Vacuum Experiment

Fortgeschrittenen Praktikum I

Abstract

This experiment examines the operation and several properties of a typical 'high' vacuum system, based on a diffusion pump. The ultimate pressure of the system will be measured and the pumpdown characteristics will be charted. The performance of various vacuum gauges will be examined.

In this experiment you will be introduced into the creation and utilization of vacuum. Different types of pumps and pressure gauges will be used, to understand their operating principles. In the second part of the experiment the resonance behavior of a quartz oscillator, commonly used in watches and latterly in atomic scale analysis by Tuning Fork - Atomic Force Microscopes, will be analyzed at different pressures.

Contents

1 Theory

A vacuum is a volume of space that is empty of matter, including air, so that gaseous pressure is much less than standard atmospheric pressure. The root of the word vacuum is the Latin word vacuus (pl. vacua) which means 'empty', but space can never be perfectly empty. A perfect vacuum with a gaseous pressure of absolute zero is a philosophical concept with no physical reality.

The quality of a vacuum is indicated by the amount of matter remaining in the system. For industrial purposes, vacuum is primarily measured by its absolute pressure, but a complete characterization requires further parameters, such as temperature and chemical composition. One of the most important parameters is the mean free path (MFP) of residual gases, which indicates the average distance that molecules will travel between collisions with each other. As the gas density decreases, the MFP increases, and when the MFP is longer than the chamber, pump or other objects present, the continuum assumptions of fluid mechanics do not apply. This vacuum state is called **high vacuum**. The MFP of air at atmospheric pressure is very short, 7×10^{-8} m, but at 0.1 hPa the MFP of room temperature air is roughly 10 cm, which is on the order of everyday objects such as vacuum tubes.

Vacuum quality is subdivided into ranges according to the technology required to achieve it or measure it. These ranges do not have universally agreed definitions (hence the gaps below), but a typical distribution is as follows:

Vacuum Range	**Pressure (hPa)**	**Molecules ($1/cm^3$)**	**Mean Free Path**
Low Vacuum	300..1	$10^{19}..10^{16}$	0.1..100 μm
Medium Vacuum	$1..10^{-3}$	$10^{16}..10^{13}$	0.1..100 mm
High Vacuum	$10^{-3}..10^{-7}$	$10^{13}..10^{9}$	10 cm..1 km
Ultra High Vacuum	$10^{-7}..10^{-12}$	$10^{9}..10^{4}$	1 km..10^5 km
Extremely High Vacuum	$<10^{-12}$	$<10^{4}$	$>10^5$ km

Vacuum is useful in a variety of processes and devices. Its first common use was in incandescent light bulbs to protect the tungsten filament from chemical degradation. Its chemical inertness is also useful for vacuum welding, for chemical vapor deposition and dry etching in semiconductor fabrication and optical coating fabrication, and for ultra-clean inert storage and measurements. The reduction of convection improves the thermal insulation of thermos bottles and double-paned windows. The electrical properties of vacuum make electron microscopes and vacuum tubes possible, including cathode ray tubes. Within this experiment the beneficial effect of vacuum on the oscillation properties of an oscillator used in various scanning probe techniques will be analyzed.

For an electrically resonant system, the quality (Q) factor represents the effect of electrical resistance and, for electromechanical resonators such as quartz crystals, mechanical friction. The Q factor is defined as the resonance frequency (center frequency) f_c divided by the bandwidth Δf

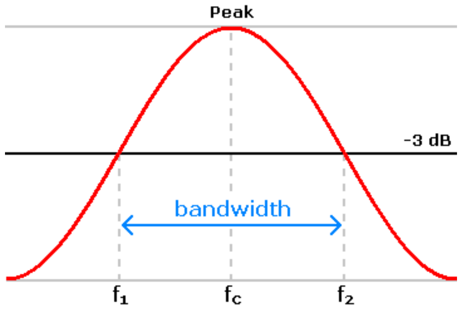

Figure 1: Defenition of the bandwidth of a resonance.

$$Q = \frac{f_c}{f_2 - f_1} = \frac{f_c}{\Delta f}. \tag{1}$$

The Bandwidth is given by $\Delta f = f_2 - f_1$, where f_2 is the upper and f_1 the lower cutoff frequency. On a graph of response versus frequency (Fig. 1), the bandwidth is defined as the 3 dB change in level (voltage, current, or power) on either side of the center frequency. For the case of power, the bandwidth is the same as the 'full width at half maximum' or FWHM. This is the width in frequency where the power falls to half of its peak value. When dealing with voltage or current, the bandwidth is the width where the level falls to $1/\sqrt{2}$ of its peak value and thus is not equal to the FWHM.

For a single damped mass-spring system, the Q factor represents the effect of mechanical resistance.

$$Q = \frac{\sqrt{mk}}{R} \tag{2}$$

where m is the mass, k is the spring constant, and R is the mechanical resistance. From the expression for the resonance frequency of a mass-spring system,

$$\omega = \sqrt{\frac{k}{m}} \tag{3}$$

the alternative formulation:

$$Q = \frac{\omega m}{R} \tag{4}$$

can be derived. Details about tuning forks and their preparation and utilization in scanning probe microscopy can be found in the dissertation of Jörg Rychen [9].

