by electrokinetics. The resulted data observed and compared it with the tested result of the ultrasonic. After that we did some testing with the combination of electrokinetics and ultrasonic and observed the result. After analyzing the resulted data from the experiments seems that the dryness of the sludge from the combination of electrokinetics and ultrasonic are much better than the resulted data from the each ultrasonic and electrokinetics.

After running 15 kHz ultrasonic transducer for an hour with 9mm thickness of sludge we have received 20.5% of the dryness. On the other hand, when applied only electrokinetics with three voltage ranges such as 15, 30, and 45 the dryness is about 40%. After combining them together the result of the dryness satisfied which is around 60%. Here we use 15 kHz transducer with 30 V electrokinetics.

5.2 The practicality of this dewatering method in industrial sizes

From the research done by (Gallego-Juarez, 1989) [66] that high power ultrasonic transducer has huge viability ultrasonic cleaning and welding. To run ultrasonic transducers in an efficient way energy conversion technology needs to be assured.

Our designed system cost total around euro 10000. We have used to 3 different size transducers to compare the dewatering result each one of them. After having several experiments, we have noticed that the lower frequency transducer can provide better dewatering result from sludge compare to the greater one. In our case, a 15 kHz transducer able to dewater 60% of water from the sludge whether a 30 kHz can extract only 45% from

the sludge. A piezo driver PDUS 200 is used to drive the transducer in resonance frequency. To get the optimal output from the transducer it's obvious to run the transducer in resonance frequency. This driver can be used to find the resonance frequency automatically or manually. For electrokinetics, a DC power supply is used in the system at 30 V range. Applying several transducers in series with electrokinetics, we can increase the capability of dewatering sludges. This system can run without major maintenance for long time. Because of time running of these transducers it's become heated which also effect the result of dewatering. The DAQ box USB 6341 is used to measure the temperature. By collecting data of temperature from this box we can analysis the current heating condition of the transducer. According to [67] ultrasonic transducer has thermal influence in dewatering quality. When energy is absorbed by ultrasonic transducer is converted to heat which lead to decrease the viscosity and surface tension. Smolen, M says in his research [68] that in solid and liquid high frequency acoustic wave causes extreme inertial and elastic forces in the solid liquid surface. Which results water separation from sludge, reduce viscosity improves dewatering quality.

Energy consumption of this piezo driver changes with frequency of transducer. Different frequency range transducer consumption of electricity varies with them. Here 15 kHz transducer electricity consumption obviously different from the 30 kHz transducer. A

A sludge dewatering belt filter press machine DNY 500 will cost around euro 9000, which can dewater 45 kg per hour. The weight of this machine 1 to 6 ton which require a big space to operate. The major fact is that its dewatering percentage is 38% from table 8, which will change with the type of sludge. This large machine needs proper maintenance to operate in long term. The maintenance of this type of machine very costly and need to do under professional supervision. Before injecting the sludge to the filter plate, sludge need to go through the material extraction process. The extraction of material is like metal, plastic etc. Which can damage the machine. Belt filter press machine is highly recommended for the sludge with higher moisture content. [28]

In addition to rotary press is machine is also very popular for dewatering purpose. A rotary press machine will cost euro 10000. Machine weight is 1100 kg, which is also like the belt press machine. The capacity of dewatering is comparatively low compared to the other technology. Rotary press machine limited space to store solid inside of the machine.

Maintenance is the biggest issue here for the rotary press because some special design machine requires major maintenance. Not suitable for the incompressible solids. [69]

Dewatering machine	Energy consumption (kWh/ton/10% increase in TS)	Price (€/ton/10% increase in TS)
Rotary press	0,083	0,006
Centrifuge (decanter)	0,583	0,042
Belt filter press	0,111	0,008
Filter press	0,125	0,009

Table 8: Energy consumption with the price of conventional dewatering machines [70]

