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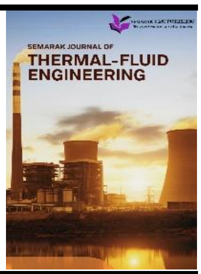

Application of Archimedes' Principle using a Digital Strain Gauge Buoyancy Reading Prototype

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ABSTRACT

Archimedes' Principle states that the buoyancy force acts on a body which is completely or partially immersed in a fluid. This Principle is a foundation for the calculation of the densities of fluids using hydrostatic weighing. The conventional ways of determining the densities of fluids using glass hydrometers or a manual triple-beam balance have some limitations in terms of ruggedness, the potential for human error, and the lack of portability. This research was conducted to address the limitations associated with the conventional ways of measuring the densities of fluids by designing a rugged stand-alone digital density analyser for the verification of Archimedes' Principle using digital instrumentation. The objective of the research was to design a portable device for the rapid hydrostatic analysis of fluids, which is normally impossible using microcontrollers due to the instability of the signals. The research methodology was to design a rigid test stand using a shear beam load cell and a digital decoder. This setup measured the variation in the apparent weight of a constant-volume probe submerged in three distinct fluid media: freshwater, saltwater, and cooking oil. Experimental results demonstrated a clear, quantifiable inverse relationship between fluid density and the raw sensor reading; the high-density saltwater medium exerted the maximum buoyant force, resulting in the lowest tension reading, while the low-density cooking oil resulted in the highest reading. In conclusion, the developed standalone prototype successfully validates the theoretical relationship between fluid density and upthrust force, proving that optimized strain gauge technology can serve as a precise, rugged, and cost-effective alternative to analog hydrometers for non-destructive testing and educational demonstrations.

1. Introduction

Fluid mechanics is a fundamental branch of engineering science that deals with the behaviour of fluids at rest and in motion, as well as the interaction of fluids with solids or other boundary surfaces [1]. One of the most important aspects in this domain is the measurement of intrinsic fluid properties, such as density and specific gravity. These are parameters used across industries, from manufacturing quality control to chemical processing. Accurate density determination is vital for characterising

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materials and ensuring process safety and efficiency, as noted by Nishihashi *et al.,* [2] and Assael *et al.,* [3], who emphasize the need for precise reference data in thermodynamics. Traditional apparatus, however, such as glass hydrometers or manual triple-beam balances, are usually used for the determination of fluid density at a large number of educational and industrial sites with several attendant operational limitations.

According to Morris [4], glass hydrometers are inherently fragile, and hence liable to break, for rugged field environments. Furthermore, standard analytical balances are often non-portable and require time-consuming manual calibration. At the same time, the reliance on analogue scales makes these methods susceptible to human error, particularly parallax issues during data reading [5]. Therefore, there exists an immediate need for a sturdy yet digital instrumentation system that uses principles of fundamental fluid mechanics in applying appropriate density measurements in a portable and user-friendly style. This aligns with recent trends in the Internet of Things (IoT), where Flores-Iwasaki *et al.,* [6] highlights the growing importance of smart sensing for real-time water quality monitoring.

This project focuses on the design and development of a Standalone Digital Density Analyzer to verify Archimedes' Principle. The principle posits that a body wholly or partially submerged in a fluid is acted upon by an upward buoyant force equal to the weight of the fluid it displaces [7]. By measuring this buoyant force, the density of either the solid object or the surrounding fluid can be mathematically derived using hydrostatic equilibrium equations. Recent educational initiatives by Hoffman [13] have demonstrated the feasibility of using low-cost microcontrollers for chemical analysis. However, a major challenge in low-cost prototyping is the Signal-to-Noise Ratio (SNR). As noted by Schmalzel and David [8], general-purpose microcontrollers often introduce digital switching noise into sensitive analog lines, a phenomenon thoroughly documented by Doebelin [9] in measurement system design. To address this, this project utilizes a dedicated Shear Beam Load Cell integrated with a V774 Digital Decoder Module. This optimization allows for a standalone"architecture, effectively decoupling the sensing unit from external microcontrollers to minimize electronic signal noise. Pallas *et al.,* [10] argue that such dedicated signal conditioning is essential for reducing interference in high-impedance sensors.

