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A Foundation for the Development of Deaeration-Efficient Hydraulic Tanks

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Abstract

As the sole component capable of releasing entrained air, a well-designed hydraulic reservoir is crucial for the health of any hydraulic system. This is especially important in mobile machinery, where even more air is entrained via the free surface. Entrained air in hydraulic fluids poses an unavoidable obstacle within mobile machinery, forming a complex multiphase liquid-gas system. This entrained air influences the behaviour of the hydraulic fluid, causing fluctuations in various parameters such as density, viscosity and bulk modulus. These fluctuations often result in a loss of efficiency, as well as reducing the dynamic performance of the system. As electrification of mobile machinery increases, the installation space for hydraulic components shrinks, demanding spatially efficient redesign. The hydraulic tank has long since been designed with a spectrum of rules of thumb - overestimating the required space - to complex CFD simulations. As multiphase CFD already requires ample computing power, additionally considering the relative motion a hydraulic tank experiences, is currently outside the scope of feasibility, coming either at the cost of three dimensionality, or exceeding reasonable computing times - with no guarantees for accuracy. A test-rig, however, would allow for the investigation into the effect of relative motion on deaeration. This paper provides a foundation for a test-rig to re-examine the design of deaeration efficient mobile hydraulic tanks. For this purpose, the main aeration and deaeration mechanisms occurring within the tank have been outlined, and current design elements used to promote deaeration, gathered.

Keywords: Deaeration, Entrained air, Hydraulic reservoir, Hydraulic tank, Tank design, Test-rig development

1 Introduction

Whilst air can enter a hydraulic system in many places, deaeration only takes place within the hydraulic reservoir. Hydraulic systems are constantly pulling in air via cylinders or across seals which must then be released within the tank to prevent damages to the hydraulic system. Within stagnant oil deaeration occurs naturally but slowly, in flowing systems however, turbulence can prevent the rise of the bubbles, creating a race against the clock for the bubbles to reach the free surface lest they are once again sucked into the hydraulic circuit. Even though the size of tanks in mobile machinery is vastly smaller than those employed within stationary hydraulics, this time-pressure is still being exacerbated by shrinking installing space for tanks, especially in the face of steadily increasing electrification of mobile machinery. In addition to the influx of air via the remaining hydraulic system, tanks in mobile machinery also face additional air entrainment via the free surface due to relative movement. These many challenges - especially those of relative movement - have yet to be addressed holistically.

The current design methodologies mostly sit at two extremes of complexity - ranging from rules of thumb to CFD simulation - with the middle ground mostly empty. This middle remains insufficient, even as the number of publications on CFD tank simulations steadily rise, owing to their focus narrowing to machine-specific design. The lack of holistic design guidelines is reflected in the methodologies currently used in the industry. Often times, the selection of a tank is limited to simply finding an appropriately sized tank using a simple flow-demand calculation combined with a large safety factor. Following this, the tank may then also undergo trial-and-error experiments to place inserts such as baffles and sieves. This process may be lengthy and thus costly, particularly if no prior iterations of the mobile machinery or personnel experienced with tank designs are available. The other end of the spectrum, CFD simulations, require extensive computing power and experience, and are thus often outsourced. Additionally, CFD is currently not capable of depicting the system fully. As multiphase CFD already requires ample computing power, considering the relative motion a hydraulic tank experiences in addition to the miscibility between the air and hydraulic oil, remains currently outside the scope of feasibility. Including relative motion into the simulation would come at either the cost of three-dimensionality or exceed reasonable computing times - with no guarantees for accuracy.

In light of these limitations, further experimental investigation is required to develop design guidelines for hydraulic tanks in mobile machinery. First, the mechanisms of changes in air entrainment that can occur within the tank is outlined in Section 2. Following this, the current reservoir designs will be discussed in Section 3 with special attention on the tank geometry and inserts commonly used to support deaeration and prevent additional entrainment. Finally, the concept for a test rig will be presented; where the challenges associated with the measurement of the change in air content and possible solutions will also be discussed.

2 Air Entrainment

The relevant air content within the design of hydraulic tanks, is the undissolved, dispersed air, also called the "free air". Dissolved air can never be removed entirely, and if the air remains in its dissolved state, only negligible damage will be caused by its presence as it does not change the physical properties of the oil [1]. The dissolved air may be released due to pressure drops as the saturation limit decreases, this can only be influenced via the tank if it were pressurised or there was no air to dissolve in the tank. So-called closed tanks are in use to prevent pump cavitation and increase efficiency, however since the tank continuously sits at this elevated pressure level, the oil would simply saturate at this new limit. Since the tank must remain under the least pressure within the system, to ensure its functionality, this dissolved air would not be released. Free air however can cause significant problems within hydraulic systems and must therefore be minimised. Accordingly, any further mentions of air entrained by the hydraulic oil will refer to the undissolved, free air. In order to reduce the amount of free air within a system, the entrainment of air must be minimised and the oil must be allowed to de-aerate. The problems caused by entrained air arise mostly from the changes in the behaviour of the hydraulic medium, as the air content causes fluctuations in parameters such as density, viscosity and bulk modulus. These fluctuations often result in a loss of efficiency, as well as reducing the dynamic performance of the system. The presence of entrained air can lead to increased wear and damage to the components and increased ageing of the oil, through processes such as cavitation and oxidation. Aside from the ageing of the oil, the damages occur when the entrained air enters the remaining hydraulic circuit, consequently it must be removed prior to leaving the tank.