5.3 Dewatered sludge dryness

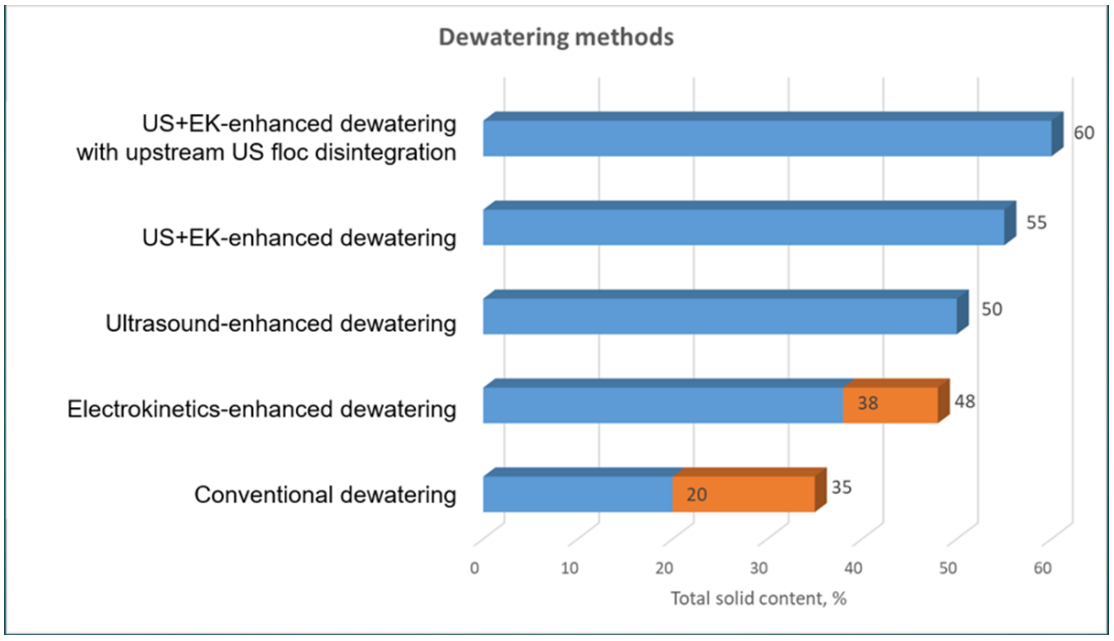


Fig 47: Graphical representation of Dryness of solid content

After having several experiments with our designed system, we got this result presented in figure 47. Here in the figure we have compared the dryness of our designed with the other conventional dewatering method. Using ultrasonic transducer for dewatering able to provide 50 % of solid content. Whether electrokinetics is can do slightly lower than the ultrasonic transducer. However, using both ultrasonic and electrokinetics in the same time can enhance the result of dewatering. According this method we have achieved more than 50 % of solid

content. The dramatic result we have achieved from the dewatering method which is contains both ultrasonic and electrokinetics with UP stream floc disintegration. Dryness of solid content after having the experiment is 60 %, which is greatest number of dryness from all the other dewatering method. Compared to the other dewatering method this technology become most effective regarding the dryness of solid content. According to [71] dryness of dewatered sludge depends also the time of operation. Different type of sludge required various amount of time to reach that percentage of dryness. Like as the municipal sludge dryness time will be different from the industrial sludge, which contains metal, ceramic etc.