2 Experimental

In the experiment, there are three kinds of pumps which allow you to create a vacuum in different ways. Since these pumps are quite sensitive, it's important

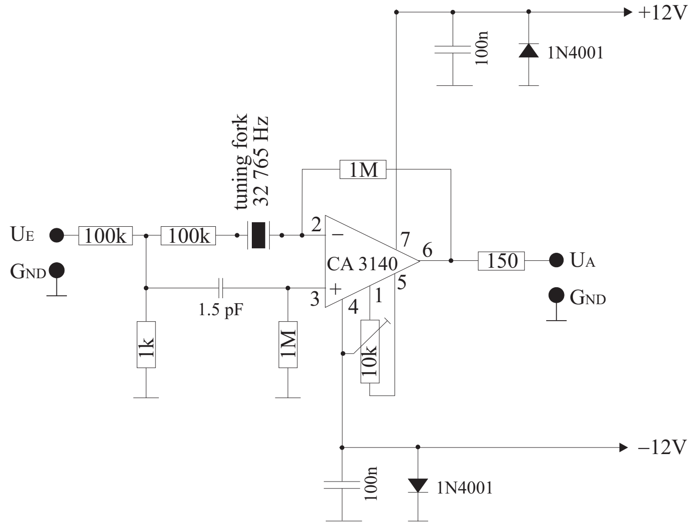

Figure 2: Circuit diagram of the tuning fork driver.

to follow the instructions carefully!

2.1 Material

Attached on the vacuum system are: A rotary pump, a turbo pump, a diffusion pump as well as two different pressure gauges, a Pirani and a cold cathode. A tuning fork is attached together with a driver (Fig. 2) to a vacuum flange wich can be excited by function generator and displayed by an oscilloscope.

2.2 Pumping Down and Venting the System

2.2.1 Rotary Pump

1. Make sure **all the valves are closed**. Turn the Rotary Pump on, and wait till the indicator of the right gauge (Pirani) stop moving.

2. **Open valve 1**. The connection between the Rotary Pump and the chamber is now open. Wait until the indicator of the Pirani gauge is not moving anymore. This is the minimum of pressure that can be achieved with this kind of pump.

2.2.2 Diffusion Pump

1. **Start the Rotary Pump** as described in the section above, to create a pre-vacuum. Without this procedure the Diffusion Pump could be damaged.

2. **Open valve 2** to evacuate the Diffusion Pump. The pump needs some vacuum before starting, otherwise the silicon oil will be contaminated and needs to be changed. . . .

3. **Close valve 1** and **open the red gate valve 1** between the chamber and the Diffusion Pump. In order to open the gate valve correctly, you have to turn it by 90°, pull it outwards and then turn it back by 90°. Caution: valve 1 must always be closed before you do this, because the oil in the Diffusion Pump / Rotary Pump will otherwise contaminate the chamber!

4. Because the Diffusion Pump gets really hot (!) while working, you have to **turn on the cooling water** before you switch on the pump. Start the water circulation by turning on the switch at the wall to the left of the entrance door. The green light should glow. Back at the experiment, push the 'Wasser ein' button and check if the red light behind the Diffusion Pump is on. Shortly before you turn on the cooling water **switch on the Diffusion Pump**, otherwise the cooling water is automatically stopped.

5. Until you get the optimal pumping range, you have to **wait approximately two hours**. Make sure that the pressure is decreasing by turning on the gauge named 'Kaltkathode'. This gauge shouldn't be left on for too long. The indicator may fluctuate, due to contamination of the cathode.

6. **Before switching off the Diffusion Pump,** close the red gate valve 1 to the main chamber first! Leave valve 2 open and the Rotary Pump switched on till the pump is cooled down.

7. Close valve 2 and switch off the Rotary pump. Be sure all valves are closed before doing this!!!

2.2.3 Turbo Molecular Pump

1. **Start the Rotary Pump** as described in the section 'Rotary Pump', to create a pre-vacuum. This step is very important, since the Turbo Molecular Pump can be overloaded by pumping too many molecules out of the chamber.

2. **Open valve 3 and close valve 1**. Then **open the red gate valve 2** by the Turbo Molecular Pump. Now the connection from the chamber through the Turbo Molecular Pump to the Rotary Pump is open.

3. **Turn on the Turbo Molecular Pump**. As soon as the green light is glowing, the pump has reached its maximum frequency. Wait until the value of the pressure doesn't change any more.

4. **Before switching off the Turbo Pump,** close the red gate valve 2 to the main chamber! Close valve 3.

5. Turn off the Turbo Molecular Pump first, and then the Rotary Pump.

3 Exercises

1. Describe the function as well as the utilization of the vacuum pumps and pressure gauges. Which other pumps and gauges are used commonly in the field of research?

2. Become familiar with pumping down and venting the system.

3. Measure the amplitude (voltage) in dependence of the oscillation frequency at different pressures. For example at atmospheric pressure or at a vacuum generated by the diffusion pump. To get an interesting result, you can leave the pumps working for several days. The function generator is used to vary the frequency of the excitation voltage. Start at a frequency of around 32.765 kHz with an excitation amplitude of 1 Vpp

4. Plot the resonance curves with a suitable programme like Origin. Try to explain the differences between the curves at different pressures and determine the Q factors.

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