In most hydraulic tanks, the oil is exposed to a significant air layer. The interfacial boundary between the gas and liquid phase is referred to as the free surface. Due to their lower density, air bubbles are buoyant and naturally tend towards the free surface, where they can escape. The precise trajectory of the bubbles is governed by the shape and size of the bubble, as well as the flow conditions within the tank, with bubbles rising faster in lower viscosity oils. Multiple functions approximate the bubble rise velocity, depending on the bubble size, and fluid conditions such as temperature and pressure, these have been expansively reviewed in [2]. Currently available additives, including defoaming agents cannot improve the air-release of hydraulic oils [3]. Local turbulences often cause the bubbles to be swept along and downwards, resulting in continued entrainment within the hydraulic system. Air entering the system in the form of bubbles via the free surface must only traverse a short distance to be released. This means that the penetration depth of the bubbles and the proximity to the tank outlets, influences deaeration.

As previously mentioned, mobile hydraulic systems are not only more vulnerable to increased air contents due to the low residential times, but also due to the relative motion of the tank causing aeration within the tank. A positive aeration rate is especially critical, as the tank itself is the only place within the hydraulic system where air is able to leave the oil. Thus, mobile hydraulic tanks must not only be optimised to support deaeration but also to prevent additional aeration. Six aeration mechanisms will be described in the following section. For some of these mechanisms countermeasures are widely available, their efficient application is however still disputed. Specific countermeasures will be discussed in the Section 3 . The aeration rate AR in this work is defined as the difference between the void fraction β_{out} of the flow leaving the tank and the void fraction β_{in} of the flow returning to the tank (see Equation 1).

$$AR = \beta_{out} - \beta_{in} \tag{1}$$

The six aeration mechanisms or events shown in 1 will be outlined. In the tank, free air enters the oil via local turbulences, where the surface tension of the oil is smaller than the turbulent shear stress [4] or via the trapping of large bubbles. The former case may take place due to the flow of a jet (Nr. 3 in Figure 1) or splashes of liquid impacting the free surface whilst the latter occurs when pockets of air are enveloped by the folding of the free surface. This can occur due to waves breaking when they reach critical heights or due to their impact with the tank walls (Nr. 2 and 1 in Figure 1). The latter phenomenon is called wall- or roof-slamming [5] and like most of the other aeration events in this section, it requires "sloshing".

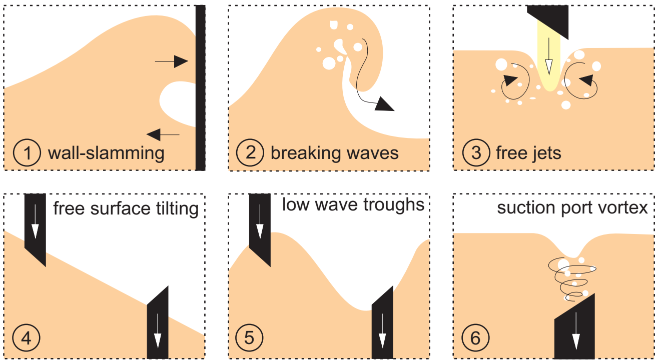

Figure 1: Overview of selected air entrainment mechanisms within the tank

2.1 Sloshing

Sloshing is broadly defined as any movement of a liquid within a container it does not fully fill [6]. Aeration mechanisms influenced by sloshing are susceptible to resonance phenomena. Sloshing at resonance frequencies results in high strain on the containers due to concentrated energy transfers when the liquid impacts the walls [7]. Resonance also introduces non-linear behaviours causing more air entrainment as the amplitude rises exponentially and should thus be avoided. Estimations of the eigenfunction of a sloshing liquid can be made by simplifying the shape of the container without significant accuracy losses [6], with analytical solutions existing for rectangular, conical, and cylindrical tanks. The estimation of the resonant frequencies may be particularly beneficial for the design of tanks in mobile machinery with oscillation working modes. The resonant frequency of a tank can be increased using longitudinal partitions or ring baffles [6] which provide a dampening effect on sloshing [5]. The severity of the air entrainment outside resonance is dependent on the frequency and amplitude of the excitation. Even without the trapping of large pockets, the shaking of the tank can disrupt the surface tension of the free surface, trapping small bubbles within the liquid [8]. In extreme cases the liquid flow disperses and the gas is suspended as small bubbles within the liquid, forming a foam. Although the effects of the above mentioned aeration events might be contained to the tank itself, the following mechanisms will result in free air entering the hydraulic system. This is due to their immediate involvement with the suction outlets of the tank.