5.4 The cost per kg total solid content

Ultrasonic system consumption

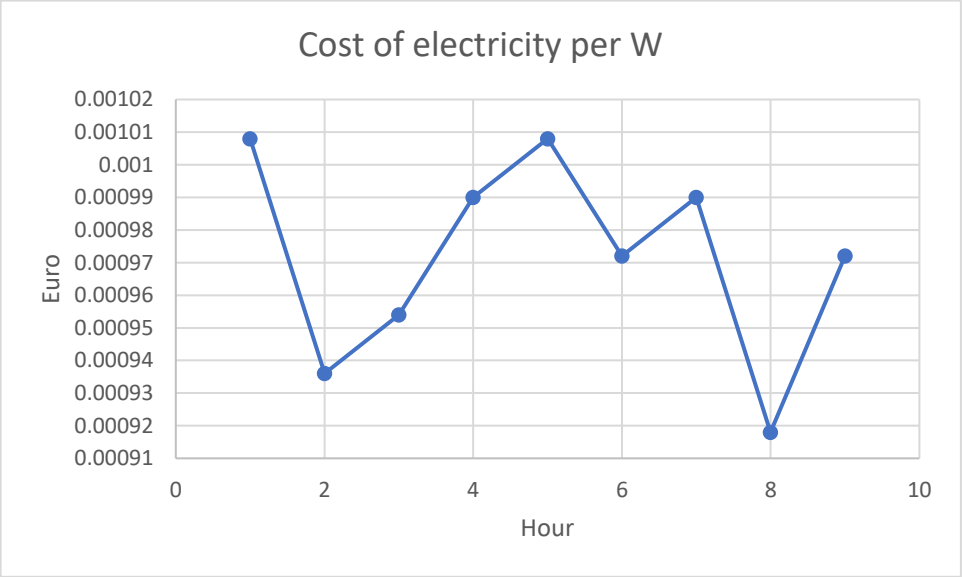


Fig 48: The cost of electricity consumption by amplifier

The consumption of electricity by the ultrasonic system is presented in the figure 48. Here the information about the price of the unit of electricity collected from online. The data is presented for the 10 hours consumption by a power amplifier that we have been used to drive the ultrasonic transducer. [72]

Combination of Electrokinetics and ultrasound

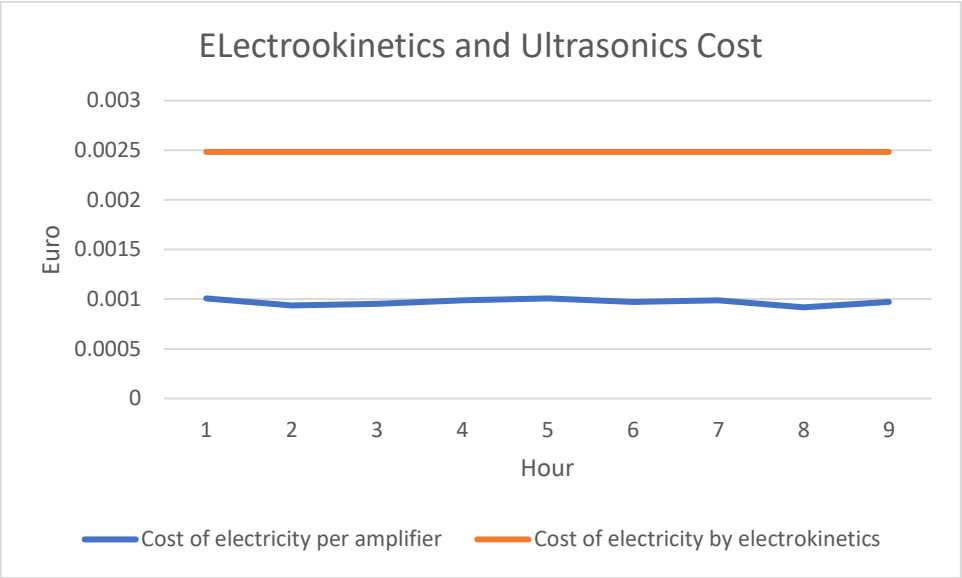


Fig 49: Cost of electricity of electrokinetics and Ultrasonic

Figure 49 is the graphical representation of the consumption of electricity by ultrasonic and electrokinetics. From the figure the power consumption by the electrokinetics is higher than the consumption by amplifier. Because the consumption of power by electrokinetics is 13,8 W where the consumption of amplifier is 5,6 W. If the power consumption is higher of any device its results higher running cost.

Cost estimation for current dewatering method

No	Name of the Apparatus	Price
1	Transducers	
	15 kHz	185
	20 kHz	185
	30 kHz	175
2	Electrical connection of transducers	200
3	DAQ box (USB 6341)	1450
6	Amplifier	500
7	Piezo Driver (PDUS 200)	5200
8	DC Power Supply	80
9	Pneumatic Cylinder	114,95
10	Vortex tube and Accessories	1325,56

11	Scales	242,25
12	Linear roller bearings	247,75
13	3D Printed Parts	340,47
14	Filter Paper	96,256
15	Fasteners	50
16	Miscellaneous	200
17	**Total**	9892,236

Table 9: Experimental equipment cost

To prepare the experiment setup for dewatering we have spent around ten thousand euro. The most expensive apparatus of this experiment has cost us 5000 euro which is the power amplifier. The one we used to drive the ultrasonic transducer. Next the most expensive is the DAQ box used to measure the temperature of the transducer. The transducer we have used to do the testing is cost 185 euro for 15 and 20 kHz. The pneumatic cylinder is used to pressure to the sludge has cost us 115 euro. For cooling the ultrasonic transducer, a vortex tube used to keep the transducer safe from critical temperature. The measurement scale used to measure the extracted water has cost us 250 euro. And linear roll bearing for pneumatic cylinder setup has cost us more 250 euro.

