## 1. Introduction:

Operational amplifiers (opamps) are usually used in two different modes, mainly the positive feedback mode and the negative feedback mode. These two modes have very different effects on the input-output relationship of opamps. This report will be looking at the effects of negative feedback on inverting and non-inverting operational amplifiers, the extent of proportionality of the input-output relationship of an opamp with negative feedback, and the Schmitt trigger and oscillator to illustrate the non-linear input-output relationships of opamps.

## 2. Theory:

An ideal op-amp draws no current and the output voltage is only dependent on the difference between the two input voltages. The output voltage is determined by: $V_{OUT} = A(V_+ - V_-)$, where A is open loop voltage gain. The open loop voltage gain is defined as the gain of the opamp when the output terminal is not connected to any of the input terminals. For the ideal case, the difference of voltage between the two input terminals is zero, and the gain of the opamp is infinite.

An opamp has negative feedback when the output of the opamp is connected to back to the negative input, usually through some intermediary components. A basic opamp with negative feedback is shown below in *figure 1*:

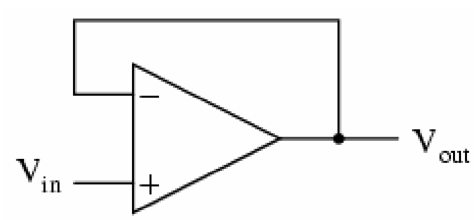



*Figure 1: A basic operational amplifier with negative feedback*

The output voltage of an opamp with negative feedback can be shown to be proportional to its input. However there is a limit to this proportionality as we will see later. For a more detailed explanation of the mechanism of an opamp with negative feedback, please refer to *appendix 1.*

Similarly, an opamp is said to have positive feedback when its output is connected back to the positive input terminal also usually through some intermediary components. A basic opamp with negative feedback is shown below in *figure 2*.

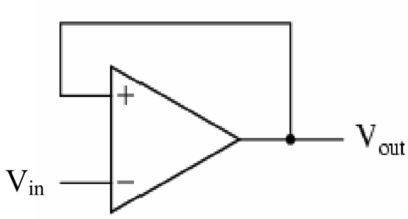



*Figure 2: A basic opamp with positive feedback*

Contrary to opamps with negative feedback, opamps with positive feedback have non-linear input-output relationships. The output voltage will always be either the maximum or minimum voltage possible. For a more detailed explanation on the non-linearity of opamps with positive feedback, please refer to *appendix 1.*

## 3. Negative feedback around an operational amplifier:

### 3.1 Negative feedback in an inverting amplifier:

In lab experiment 2.1 of the "Operational Amplifier Applications" module, an inverting amplifier with negative feedback was constructed as shown in figure 3 below:

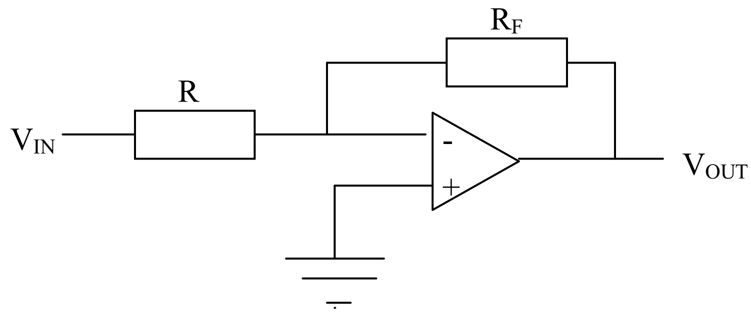
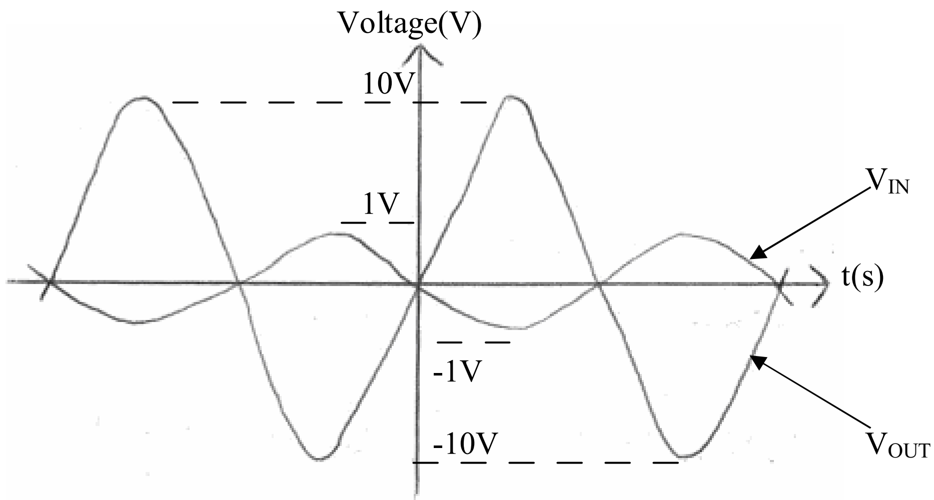