2.2 Suction port

If the outlet is exposed to air or insufficiently covered, pumps may directly suction air into the system. The simplest way this may happen, is due to the free surface tilting at low oil levels. Generally this is accounted for in the design of a new tank, should however be re-examined when additional outputs, especially cylinders are added to machines without a full tank-redesign. The free surface may tilt due to the entire vehicle tilting - the degree of which is generally limited within mobile machinery - or due to inertial forces acting upon the liquid [9]. In the latter case, the acceleration of the vehicle a in relation to the acceleration due to gravity g determines the tilt angle Φ (Equation 2).

$$\Phi = \arctan(\frac{a}{g}) \tag{2}$$

A less predictable event may however arise due to the previously mentioned resonance phenomena. If the trough of a wave is below the suction outlet, air will enter the system. Whilst the level within the tank may not drop below the opening of the tank outlet, air may still be entrained via a fluid vortex.

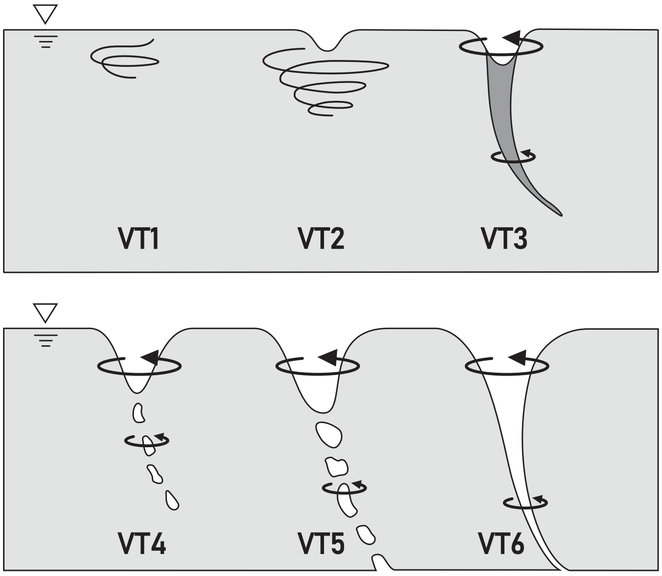

Figure 2: Hecker Vortex Classification Scale [10]

The final aeration event is the formation of a vortex, where the oil level does not drop below the opening of the tank outlet but where the free surface is locally deformed, splitting the oil layer. The formation of a vortex on a free surface is shown in Figure 2 where the vortex types (VT) are classified using the "Hecker vortex classification scale" and are qualitatively categorised from VT1 to 6. A free surface vortex generally develops from a "coherent surface swirl" (VT1) which proceeds to dimple the surface (VT2) then connects the axis of rotation to the suction intake (VT3) . At first, only debris is entrained (VT4), as the vortex develops air bubbles (VT5) follow and finally an air core is formed (VT6). Air entrainment thus only occurs in VT5 and VT6, with significantly more air entering the system due to VT6 [11]. Once the tip of the air core reaches the (pump) inlet depth, air enters the inlet [12]. The vortex may not stabilise fully, instead cyclically forming and collapsing due to the pump flow dropping as air is sucked in, and reforming once the pump flow increases again [11]. To prevent the formation of an air core - unstable or not- the critical Submergence is calculated in water hydraulics. This is the distance between the inlet and the free surface at which the vortex makes contact. Vortices are not exclusive to tank outlets in the floor of the tank and are highly dependent on the geometry of the outlet and the flow conditions, as well as the viscosity of the liquid.

In water hydraulics close attention has been paid to the critical submergence, with several models and equations existing to control vortex formation in reservoir designs. Generally the critical submergence is considered to be a function of the Froude Number Fr; which is the ratio between the inertia of the flow to gravity; and the geometric configuration of the tank. Multiple analytical models, mainly based on work by Rankine, and the Navier-Stokes equation have been proposed to model the vortex velocity [13] or gas-core length [14] and estimate the critical submergence . These models have to be separated into the positioning of the suction ports as only a vortex directly above the port can have an axially symmetrical shape. When considering multiple different liquids however, the Weber We and Reynolds Re Numbers also have been used to estimate the critical submergence [15], incorporating effects from surface tension and viscosity. Unlike the models available for inviscid liquids however they require knowledge of difficult to measure parameters, such as the circulation number, or use empirical factors. The simpler equations used in water-reservoir design cannot be transferred to oil hydraulics, in part due to the vastly different geometries, but also due to the models neglecting the effects of viscosity [10]. The energy decay along the vortex increases with viscosity, making oil-hydraulic systems less susceptible to the formation of stable air-cores. However the formation of vortices within hydraulic machinery has not been disproven but merely neglected. In spite of the lower risk, this aeration event may still take place within mobile hydraulic tanks, especially at low tank levels.

3 Hydraulic reservoir design

The main task of hydraulic reservoirs is to store hydraulic fluid and to compensate for uneven oil requirements (e.g. due to the movement of differential cylinders). Besides this primary function, hydraulic reservoirs cool the hydraulic fluid and remove contaminants like particles, water, and air. In this regard, the hydraulic reservoir is the only place in a hydraulic system where air can be removed in significant quantities. Still, it can also be entrained due to effects like sloshing.