6 THOUGHTS ON THE POTENTIAL PRACTICALITY OF ULTRASOUND- AND ELECTROKINETICS-ENHANCED DEWATERING

The main idea of the thesis is to concentrate removing capillary and bound water from municipal sludge. After extracted water from sludge can sludge converted into a useful fuel. The conventional mechanical dewatering method can remove up to 40% of sludge water content with relatively low expenditure. On the other hand, the thermal dewatering is comparatively expensive dewatering method.

We have designed a whole system which includes mechanical and electrical dewatering technique. In mechanical system we have used pressure on to the sludge, which helps to water to separate from the sludge to the measurement scale. From the electrical side we used ultrasonic transducer and electrokinetics to extract water from the sludge. The designed system has wide range of markets. Our designed dewatering system can be used in mining, paper, municipal, wood industry, where they face big issue about the management of the sludge management. The designed system applicable for all type industry. So, the business market of this project has great future. The setup cost of this dewatering method is considered very cos effective compare to the other conventional dewatering method. The setup cost will be around 10 thousand euro where the other dewatering machine cost more than this.

Therefore, from the commercially available dewatering method 40 % of total solid content is achievable. This level of total solid content can be improved by ultrasonic dewatering system. Some mechanism of ultrasound system such as sponge effect, cavitation, atomization, microchannel production etc. are considered as effective mechanism for dewatering. From the ultrasonic mechanism cavitation creates better evaporation rates at initial stage. Theoretically, from the ultrasonic dewatering system around 60 % of total solid content is achievable.

Future research

The proposed method of dewatering will be beneficial for different types of sludge's available in the world such as mining, municipal etc. our future research will be testing the ultrasonic system on this type of sludge's and compare the result to decide which type of

sludge is more effective for out designed system. The decision will be made based on how much water extracted from the sludges.

The dewatering method of conditioning with chemical improves the result of mechanical dewatering. Calcium oxide, ferric acid, and polyacrylamide are considered as the chemical conditioner. In addition to using hydrogen peroxide as chemical oxidation improves the result of sludge dewatering in two ways. Hydrogen peroxide decreases the content of water in sludge by degrading the extracellular polymeric substance (EPS) proteins and polysaccharides. Another way to reduce water content by promoting flocculation helps to eliminate the content of fine flocs. [73]

Adding sulfuric acid improves dewatering result. Because the acidification creates gas bubbles on sludge's and leads which might leads to increase of sludge volume. Sulfuric reaction with sludge's results increase of dissolved phosphate concentration in the extracted water. In addition to adding too much acid results in a high concentration of dissolved phosphate in the extracted water. Adding optimal amount of acid helps to gets high percentage of dry solid content.

