A novel approach for assessing the instantaneous flow rate of an external gear pump using 3D printing and computer vision

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Abstract. The flow rate ripple inherent in gear pumps is already well researched with varying degrees of accuracy. The usual approach for determining the instantaneous flow rate includes mathematical models, computational fluid dynamics (CFD) and the practical approach, measuring the flow rate on an existing system using sensors. This paper presents an original method for determining the flow rate using new technologies, specifically 3d printing, edge computing and image processing. The target is a 3d printed scale model of the gears and casing attached to a stepper motor; a raspberry pi zero acts as a remote image capture device and position controller. The frames captured at key positions are wirelessly transferred to a computer running MATLAB for processing and extracting the flow data using special algorithms. Results were very good and reasonably accurate.

1. Introduction

Rotary pumps are primarily used as a source of fluid power in hydraulic systems. They are found in a wide variety of applications such as machine tools, aircraft, rockets, automotive, press and mechanical transmission;

These types of pumps fall into the category of positive-displacement pumps with circular motion; they can be also separated in categories depending on the impelling element: gear-type, vane-type and piston-type. [1]

The gear-type pump is being studied in this article as it is the most widely available due to its simple construction and therefore reduced purchase price. Gear type pumps (figure 1) are power
driven units consisting of two or more intermeshing gears or lobed members enclosed in a suitable housing. They are usable in a wide range of pressures and cover many flow rates. [2]

The movement of the gears, also relative to the casing acts upon the fluid in four different methods:
- The unmeshing of the gears near the inlet causes a pressure drop that results in outside fluid rushing in.
- Fluid is being transported from the inlet to the outlet in the outer tooth gaps of the gears.
- The meshing of the gears near the outlet results in a pressure increase that forces fluid out providing flow.

The fluid trapped between the gears (crushed volume) is released through slots in the casing. [3]

The purpose of the article is to describe a simple and interactive way to visualize these phenomena at work using low cost readily available parts.

![image](image1.png)

**Figure 2.** – Control volume method. [5]

The idea for this is original, the need for it came about while doing mathematical models of the pump gears as the only feedback for correctness was getting results that match the technical spreadsheet and existing theory.

The displacement of the pump is a very important constructive parameter to consider when assessing the pump performance and flow ripple. In the previously published article [4] several methods for determining the pumping capacity of an external gear pump were made, since the same pump was used for the results will therefore be compared. Another method for measuring the displacement is through the practical method, mainly measuring the amount of hydraulic fluid that leaves the pump at one single rotation or by measuring the flow rate at a well-known pump rotational speed.

![image](image2.png)

**Figure 3.** – CFD simulation a) compared to real pump with slow motion b). [6]

Other researchers have used different approaches like: usage of control volumes for determining the flow rate (figure 2) [5], complete 3d models based on CFD (Figure 3a) simulation or even
designing a transparent acrylic pump cover coupled with slow motion cameras to capture the cavitation and fluid motion (Figure 3b) [6].

2. Description of the hardware setup
The whole process starts with the disassembly of the real geared pump that is to be studied; this step is only required if the geometry is not known from the technical drawings. The real gear pump assembly can be directly studied if the gear faces are color coded (painted or masked tape) so the algorithm can recognize them; otherwise the measured gears should be 3d printed to fit a standard stepper motor shaft on one side and a bearing on the other.

The gear assembly studied in this article had measurements that were conforming to a spur gear with a module of 3 and tooth face width of 12mm.

Part of the hardware structure was designed in a CAD software package, mainly SolidWorks. It started out as a concept as seen in Figure 4.

![Figure 4. – First concept.](image)

The concept and all the future revisions were printed on a consumer readily available printer (UP Mini 2).

First version included a Raspberry pi 3b+ with the official camera attached. The gears were 3d printed to be attached to a geared dc motor powered by a Laboratory Power Supply Unit (PSU).

This whole setup was completely replaced after the first tests proved unreliable for dynamic measurements. The official PI camera had a fixed focus from 0.5m to infinity, the geared motor speed motor was not constant and depended on friction between gears and casing and finally the raspberry pi 3b+ required a separate powerful power supply.

The final setup (Figure 5) was made with a stepper motor as the constant rotation speed source, raspberry pi zero was ensued as the acquisition and motor control, easily powered from a PC USB port, and a generic webcam was used for image acquisition. The passive gear was redesigned to use a ball bearing as opposed to PLA bushing to reduce friction and increase accuracy.