*Figure 3: An inverting opamp with negative feedback*

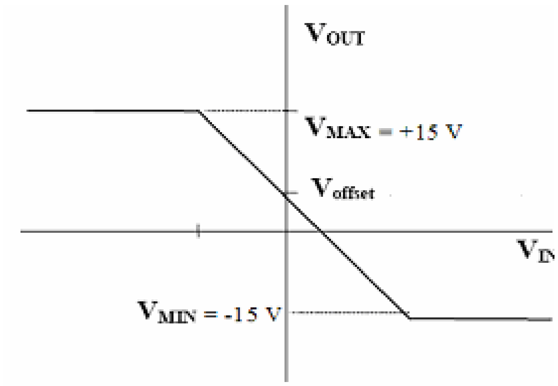
For the opamp above, $V_{OUT} = -(R_F/R)V_{IN}$, where $V_{IN}$ and $V_{OUT}$ are the input and output voltages respectively. For a rigorous derivation of the formula, please refer to *appendix 2*. As can be seen from the equation, $V_{OUT}$ is proportional to $V_{IN.}$ Using a value of 27KΩ for $R_F$ and 2.7KΩ for R, the expected gain of the circuit would then be $V_{OUT}/V_{IN} = -(R_F/R) = -10$. This theoretical result was verified by measuring the input and output voltages using two different channels of an oscilloscope. A 1V p-p sine wave at 1 KHz was applied to the input and the following graph was obtained, where $V_{IN}$ and $V_{OUT}$ are the input and output voltages respectively.




*Graph 1: Output voltage for a 1V p-p sine wave input. As can be seen, the output wave had an amplitude of 10V p-p, and is 180° out of phase with the input wave. This shows that the opamp has a gain of -10.*

When the amplitude of the sine wave was increased to 1.2V p-p at 1KHz, an output waveform similar to that of *graph 1* was obtained but with an amplitude of 12V p-p. As we can see from the experiment, the output of the opamp varies linearly with the input if there is negative feedback.

However, there is a limit to the proportionality of an opamp with negative feedback. Since the maximum voltage that can be attained in the circuit is equivalent to the supply voltages (-15V and +15V in this case), the opamp will exhibit non-linear behaviour if the expected output voltage exceeds +15V or -15V. This was verified by holding both the inputs at common zero to obtain the *graph 2* shown below:




*Graph 2: The output voltage ($V_{OUT}$) plotted against the input voltage ($V_{IN}$) for an inverting amplifier with negative feedback and a gain of -10. As can be seen, the linearity of an opamp with negative feedback is limited to the region where the output voltage is between the supply voltages (in this case, +15V and -15V).*

The output voltage was measured from the oscilloscope to be -15V. This was because the input was 0V and the gain of the opamp had to be infinite because of the negative feedback. However, the circuit also had to satisfy the constraint that the magnitude of the maximum and minimum allowable voltages were +15V and -15V respectively. Since this was an inverting opamp, the output was driven to -15V.