The resulting prototype serves as a functional educational tool and a proof-of-concept for low-cost, digital non-destructive testing (NDT) instruments. Although microcontroller-based learning kits have achieved significant popularity, a critical research void exists to implement cost-effective instrumentation systems possessing high signal integrity for fluid medium analysis. Indeed, commonly available prototyping platforms, as emphasized in Schmalzel and David [8], exhibit low SNR, which makes it difficult to detect minor force changes being experienced by buoyancy probes in fluids having similar densities. Current educational solutions documented by Pino *et al.,* [11] often sacrifice measurement precision for simplicity, while industrial-grade densitometers discussed by Fujii [12] remain cost-prohibitive for widespread field deployment.

The significance of this research lies in bridging this disparity by validating a standalone sensor architecture that prioritizes signal stability over general programmability. By optimizing the instrumentation design to utilize a dedicated digital decoder, this study demonstrates a cost-effective pathway for high-precision Non-Destructive Testing (NDT) in resource-constrained environments, aligning with the growing demand for smart sensing solutions identified by Flores-Iwasaki *et al.,* [6]. Therefore, the primary objective of this research is to design and develop a robust Standalone Digital Density Analyzer to verify Archimedes' Principle, specifically aiming to minimize electronic signal drift and accurately differentiate fluid densities through rigorous hydrostatic weighing.

2. Methodology
2.1 Prototype Instrumentation and Design

This section describes the design, fabrication, and experimental validation of the Digital Strain Gauge Buoyancy Reading Prototype. This methodology was developed to transition from traditional analog hydrostatic weighing to a digital instrumentation approach to provide superior measurement repeatability and data readability [1]. The prototype architecture is based on a cantilevered force-measurement system that identifies small changes in vertical tension. At its core, a 1 kg Shear Beam Load Cell is configured in a Wheatstone bridge. This type of sensor, illustrated in Figure 1(a), provides high linearity and can measure static loads with minimal hysteresis as reviewed by Hoffmann [13] for various applications involving strain gauges. To interpret the change in analog voltage output of the Wheatstone bridge, a V774 Digital Decoder Module shown in Figure 1(b), has been employed in the system. Unlike general purpose microcontrollers that tend to have high frequency noise from the breadboard connections, this dedicated module provides both a regulated excitation voltage and stable ADC [14]. Hence, the data reflected is a true representation of the tension force without signal drift.

The mechanical setup was also critical to the experiment's success. The load cell is rigidly mounted to a custom stand to isolate it from external vibrations, following the mechanical design principles suggested by Venkateshan *et al.,* [15]. A non-elastic, thin filament is used to suspend the test object. This specific design choice was made to minimize errors caused by surface tension at the fluid interface, a significant source of error in hydrostatic weighing identified by Naylor and Scott [16]

(a) (b)

Fig. 1. Experimental instrumentation (a) Shear beam load cell sensor (b) V774 digital decoder module

2.2 Experimental Materials

To ensure the sensitivity of the prototype over a range of densities, various samples were chosen for testing. For instance, in the case of solid samples, the low-density material chosen for testing was a rubber eraser, and the high-density material chosen was a steel bolt. In the case of fluid samples, three different samples were chosen to verify the buoyancy reading ability of the prototype. Three different liquids were chosen for this purpose. Table 1 lists the properties of the fluid samples chosen. Fresh water has been chosen as the standard fluid sample. Saltwater has also been chosen to verify the effect on the prototype with an increased density fluid. Additionally, oil has also been chosen as a fluid sample with low density.