The basic mechanisms highlighted in Section 2, which lead to the entrainment or separation of air, can be influenced by different design elements in a targeted manner. A distinction can be made between passive and active elements, whereby active elements, like cyclones, are currently not planned to be implemented in the test bench and are therefore not considered in this section.

Passive elements include the general reservoir geometry, the use of different inserts and the design of the reservoir inlet and outlet. The test rig to be designed should be able to map the influence of the above-mentioned elements and allow a combination of different configurations. For this reason, the general function of the named passive elements is described shortly in the following and the corresponding requirements for the test bench are derived.

3.1 Hydraulic reservoir geometry

Sufficient residential time of the hydraulic fluid in the reservoir is crucial for effective air separation. The longer the fluid stays in the reservoir, the more time bubbles are given to rise to the surface and be separated from the fluid. The mean residential time $t_{residential}$ is calculated by dividing the reservoir volume $V_{reservoir}$ by the maximum volume flow Q_{pump}.

$$t_{residential} = \frac{V_{reservoir}}{Q_{pump}} \tag{3}$$

Depending on the application the suggested residential times varies as shown in Table 1.

Table 1: Suggested residential times for different hydraulic applications

Application	Residential time $t_{residential}$
Stationary hydraulic systems	3 ... 5 min
Stationary hydraulic systems (HFC and HFD)	8 min
Mobile hydraulic systems open loop systems	2.5 min
Mobile hydraulic systems closed loop systems	1.5 ... 2 min
Aircraft applications	0.5 ... 1 min

In addition to the volume, the reservoir height in relation to the base area is particularly relevant for the separation of air. If the fill level is low, air bubbles can rise to the surface in a shorter time and be separated more quickly.

Furthermore, the basic shape has a crucial influence on the field of flow. In trapezoidal containers per example, a significantly decreased slosh response is observed when compared to a cylindrical or rectangular tanks with non-inclined walls [16]. The flow dynamics within the tank also impact air-release directly, as shown in 3 the rectangular shape of the left reservoir leads to dead zones (red) in each corner. In these areas, air bubbles have a lot of time to rise to the surface, but fluid flowing from the return line can only reach these areas with difficulty. For this reason only small amounts of air can be separated effectively in these areas.

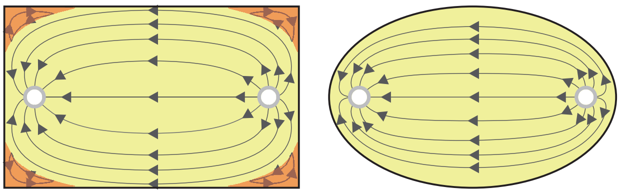

Figure 3: Influence of basic reservoir geometry on the flow field

To enable the test bench to map the described effects on air release, it should be possible to adjust both the reservoir volume and the filling level. This way also varying residential times for different hydraulic applications can be considered. The entire reservoir should be interchangeable to investigate the influence of the different base geometries.

3.2 Inlet and outlet design

In addition to the general reservoir geometry, the design of inlet and outlet geometry has a significant influence on the entrainment and the separation of air. To avoid a vortex, as described in Section 2, it should be ensured that the suction line is always sufficiently immersed during operation. Otherwise, air can be dragged along by the flow and enter the system through the suction line (Figure 4 l.).

The stream distance between the return line and suction line should be as large as possible to give air bubbles more time to rise to the surface, and ideally creating an even velocity field [17]. Belov et al. recommend that the flow length should be balanced with the costs, as the unevenness of the flow field decreases hyperbolically with an increase in length.

The return line should end below the fluid level so that no air can be entrained via the free jet. To increase the cross section of inlet and outlets, the pipe opening is often cut at a 45° angle [18]. The geometry of the tank inlet can also be adjusted from a simple pipe to instead include perforations on the side. [19] found that in a CFD simulation of their specific tank geometry, a perforated inlet resulted in significantly better air release than a bottom opened inlet. This improvement was attributed to the perforations resulting in better flow distribution and a quicker momentum exchange between the fluid entering and the fluid already within the tank. This effect can also be achieved using diffuser-attachments for the pipe, which often come integrated into the return filter.

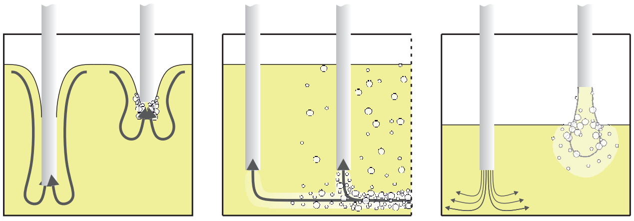

Figure 4: inlet and outlet design

To investigate the effects of the design of the tank ports on deaeration, the height and position of the suction and return pipes in the test-reservoir should be variable.