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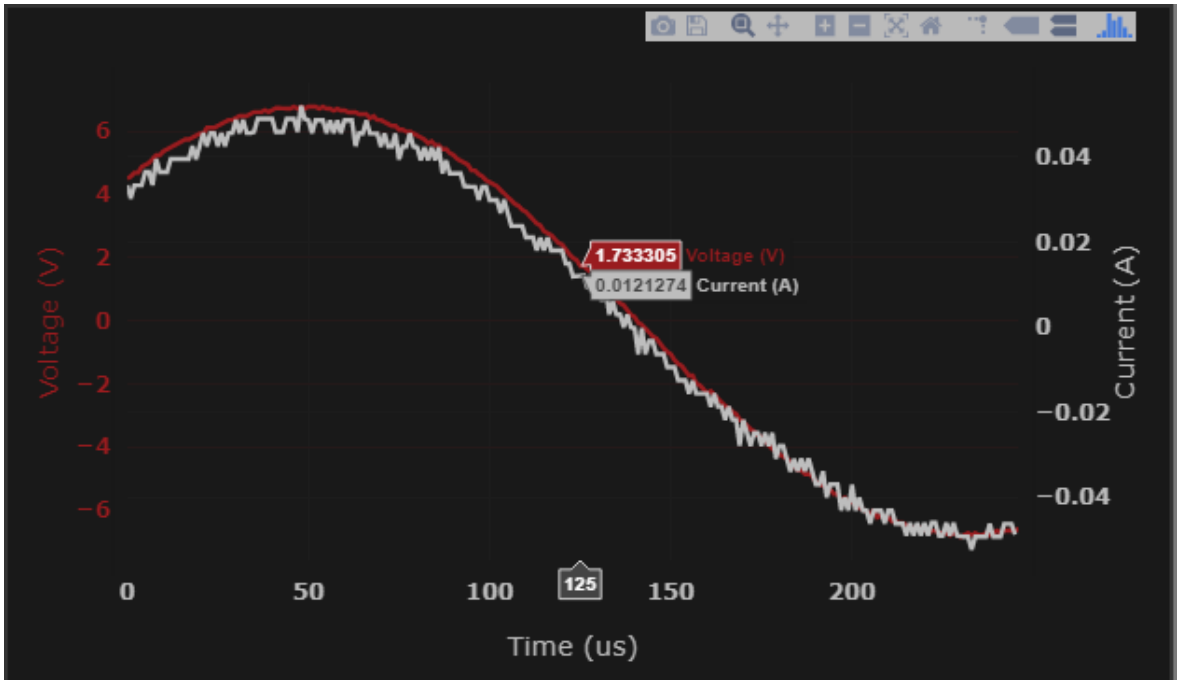
APPENDIX

Laboratory setup for transducer tuning

The transducer response at running at resonance frequency

The phase difference of the volatge and current for 15 kHz transducer



Running at resonance

The dryness of the sludge after applying before and after applying ultrasound

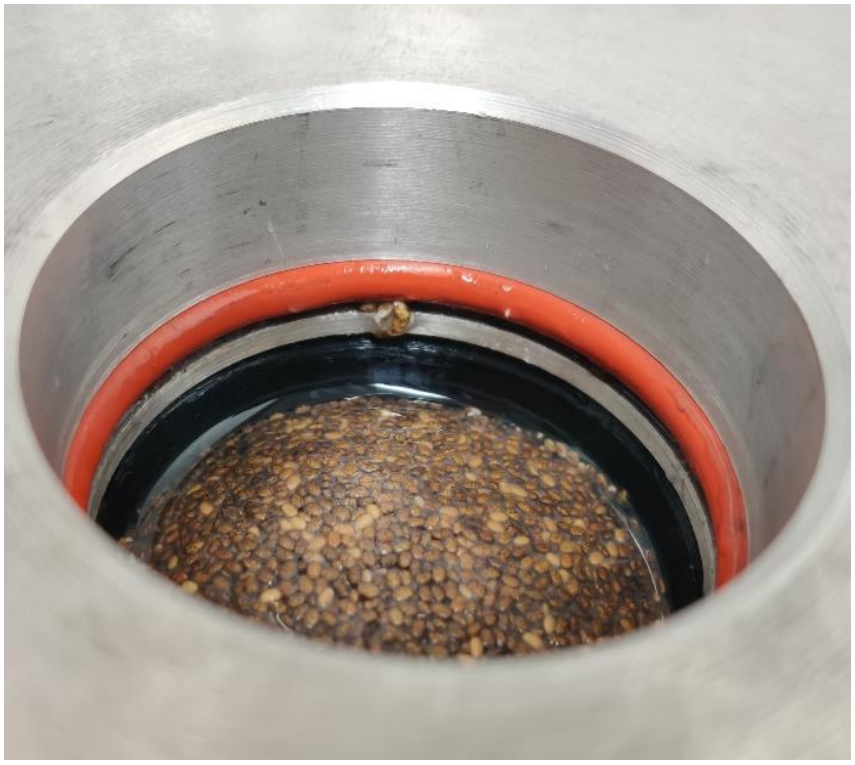
Before ultrasonic (TS 20%)

After ultrasonic (TS 35%)