Table 1
Properties of fluid samples used in the experiment

Fluid sample	Approximate density, kg/m^{3d}	Classification
Cooking oil	<1000	Low density medium
Freshwater	≈1000	Reference medium
Saltwater	>1000	High density medium

2.3 Experimental Procedures

This experiment has been carried out in two phases to achieve the project objective of using Archimedes' Principle. In Phase 1, verification of solid densities is achieved by applying the weight loss method. In this case, the body being tested was subjected to weight in air, then submerged in water. According to Munson *et al.,* [17], the reading taken corresponds to buoyancy force. In Phase 2, comparative fluid analysis using a control probe, where the object of test is a stone of constant volume used to compare two or more fluids based on their densities, will be used. In this case, cooking oil, freshwater, and saltwater are used as they will be submerged in the fluid being analysed. Since the depth of the object is constant, any difference in reading can be mathematically attributed to fluid density variation.

2.4 Analytical Framework
2.4.1 Buoyant force

Data analysis was performed using the comparative ratio method. Since the V774 decoder provides raw digital steps proportional to force, the analysis relies on the calculation of the Buoyant Force (FB). According to Archimedes' Principle, this force is equivalent to the weight of the displaced fluid, which is expressed in Eq. (1).

$$FB = \rho_{fluid}\, gV_{displaced} \tag{1}$$

where ρ_{fluid} is the density of fluid, g is gravitational acceleration and $V_{displaced}$ is volume of fluid displaced.

2.4.2 Buoyant force

For the solid density calculation, the Specific Gravity (SG) is derived without converting to absolute grams, utilizing the ratio of readings as shown in Eq. (2). This approach highlights the utility of the prototype as a rapid, relative density analyser for field applications where calibration standards may be unavailable [18].

$$SG = \frac{R_{air}}{R_{air} - R_{water}} \tag{2}$$

where R_{air} is raw reading in air, R_{water} is raw reading in water.

2.4.3 Percentage error

For the percentage error calculation, it is crucial for engineering studies to justify their research. The formula is shown in Eq. (3).

$$Percentage\ error = \left|\frac{SG_{ref} - SG}{SG_{ref}}\right| \tag{3}$$

where SG_{ref} is reference specific gravity of material and SG is specific gravity of material.

3. Results

3.1 Hydrostatic Weighing

The results obtained from the hydrostatic weighing study using the prototype, and the effects of object mass displacement and fluid densities are discussed. The experimental data validate the theoretical framework of Archimedes' Principle established in the methodology.

3.1.1 Density determination of solids

The setup for testing the density of the solids is summarized in Table 2. Two different materials were tested which are Rubber Eraser and Steel Bolt, to see the magnitude of buoyant force with respect to the object's densities. According to the table, the Steel Bolt experienced a huge drop in apparent weight when submerged into water, while the Rubber Eraser experienced almost none since it has a very low volume to displace.

To quantify the density of the steel bolt without absolute mass calibration, the Specific Gravity (SG) was calculated using the ratio of the forces measured in air and water. This calculation was performed using Eq. (2). The calculated SG of 7.27 aligns closely with the standard values for steel alloys found in literature [19], validating the prototype's accuracy for solid density determination. Standard engineering references typically list the specific gravity of mild steel is 7.85. Using Eq. (3), the percentage error can be calculated as 7.4%. The 7.4% deviation is within the acceptable range for a low-cost prototype. The slightly lower density reading suggests the presence of minor air bubbles trapped in the threads of the bolt during submersion. This would increase the displaced volume V without adding mass which increase the buoyant force slightly.