**3.2 Negative feedback in a non-inverting amplifier:**

Similar to an inverting amplifier, the output of a non-inverting amplifier with negative feedback can also be shown to be proportional to its input. A basic non-inverting amplifier is as shown below in *figure 4*:

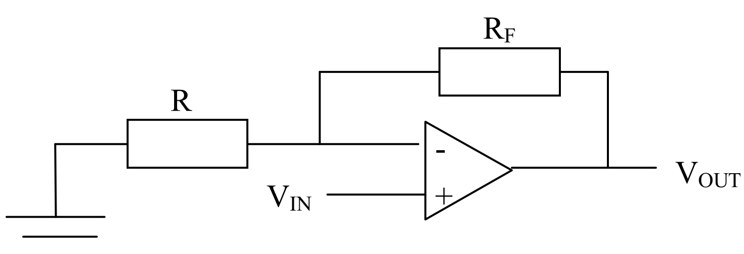
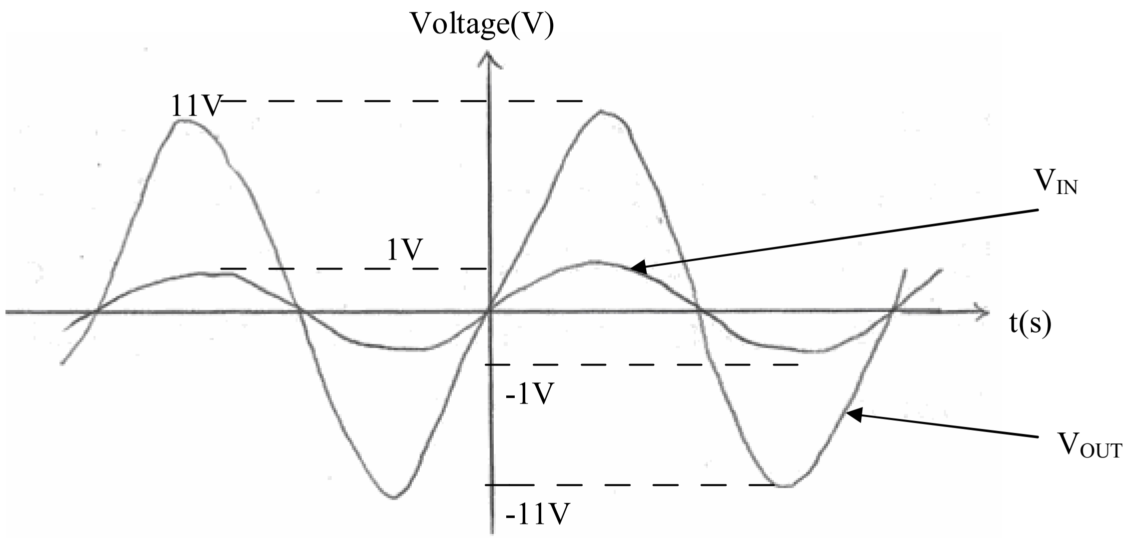



*Figure 4: A non-inverting opamp with negative feedback.*

For the opamp above, $V_{OUT} = (1+R_F/R)V_{IN}$, where $V_{IN}$ and $V_{OUT}$ are the input and output voltages of the opamp respectively. For a rigorous derivation of the formula, please refer to *appendix 2.* In this case, it also can be seen from the equation that $V_{OUT}$ is proportional to $V_{IN.}$ Using the same values for $R_F$ and R, namely 27KΩ and 2.7 KΩ respectively, the expected gain of the circuit would then be $V_{OUT}/ V_{IN}= (1+R_F/R)$= 11. Applying a 1V p-p sine wave at 1 KHz to the input produced *graph 3* and confirmed the theoretical gain, as well as showed that the output of an opamp with negative feedback is again proportional to its input.




*Graph 3: Output voltage for a 1V p-p sine wave input. As can be seen, the output voltage has an amplitude of 11V p-p. This shows that the opamp has a gain of 11.*

## 4. Positive feedback around an operational amplifier:

### 4.1 The Schmidt Trigger: A look at the non-linearity of opamps with positive feedback

Since the positive feedback in an opamp results in its output being driven to either its maximum or minimum value, we have now a device which is bistable: stable in one of two states (saturated positive or saturated negative). In order to get the device to switch states, we will have to apply a voltage to the inverting (negative) input of the same polarity, but of a greater magnitude. For example, if our circuit is saturated at an output voltage of +15 volts, it will take an input voltage at the inverting input of at least +15 volts to get the output to change. When it changes, it will saturate fully negative.

Therefore, an op-amp with positive feedback tends to stay in the output state that it's already in. It "latches" between one of two states, saturated positive or saturated negative. An opamp with positive feedback is therefore a non-linear device.

A Schmitt trigger was constructed as shown in *figure 5* below to test the ability of the opamp as a latch/switch.