The gears were designed in SolidWorks and 3d printed to match the real geometry of the external gear pump assembly. The necessary information was obtained from disassembly of the pump and manual measurements of the gear and assembly.
A raspberry pi zero is connected to an Allegro A4988 stepper motor driver to precisely control the position of the gears before each picture is triggered. A program written in MATLAB, running on a separate pc is responsible for image acquisition and post processing.

3. Program algorithm
The series of snapshots acquired are enhanced and post-processed to accentuate the colors of the gears and edge, then they are converted to Grayscale and finally converted to a Boolean array using a threshold.

The resulting binary arrays are cropped, filled in the region of interest and an Exclusive OR is performed on the processed image thus comparing it to the original image. All the pixels in the area of interest are counted. The angle can be adjusted and the algorithm repeats for every increment with great resolution given the usage of a stepper motor.

This pixel counting is essentially measuring the dimensionless area occupied by the fluid at every angle increment; although this number has no real dimension, by using a reference geometry the algorithm can calculate the pixel per millimeter equivalent to the part and transform every pixel to square millimeters (figure 6, figure 7).
The area resolved from the previous step is then multiplied by the tooth thickness to get the volume of the at every angle needed. By applying a derivative operation on the volume, we can also obtain the instantaneous flow rate.

Selecting a different region of interest (ROI) results in graphical representation of the fluid volume in different conditions. An example processed sequence is shown in figure 8.

4. Results
4.1. Outlet region volume waveforms:
The region of interest (ROI) was first set up to point to an area belonging to the outlet. The waveforms captured must be post-processed in order to exclude the sudden volume changes that occur when a new tooth-gap enters the measured region. Figure 9 shows the resulting waveform and post-processed waveform. The measurement is done for a 36-degree rotation (full tooth) and therefore includes the volume change resulting from two tooth gaps.

Figure 8. Outlet flow.
As can be seen from figure 9, the volume does not change linearly in time that implies the existence of a flow ripple characteristically found in these pumps.

4.2 Fluid transport volume
This measurement is done by selecting an isolated fluid volume in between the tooth-gap and the outside casing as the region of interest (ROI). The resulting pixel count is then multiplied by the total number of teeth, tooth face width and “pixel to mm² constant” to obtain the estimated discharge volume.

The resulting volume is about 8.6 cm³, close to the technical specifications as will be discussed in the results.

4.3 Crushed volume
The last interesting particularity of the pump in discussion is the crushed volume of fluid where the teeth are meshing. It is difficult to mathematically model and simulate as it implies the meshing of two spur gear profile. The image sequence (reduced from total sample size) is presented in figure 11 with the volume highlighted in green.

The resulting waveform from the algorithm for the crushed volume is available in figure 12.
Figure 11. Crushed volume variation.

Figure 12. Crushed volume waveform.
5. Conclusion
As previously mentioned, the results are to be compared to the previous article [4] that used mathematical models to estimate the displacement.

Rexroth was contacted to provide the displacement of the 1PF2G-2X pump that is present in the hydraulic generator. The value provided by means of a technical catalogue page was 8.6 cm³. All results were copied in the following table 1 to ease comparison.

| Method                      | Tooth volume $V_t$ [mm³] | Tooth gap volume $V_g$ [mm³] | Displacement $V_d$ [cm³] |
|-----------------------------|--------------------------|-----------------------------|--------------------------|
| Method1                     | -                        | -                           | 6.785                    |
| Method2                     |                          |                             |                          |
| - Approach 1                | 347.2504                 | 442.8759                    | 8.8575                   |
| - Approach 2                | 350.0588                 | 440.0675                    | 8.8013                   |
| - Approach 3                | 350.1388                 | 439.9875                    | 8.7997                   |
| Method3                     | 350.1323                 | 439.9940                    | 8.7999                   |
| Method4                     | -                        | -                           | 9.4757                   |

Figure 13. Previous article results [4]

As mentioned in the introduction, a practical approach is also valid for measuring the displacement. In a previous article [7] the same pump was modified to work with a variable rotation AC motor. During maximum rotation speed the flow rate can be seen to be about 12 L/min, (after correcting a 2x flow rate scaling error). Given a measured rotational speed of about 1420 revolutions per minute the pumping capacity can then be found by just dividing the measured flow rate by the RPM value. That
results in about 8.45 cm³.

The results are reasonably accurate and further research in this area can result in greater accuracy and repeatability. The capabilities of MATLAB for image processing are much greater than was explored here and stunning graphics can also be obtained from just using functions like “volshow” coupled with “imwrite” to also generate 3d animations.

The purpose of this paper was to provide a new method to aid in the study of the geared pumps using readily available parts. Given the results obtained there is no doubt that this method is viable and quite interactive for helping students and alike understand the inner workings of the gear pump while providing instant feedback.

6. References

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