Table 2
Raw sensor readings for solid density verification

Test sample	Medium	Raw sensor reading, R	Difference, ΔR
Rubber eraser	Air	150 (R_{air})	-
	Water	50 (R_{water})	100
Steel bolt	Air	800 (R_{air})	-
	Water	690 (R_{water})	100

3.1.2 Comparative analysis of fluid densities

To further differentiate these effects, the experiments were performed using a constant-volume probe immersed in three distinct media: Cooking Oil, Fresh Water, and Saltwater. The results were summarised as depicted in Table 3. The data depicted in Table 3 indicates an inverse relationship in terms of the density of the medium used in the tests with the output reading from the sensor. It can be observed that Saltwater, with a higher density compared to Fresh Water, resulted in an upthrust force that caused a reading of 2500. In contrast, Cooking Oil, with a lower relative gravity compared to Fresh Water was resulted in a lesser upthrust force, thus a higher output reading of 3500. This observation confirms indirectly the theoretical principles suggesting that there is a direct proportionality between density and buoyant force, as discussed by Munson *et al.,* [17]. From a quantitative perspective, the ratio of the Saltwater buoyant force with respect to the Freshwater is 1.45. In short words, it confirms that a saltwater solution, as prepared, is denser, thus effectively validating the functioning of the sensor with respect to the effects of changes in salinity.

Table 3
Comparative buoyancy readings in different fluid media

Fluid medium	Raw sensor reading, R	Buoyant force indicator, (R_{air} - R_{fluid})
Air (reference)	5000	0
Cooking oil	3500	1500
Fresh water	3000	2000
Saltwater	2500	2500

3.2 Discussion
3.2.1 Interpretation of findings

The results clearly validate the theoretical relationship between fluid density and upthrust. The "stepped" increase in sensor readings from Saltwater to Freshwater followed by cooking oil correlates perfectly with the decreasing densities of these fluids density of salt is larger than density of water and density of oil. The device successfully translated microscopic changes in tension into digital steps, proving that a strain-gauge-based system can function as a digital hydrometer.

3.2.2 Sources of error and environmental factors

Even though this trend was valid, the 7.4% error of the test with the 7.4% error in the test for the solid density reveals limitations with respect to the design of the current prototype. When the suspension filament disturbs the fluid, there is a "meniscus effect" due to the particular properties of the surface tension of the fluid, which imparts a small downward-acting force on the load cell. While an ultra-fine wire can be employed in standard balance systems to resolve this issue, the use of nylon filament might possibly have had a corresponding drag effect. While a special stand has been used, any microscopic deflection of the cantilever beam due to the load might have been interpreted by the load cell sensor as a change in the amount of weight. A stiffer material, such as aluminium extrusion, would be required to minimize this kind of hysteresis. There is a particular sensitivity of the load cell to temperature. While this was negligible for the purposes of the experiment, owing to the lack of active temperature compensation, the heat from the local surroundings could cause a "zero drift" in the raw output.

3.2.3 Practical implications

Although it has minor flaws, the proof of concept offers several advantages over the conventional glass hydrometer. Firstly, the device is non-fragile and well-constructed. Secondly, it eliminates parallax error due to a digital display. These advantages make the device useful in field- based applications, including measuring the level of salinity in aquaculture and the oil viscosity in automotive tests.

4. Conclusions

In conclusion, this project successfully achieved its primary objective which is to design and develop a functional, standalone prototype to verify the principles of fluid mechanics using digital instrumentation. The fabrication of the Standalone Digital Density Analyser using a shear beam load cell and V774 decoder demonstrates significant engineering optimisation in solving issues with signal noise and portability. The experiment clearly verified Archimedes' Principle and met the requirement of relating experimental data to core concepts in fluid mechanics. Data gathered showed that the fluid density was inversely proportional to the apparent weight of the probe submerged in it. Precisely, the prototype correctly identified that Saltwater would exert the highest buoyant force compared to Freshwater and Cooking Oil, hence distinguishing between different fluids of a particular specific gravity. While this prototype is a robust proof-of-concept in conducting low-cost nondestructive testing (NDT), it still requires manual comparative analysis. Future work shall integrate onboard thermal compensation with automated calibration algorithms to further validate the system's accuracy under fluctuating environmental conditions.

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