3.3 Inserts

To improve air separation and to prevent the entrainment of air, different reservoir inserts can be used. The use of baffles, partitions and swash plates in sloshing has been examined closely for liquid storage containers, especially in marine applications, where large external excitations occur (for further reading see [7]. Although the liquid within the tank does not experience a global flow rate, this research is still a vital boost to understand insert interaction within mobile machinery, as many publications consider the effects of both air entrainment and viscosity. Baffles and partitions are used to divide the reservoir into a sections and a return flow section or to guide the flow of hydraulic oil inside the reservoir. This way short-circuiting between suction and return line is avoided. Simultaneously, the fluid can be directed to the surface by bottom mounted baffles, thus shortening the path of air bubbles to the surface. Vertical baffles also reduce the sloshing amplitude by blocking the fluid motion and causing local turbulences at the sharp baffle edges, resulting in a dissipation of energy. Bottom mounted baffles are less effective in reducing impact pressures and sloshing amplitudes, than those touching the free surface, as the highest horizontal velocity manifests at the free surface in the middle of the tank and reduces towards the bottom of the tank [7]. Whilst vertical baffles can combat heavy sloshing modes, care must be taken when sizing them, as they may severely impact the flow, causing cascading flows down the sides of a baffle [20], which also causes air entrainment. The total number of partitions used should also be limited to avoid creating more dead-zones [21]. Investigations into elastic baffles has also found that when the baffle is not immersed, those with smaller stiffnesses result in higher damping, whilst for the immersed baffles the inverse was observed [22].

Another way to improve air separation is to install screens on which air bubbles can accumulate, travel along the screen and finally rise to the surface. The performance of screens depends largely on the mesh size and the angle. The grain of the screen is recommended to not excessively hinder the flow and may be coated to promote bubble collection [17]. For this reason, the test rig should be facilitate changing between screens with different mesh sizes and vary their installation angle.

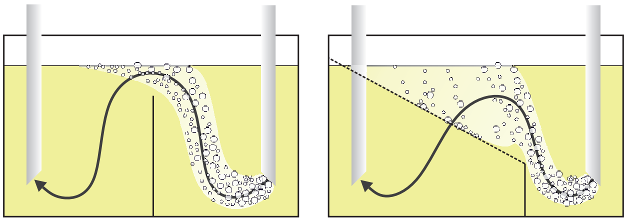

Figure 5: influence of baffles and screens on air separation

3.4 Requirements for the test bench design

The requirements for the test bench derived from the design elements described above are summarized in Table 2 below.

Table 2: Requirements for test bench design derived from tank geometry

Design Element	Test Bench Variables
Base container	Exchangeable reservoir Adjustable fluid level
Inlet and outlet design	Adjustable length of inlet/outlet line Variable positioning of inlet and outlet Variable opening geometry
Inserts	
Baffles and partitions	Changeable position and inclination
Screens	Changeable position and inclination Variable mesh size
Slit sheets and perforated baffles	Variable opening sizes

4 Test-rig Design

To account for the incompatibility of some design choices, the test rig concept is modular, enabling the swapping of the tank. In addition to the possibility of easily exchanging the test-tank, the design will also minimise the effort required to change the hydraulic fluid, by separating the hydraulic circuit carrying out the movement and generating the hydraulic work, from the fluid flowing through the test-tank. This will not only allow the investigation into the influence of different fluid characteristics, but also prevent damage to the components caused by the excess air within the test fluid . The free air content of the oil will be measured before and after the tank, allowing the calculation of the deaeration rate. These measurement methods will also be briefly discussed and evaluated below. The air content measurement will additionally be used in the control of the air content in the inflowing fluid. To control the air content, additional air will be injected. The injection of additional air is to observe the effect of the tank geometry and movement on the deaeration rate. In order to reduce the air within the tank, a second larger tank will be used as a settling tank, from which fresh oil can be sourced. A bypass will then be used if the air content is to be increased from the current air content within the test-tank. The test-circuit of the test-rig will furthermore be kept at low pressures below 10 bars to allow for the active injection of compressed air. The test rig will also investigate typical operating conditions and volume flows but will be restricted to 100 l tanks.

4.1 Movement

The intended movement capabilities of the test-rig have been adapted to simulate typical working motions of mobile hydraulic machinery. To assess the most critical external excitation of the tanks, the movements will initially be carried out in isolation. Another motive for the initial focus on isolated movement is that the overlaying of excitation directions has already been shown to increase sloshing dramatically. The most vital movement types were considered to be:

- Translational in Z (up/down)
- Rotational around Z (yaw)
- Rotational around X or Y (roll/pitch)

In order to reduce the degrees of freedom required by the test rig, motions in the X and Y direction will be achieved by switching the mounting direction of the tank. The yawing movement is especially vital due its high use in construction machinery, per example in dig-and-dump-cycles. Acceleration in the direction of travel (X) will be depicted by making use of the gravitational force and tilting the tank. Movement in the direction of travel will not be depicted within the test-rig as most hydraulic machinery can reach limited driving velocities which do not justify the additional space, costs and risks associated with implementing horizontal movement. The movement types specified above, will be examined in isolated impulses as well as oscillations to examine the effect sudden impacts and sloshing.