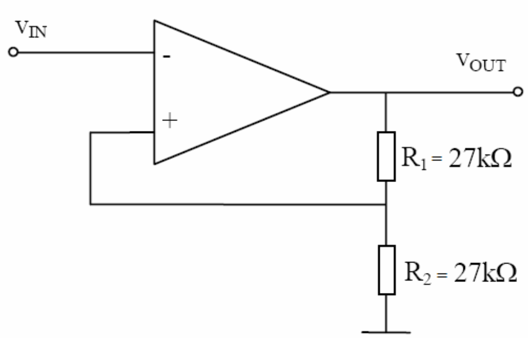
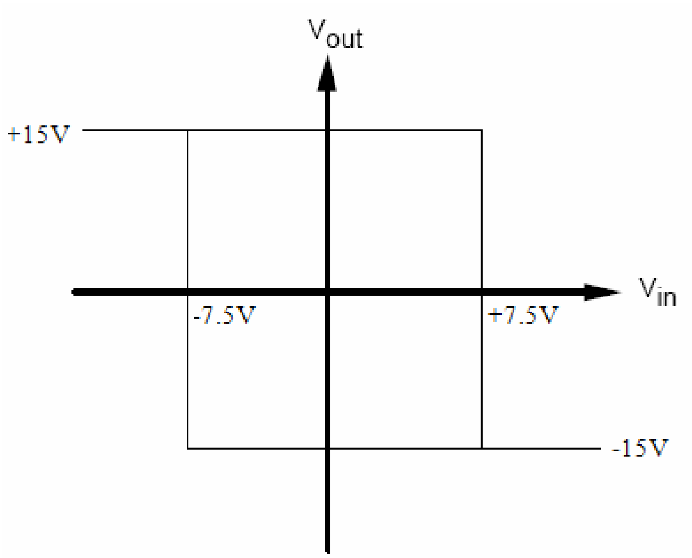



*Figure 5 :A Schmitt trigger*

The output of the opamp was connected to channel Y of an oscilloscope and the input connected to channel X. In the X-Y mode, the following graph was obtained:




*Graph 4: A plot of the output voltage against the input voltage of a Schmitt trigger. Note the non-linearity of the input-output voltages.*

Let the positive and negative input terminal voltages of the opamp be denoted by $V_+$ and $V_-$ respectively. Because of the positive feedback, $V_{OUT}$ will be driven to +15V when $V_+ > V_-$ and to -15V when $V_+ < V_-$. Assuming initially $V_{OUT} = +15V$, then $V_+ = 27K\Omega/(27K\Omega + 27K\Omega)*15V = 7.5V$. If $V_-$ is increased, there will be no change of state until $V_+ < V_-$. When $V_+ = +7.5V < V_-$, the circuits will switch state and be driven to -15V instead.

To further illustrate the non-linearity of the input-output relationship of an opamp with positive feedback, we shall look at a Schmitt trigger oscillator shown in *figure 6* below:

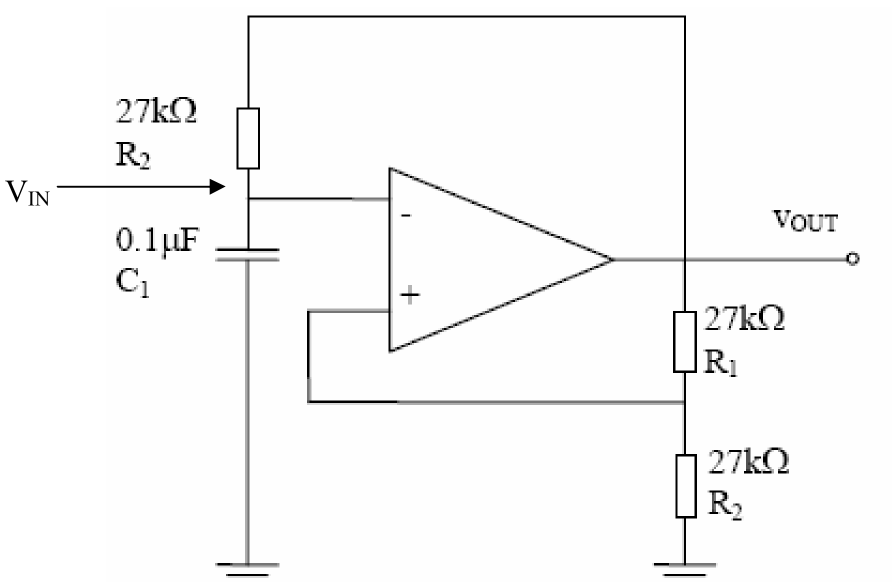
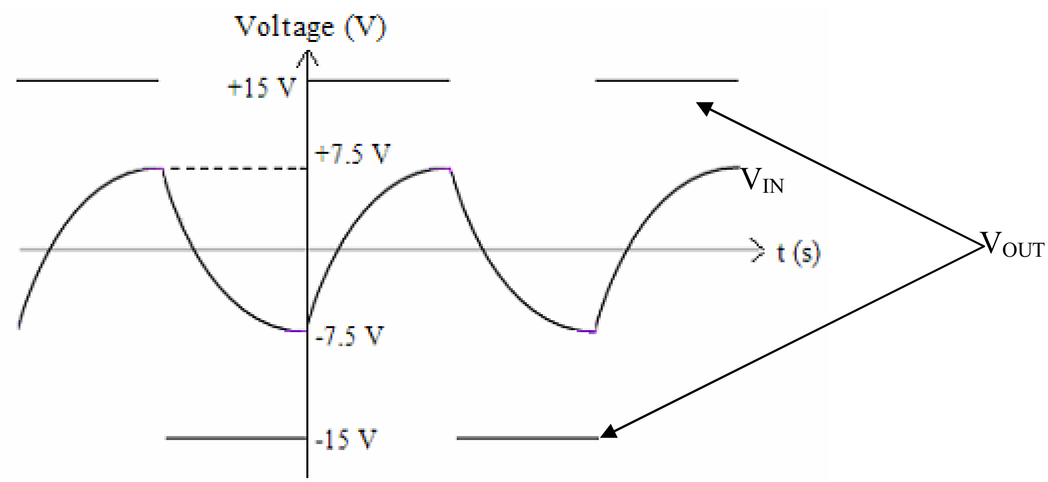



*Figure 6: A Schmitt trigger oscillator.*

The circuit in *figure 6* was constructed and the input and output terminals were connected to an oscilloscope and the following graph was obtained:




*Graph 5: $V_{OUT}$ against time for a Schmitt trigger oscillator. The output voltage ($V_{OUT}$) toggles between +15V and -15V.*

Initially, for $V_{OUT}$ to switch to +15V, $V_{IN}$ has to go to -7.5V. When this happens, $V_{OUT}$ switches to +15V and hence $V_{IN}$ = +7.5V. Since $V_{OUT} > V_{IN}$, the current flows to ground, and the capacitor charges up and $V_{IN}$ starts to rise. When $V_{IN}$ reaches +7.5V, $V_{OUT}$ switches to -15V, and the capacitor starts to discharge exponentially. $V_{IN}$ starts decreasing again, and the whole process repeats itself.

Also, note that there is no external input required for the oscillator as the whole circuit is self-oscillating.

## 5. Conclusion:

We have looked circuits and experiments illustrating the fact that an opamp with negative feedback has an output which is proportional to its input and discussed the limit of this proportionality. A Schmitt trigger and oscillator was also used as an example to illustrate the non-linearity of opamps with positive feedback. This report has shown that an opamp with negative feedback is a linear device, and can be used to implement linear circuits, and on the other hand, opamps with positive feedback are non-linear devices and can be used to implement switching in a circuit.

## References:


1. Imperial College first year Electronics Laboratory Booklet, Spring Term 2004
2. Sedra and Smith *Microelectronics Circuits third edition*, Saunders College Publishing, 1989