The dryness of the sludge before and after applying only pressure

Before pressure (TS 20%)

After pressure (TS 25%)

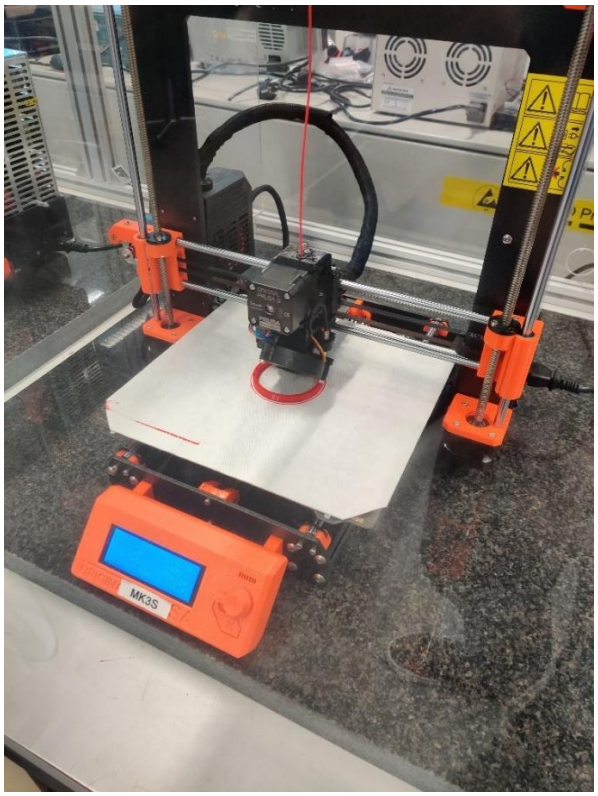


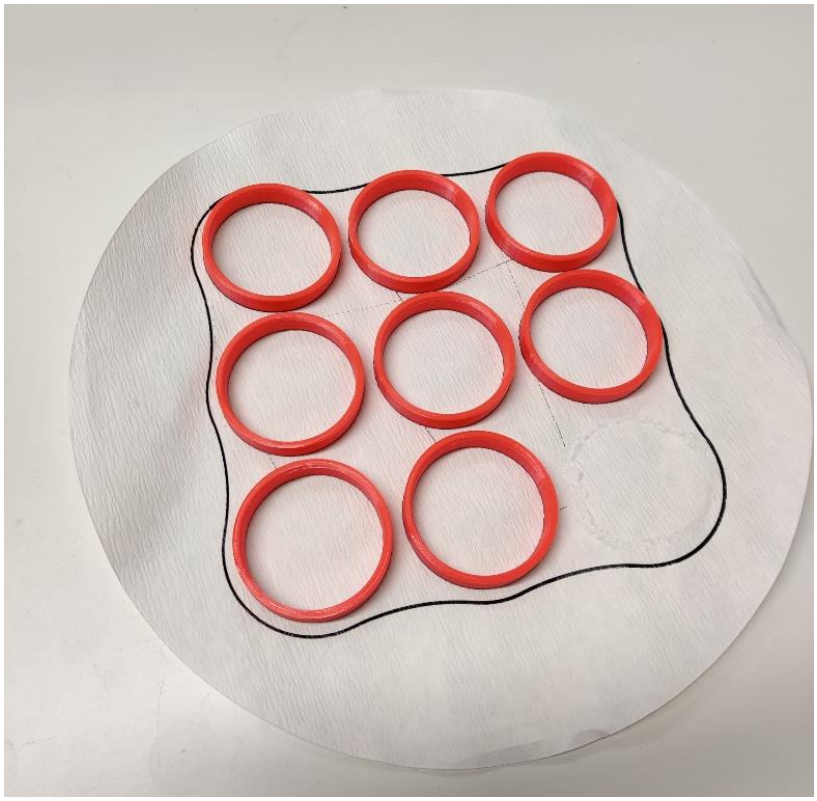
The dryness of the sludge before and after applying Electrokinetics