4.2 Measurement Methods

To accurately determine the change in aeration of the tank, the difference in the amount of free air entrained in the in- and outflow of the tank must be measured. The "amount" can be either specified by the number of bubbles of significant diameters or by measuring the void fraction. The advantage of the former is that the bubble size discerns the type of damage that may be caused and if a broad enough range of bubble diameters are captured, it may then be used to estimate to void fraction.

Whilst there has been significant research into the measurement of entrained air not all is transferable to the desired operating conditions. Much of the available technology on measuring multi-phasic flows originates within the medical field, where dynamic imaging is vital. Unfortunately the volume flows within the body are much lower than those within hydraulic systems and available sensors are for high volume flows are much rarer, nevertheless some of the measurement methodologies can be adapted for use within oil hydraulics.

Another significant restriction is high void fractions which may occur during measurement as many methods cannot accurately capture larger bubbles or slug flow. In some cases the exposure of probes to large air pockets result in sensor failures, whilst in others the signals become nonsensical. In the latter case, the measurement method could be combined with a secondary measuring system to allow for its use. In addition to the demands arising from the high flow speed and void fraction requirements, the sensors must also be suitable for use in a closed-loop control to regulate the free air within flow entering the tank. This means that the measurement must be inline, at an adequate sample rate. Other requirements for the sensors originate in the use of oil-hydraulics; the sensor-materials must be compatible with various hydraulic oils and must provide robust measurements, despite small temperature fluctuations or vibrations carried through the machine. In addition to the requirements listed above, economic restrictions, as well as safety concerns - primarily in regards to radiation - were utilized to screen current measurement systems. A selection of the evaluated measurement methodologies is listed in Table 3. The measurement methods for gas-liquid two-phase flow either emit energy into the flow or observe differences in flow behaviour, mostly in the pressure differentials, when it passes resistance components. The first group can be separated into categories by the type of energy used and will be discussed below. The sensors generally emit either sound or electromagnetic waves which are then altered by passing through the flow. The type of disturbance depends on the material characteristics and the interfaces between the components. In liquid-gas flows the waves are usually impacted the most by traversing the interfacial barrier and depending on the type of wave are either absorbed or reflected to some degree [30]. The sensor then either receives the reflected or remaining wave and compares it to a reference. The degree of change, depends on the characteristics of the gaseous phase. Scattering vs reflecting per example is determined by the size of the object relative to the wavelength, with significantly smaller isolated objects acting as point scatters [31]. Sensors working with reflected or scattered waves usually have a reflective material on the other side of the pipe or container to reflect any remaining waves back as an echo. Methods which utilise the remaining

Table 3: Overview of measurement methodologies to determine air content

Method	Pro	Contra
Compressibility [23]	Accurate	Only offline
High-speed photography [23]	Non-Invasive, High Resolution	Struggles with opaque liquids, limited frame-rate
Optical Probe [24], [25]	Versatile	Expensive tracers, Ineffective for larger bubbles
Electrocapacitance Tomography [26]	Inexpensive, high sample rate	Low spatial resolution
Electrical Impedance [23]	Inexpensive, high sample rate	Incompatible with oil
Thermal Anemometry [27]	Simple, Inexpensive	Inaccurate, invasive
Pulse Echo Technique [28]	Can measure bubble size and number	Limited void fraction measurable
Pulse Wave Ultrasonic Doppler [29]	Can measure in stratified flow (high void fractions)	May not achieve sufficient depth penetration
Continuous Wave Ultrasonic Doppler [29]	High resolution and sample rate	Precise placement of transducers required

waves are called shadowgraph methods, the most popular being shadowgraphy, an optical method. These methods often use a pulsing, rather than a continuous emission, to minimise interference between outgoing and incoming waves. The received waves are analysed on their amplitude, frequency and phase, depending on the method. From this information, the void fraction or bubble size is then reconstructed using models such as the ECAH model, which is used for ultrasonic methods [31]. In addition to optical waves, the other commonly used electromagnetic methods use electricity, heat or forms of radiation, namely X- and gamma-rays. The techniques using radiation generally require a strong insulation layer to absorb remaining rays safely, this results in larger setups and higher costs.

Since the change in the waves are observed and referenced, the depth penetration of the wave is of utmost import. The wave must be noticeably changed by the air bubbles, but not fully absorbed or reflected in order to accurately measure the air content. This is especially relevant in high volume flow rates as the pipe sizes increases with the flow. Increasing the depth penetration by increasing the energy of the wave is limited as adverse effects, such as heat damage in the components or fluid, may occur [32]. One example of this is in sound waves which, when the amplitude is too high, can result in cavitation due to pressure drops in the rarefaction of the wave. Increased power can also lead to changes in the fluid movement. In larger pipes - especially at higher void fractions- more bubbles may also "hide behind" another if the wave used is completely dispersed by a single phase transition. This is usually counteracted by the use of several probes creating a net in a 2 dimensional plane. The most literal example of this are wire-mesh sensors, which use a mesh of wires and electricity to measure the passing bubbles. Probes generally exist in sender-receiver pairs or single units, with many sensors also using bundles of probes.