# Appendix 1:

**Explanation of the proportionality of the input-output relationship for an opamp with negative feedback:**

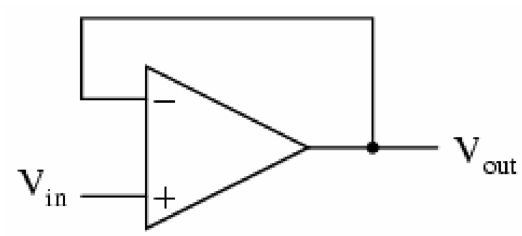



*Figure 7: A basic operational amplifier with negative feedback*

To look at the input-output relationship of an opamp with negative feedback, we shall refer to *figure 7* above. As *Vin* increases, *Vout* will increase in accordance with the differential gain. However, as *Vout* increases, that output voltage is fed back to the inverting input, thereby acting to decrease the voltage differential between inputs, which acts to bring the output down. What will happen for any given voltage input is that the op-amp will output a voltage very nearly equal to *Vin*, but just low enough so that there will be enough voltage difference left between *Vin* and the negative input terminal to be amplified to generate the output voltage. This allows the opamp to achieve a stable output. This stability is what gives the opamp the capacity to work in the linear mode as opposed to being fully "on" or "off" as in the case of using it as a comparator, with no feedback at all.

**Explanation of the non-linearity of the input-output relationship for an opamp with positive feedback:**

To analyse the effects of positive feedback on an opamp, it is useful to ground the negative input terminal as in *figure 8* below:

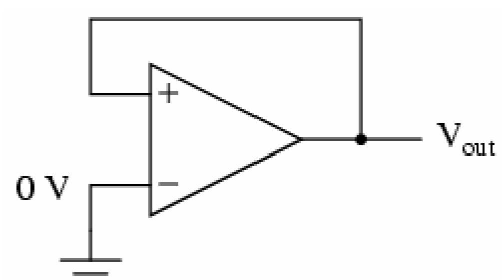



*Figure 8: An opamp with positive feedback with its negative input terminal grounded.*

With the inverting input grounded, the output voltage will be dictated by the magnitude and polarity of the voltage at the non-inverting input. If the voltage happens to be positive, the opamp will drive its output positive as well, feeding that positive voltage back to the non-inverting input, which will result in full positive output saturation. On the other hand, if the voltage on the non-inverting input happens to start out negative, the opamp's output will drive in the negative direction, feeding back to the non-inverting input and resulting in full negative saturation.

# Appendix 2:

**Derivation of formulae for the output voltage of an inverting opamp with negative feedback:**

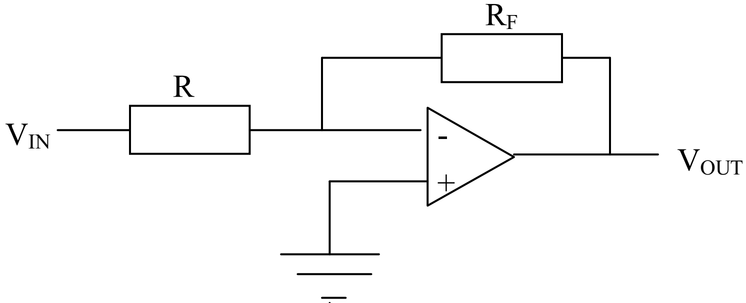



*Figure 9: An inverting opamp with negative feedback*

Using *figure 9*, the current going into the negative terminal's input will be zero. The voltage at the negative input terminal will be zero as it will tend to follow the positive terminal's input voltage for an ideal opamp. Applying Kirchoff's Current Law at the negative input terminal will give us:

$-V_{IN}/R + (-V_{OUT}/R_F) = 0$

$=> \quad V_{OUT} = -(R_F/R)V_{IN}$

**Derivation of formulae for the output voltage of a non-inverting opamp with negative feedback:**

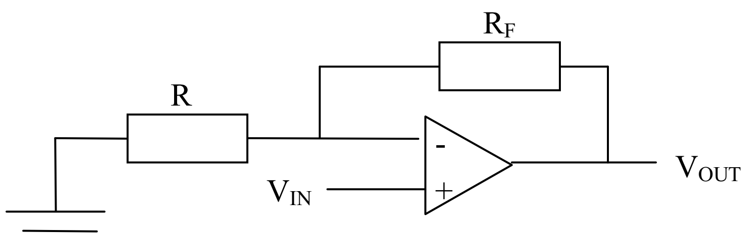



*Figure 10: An inverting opamp with negative feedback*

Using *figure 10* the current going into the negative terminal's input will be zero. The voltage at the negative input terminal will be equal to $V_{IN}$ as it will tend to keep the differential input voltage to zero. Applying Kirchoff's Current Law at the negative input terminal will give us:

$V_{IN}/R + (V_{IN} - V_{OUT})/R_F = 0$

$=> \quad V_{OUT} = (1+R_F/R)$