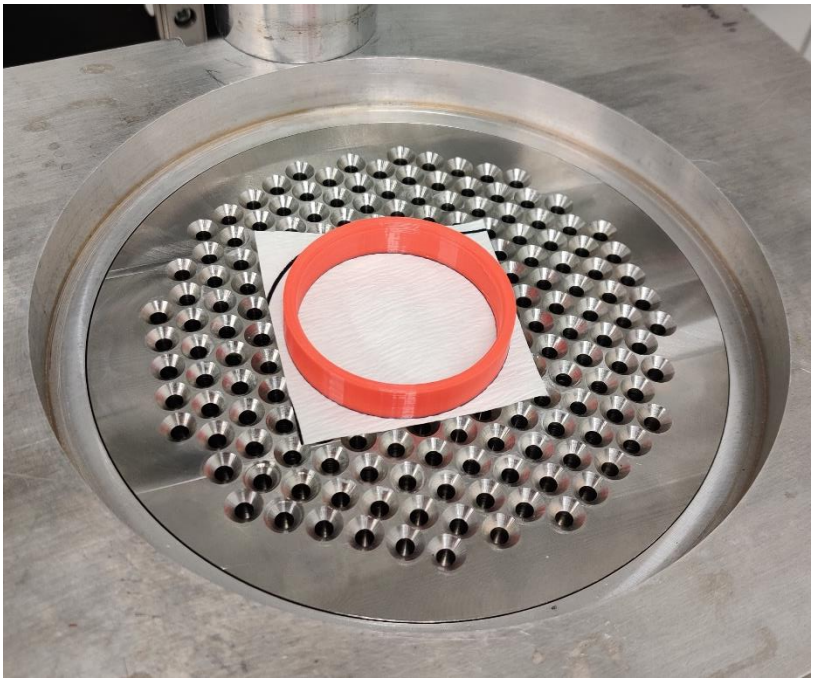
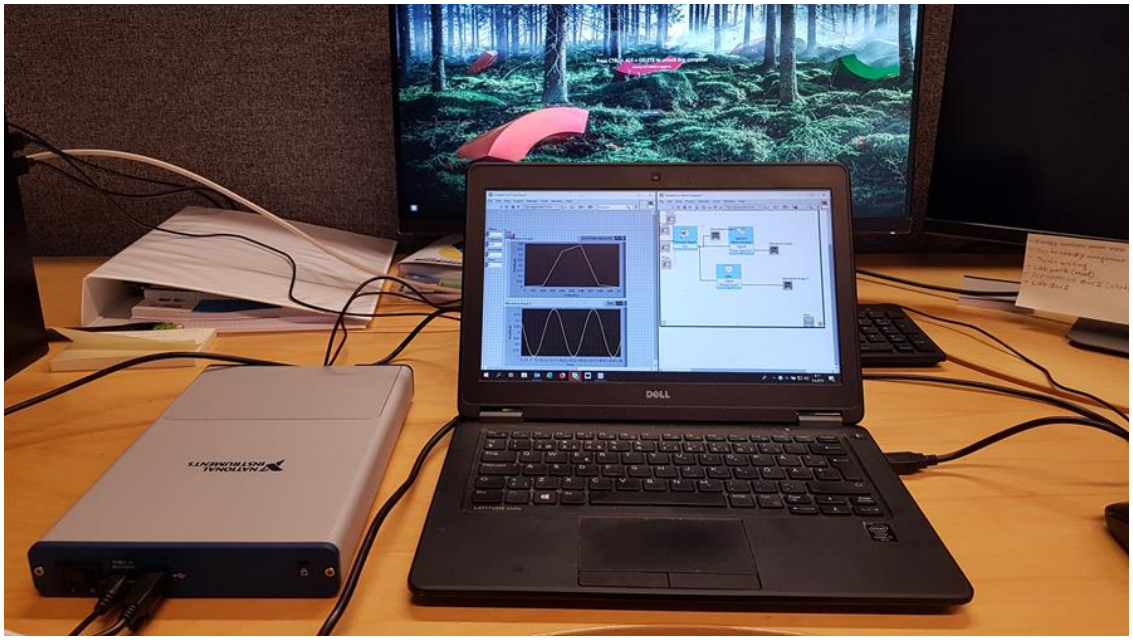
Before Electrokinetics (TS 20%)

After Electrokinetics (TS 48%)

Filter making procedure for sample







Data Acquisition box setup