Ultrasonic methods can be used to measure both void fraction and particle size distribution, due to their non-invasive nature and low costs their application is widespread in the medical and industrial field [33] . Within the ultrasonic methods, the Doppler Techniques and the Pulse Echo Technique can be used to determine the void fraction within a liquid, a comprehensive review can be found in [29]. The Continuous Wave Ultrasonic Doppler (CWUD) method appears to be the method with the fewest drawbacks amongst all evaluated methods. Unfortunately the market availability does not reflect the breadth of published articles on void fraction measurements. Instead it appears that many facilities have developed their own sensors specific to their application, providing descriptions of the used components and signal processing methods, examples of this can be seen in [34], [35]. In light of this, the development of a project specific air content sensor is a viable option if no commercial sensors can be acquired.

5 Conclusion

Due to movement of mobile machinery, additional air can be entrained in the hydraulic oil within the tank. This air may be captured in the form of small bubbles via local turbulences or jet streams, in the form of large bubbles captured during violent sloshing events where waves break, or directly suctioned into the pump inlets. Preventing these events, as well as encouraging deaeration, is crucial to maintaining the health of the hydraulic system. Several approaches to minimise the amount of entrained air by optimising the tank geometry and using inserts were discussed. The shortcomings of the current design guidelines were called to attention, especially the lack of research into the relationship between relative motion and deaeration. This work outlined the current challenges in the design of deaeration efficient mobile hydraulic tanks to highlight the need for more experimental investigation. Following this, a concept for a test-rig was introduced. The required variables and possible air-content measurements were discussed. With the research gathered from this test-rig, the design of hydraulic tanks for mobile machinery is to be illuminated, creating design guidelines.

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References

[1] Dietmar Findeisen and Siegfried Helduser. *Ölhydraulik: Handbuch der hydraulischen Antriebe und Steuerungen*. VDI-Buch. Springer Vieweg, Berlin, 6., neu bearbeitete auflage edition, 2015.

[2] Amol A. Kulkarni and Jyeshtharaj B. Joshi. Bubble formation and bubble rise velocity in gas−liquid systems: A review. *Industrial & Engineering Chemistry Research*, 44(16):5873–5931, 2005.

[3] Theo Mang and Wilfried Dresel. *Lubricants and lubrication*. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, third completely revised and enlarged edition edition, 2017]- // 2017.

[4] Hubert Chanson. Hydraulics of aerated flows: qui pro quo ? *Journal of Hydraulic Research*, 51(3):223–243, 2013.

[5] L. Constantin, J. J. de Courcy, B. Titurus, T.C.S. Rendall, and J. E. Cooper. Sloshing induced damping across froude numbers in a harmonically vertically excited system. *Journal of Sound and Vibration*, 510:116302, 2021.

[6] R. A. Ibrahim. *Liquid sloshing dynamics: Theory and applications*. Cambridge University Press, New York, 2005.

[7] Mi-An Xue, Jinhai Zheng, Pengzhi Lin, and Zhong Xiao. Violent transient sloshing-wave interaction with a baffle in a three-dimensional numerical tank. *Journal of Ocean University of China*, 16(4):661–673, 2017.

[8] Emma Frosina, Adolfo Senatore, Assunta Andreozzi, Gianluca Marinaro, Dario Buono, Gennaro Bianco, Domenico Auriemma, Francesco Fortunato, Fulvio Damiano, and Pino Giliberti. Study of the sloshing in a fuel tank using cfd and efd approaches. In *Proceedings of the ASMEBATH Symposium on Fluid Power and Motion Control - 2017*, New York, N.Y., 2017. The American Society of Mechanical Engineers.

[9] Ronja Hoch. *Zweiphasenströmung in Kühlmitteltanks von Sportwagen*. Dissertation, Universität Rostock, 2021.

[10] Jost Knauss. *Swirling Flow Problems at Intakes*. Routledge, 2017.

[11] Robert Ettema, David Z. Zhu, Susan J. Gaskin, Troy C. Lyons, Robert Boes, Shu Ning Chan, and Joseph H.W. Lee. *Vortex-Flow Intakes*. ETH Zurich, 2023.

[12] Rahul Kumar Mondal and Parmod Kumar. Experimental study of entrained air-core structures induced by a pump intake vortex. *Physics of Fluids*, 34(5), 2022.

[13] Yun-liang Chen, Chao Wu, Mao Ye, and Xiao-ming Ju. Hydraulic characteristics of vertical vortex at hydraulic intakes. *Journal of Hydrodynamics*, 19(2):143–149, 2007.

[14] Kei Ito, Takaaki Sakai, Yuzuru Eguchi, Hideaki Monji, Hiroyuki Ohshima, Akihiro Uchibori, and Yongze Xu. Improvement of gas entrainment prediction method—introduction of surface tension effect—. *Journal of Nuclear Science and Technology*, 47(9):771–778, 2010.

[15] Carlos Julián Gavilán Moreno. Determining critical submergence in tanks by means of reynolds & weber numbers. *World Journal of Engineering and Technology*, 02(03):222–233, 2014.

[16] S. Mitra, P. P. Upadhyay, and K. P. Sinhamahapatra. Slosh dynamics of inviscid fluids in two–dimensional tanks of various geometry using finite element method. *International Journal for Numerical Methods in Fluids*, 56(9):1625–1651, 2007.

[17] N. Belov and N. Sosnovsky. Design of an optimal hydraulic tank configuration. *IOP Conference Series: Materials Science and Engineering*, 779:012041, 2020.

[18] Vito Tič and Darko Lovrec. Air-release and solid particles sedimentation process in a hydraulic reservoir. *Tehnički vjesnik*, 20(3):407–412, 2013.

[19] Gorle Jagan. Coupled fluid-thermal-structural analysis of two-phase flow in a hydraulic tank. In *The Sixteenth Scandinavian International Conference on Fluid Power*, 2019.

[20] Ronja Hoch and Frank-Hendrik Wurm. Numerical and experimental investigation of sloshing under large amplitude roll excitation. *Journal of Hydrodynamics*, 33(4):787–803, 2021.

[21] V. Tic and D. Lovrec. Design of modern hydraulic tank using fluid flow simulation. *International Journal of Simulation Modelling*, 11(2):77–88, 2012.

[22] Yaru Ren, Mi-An Xue, and Pengzhi Lin. Experimental study of sloshing characteristics in a rectangular tank with elastic baffles. *Journal of Fluids and Structures*, 122:103984, 2023.

[23] Katharina Schrank, Hubertus Murrenhoff, and Christian Stammen. Investigation of different methods to measure the entrained air content in hydraulic oils. *ASME/BATH 2014 Symposium on Fluid Power and Motion Control*, 2014.

[24] G. Rojas and M. R. Loewen. Fiber-optic probe measurements of void fraction and bubble size distributions beneath breaking waves. *Experiments in Fluids*, 43(6):895–906, 2007.

[25] Christian Poelma. Measurement in opaque flows: a review of measurement techniques for dispersed multiphase flows. *Acta mechanica*, 231(6):2089–2111, 2020.

[26] Jing Lei and Shi Liu. An image reconstruction algorithm based on the regularized minimax estimation for electrical capacitance tomography. *Journal of Mathematical Imaging and Vision*, 39(3):269–291, 2011.

[27] Volfango Bertola. Two-phase flow measurement techniques. In Manuel Garcia Velarde, Mahir Sayir, Wilhelm Schneider, Bernhard Schrefler, Giovanni Bianchi, Carlo Tasso, and Volfango Bertola, editors, *Modelling and Experimentation in Two-Phase Flow*, volume 450 of *CISM International Centre for Mechanical Sciences*, pages 281–323. Springer Vienna, Vienna, 2003.

[28] Antonin Povolny, Hiroshige Kikura, and Tomonori Ihara. Ultrasound pulse-echo coupled with a tracking technique for simultaneous measurement of multiple bubbles. *Sensors (Basel, Switzerland)*, 18(5), 2018.

[29] Chao Tan, Yuichi Murai, Weiling Liu, Yuji Tasaka, Feng Dong, and Yasushi Takeda. Ultrasonic doppler technique for application to multiphase flows: A review. *International Journal of Multiphase Flow*, 144:103811, 2021.

[30] Chunwei Gu, Qian Li, Rui Ma, Yingsong Lin, Xiangfang Li, Yiming Li, Aixia Zhang, Yingjie Li, and Bangtang Yin. Propagation characteristics of doppler ultrasonic wave in gas–liquid two-phase flow in an offshore deepwater riser. *Natural Gas Industry B*, 8(6):615–621, 2021.

[31] Jinhui Fan and Fei Wang. Review of ultrasonic measurement methods for two-phase flow. *The Review of scientific instruments*, 92(9):091502, 2021.

[32] Christian Poelma. Ultrasound imaging velocimetry: a review. *Experiments in Fluids*, 58(1), 2017.

[33] Fria Hossein, Massimiliano Materazzi, Paola Lettieri, and Panagiota Angeli. Application of acoustic techniques to fluid-particle systems – a review. *Chemical Engineering Research and Design*, 176:180–193, 2021.

[34] Zihui Wei, Xinyue Zhao, Lintao Han, Ning Zhao, and Lide Fang. Ultrasonic probes and echo time algorithms in ultrasonic gas flow measurement systems: Progress and perspectives. *Physics of Fluids*, 37(1), 2025.

[35] Eduardo Nunes dos Santos, Natan S. Reginaldo, Jean N. Longo, Roberto da Fonseca Jr, Marco G. Conte, Rigoberto E. M. Morales, and Marco Jose da Silva. Advancing oil and gas pipeline monitoring with fast phase fraction sensor. *Measurement Science and Technology*, 35(12):125302, 2024.