Influence of the Rail-to-Rail Feature of the Operational Amplifier on the Performance of an Instrumentation System

ÁLVARO LLARÍA[1], OCTAVIAN CUREA[1], JAIME JIMÉNEZ[2]
[1]Laboratoire en Ingénierie des Processus et des Services Industriels (LIPSI)
Ecole Supérieure des Technologies Industrielles Avancées (ESTIA)
Technopôle Izarbel, 64210 Bidart
FRANCE
[2]Departamento de Electrónica y Telecomunicaciones
Universidad del País Vasco, Escuela Técnica Superior de Ingeniería
Alameda Urquijo, s/n, 48013 Bilbao
ESPAÑA

Abstract: - One of the usual features that an operational amplifier may offer is the "rail-to-rail" capability. This means that its output range is equal to the power voltages (positive and negative or zero) without any offset. In some cases this feature does not concern with the performance of the system because it does not operate in the limits of the output range or the offsets are small enough not to care about them. Nevertheless, when an accurate instrumentation system must be used, as in this article, the rail-to-rail capability is crucial not to degrade the performance. For instance, the circuit may loose linearity and resolution if the operational amplifiers are not adequate. In our case, a circuit to perform some discrete time control algorithms needed a maximum output range for the system to work properly. With the initial operational amplifiers, the performance was not adequate. After setting rail-to-rail ones the problem has been resolved.

Key-Words: - Operational amplifier, rail-to-rail, output range, linearity.

1 Introduction

Among the most important features of an operational amplifier (symmetry of the power, offset, CMMR, gain, input impedance, output impedance, frequency response, polarization currents, etc.) the rail-to-rail capacity sometimes is not taken into enough consideration [1].

Our system, of didactical purpose, allows the engineering students to implement discrete-time control algorithms and to observe the behavior of some real thermal, hydraulic and mechatronic processes. The main hardware parts of this module, designed and constructed in the Ecole Supérieure des Technologies Industrielles Avancées (ESTIA), are a microcontroller card and a signal shaping card. In addition, the module communicates with a PC in order to be programmed.

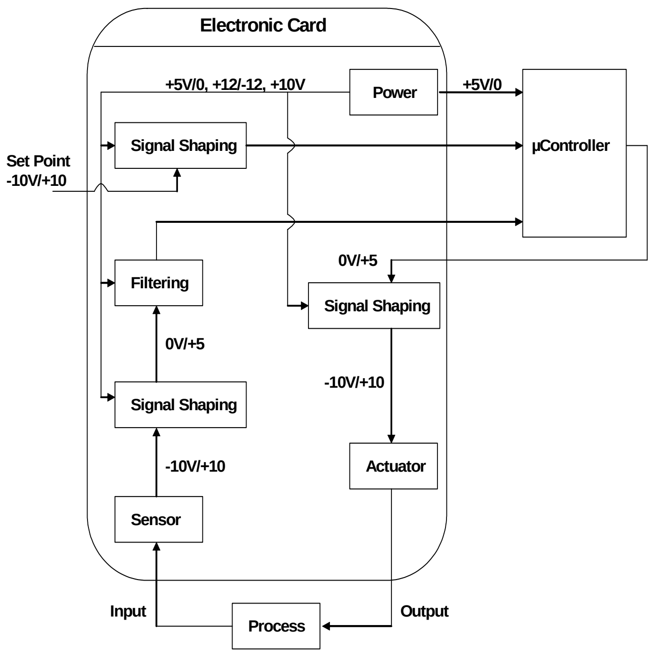

Fig. 1. Block diagram of the electronic system.

2 Description of the system

In terms of hardware subsystems, the entire module consists of two parts: the (signal shaping) electronic card and the LVCS12 module which contains a Motorola MC9S12E128 microcontroller.

The circuit, named Electronic Card in Fig. 1, makes three tasks: to give the power values employed by other modules (Power block in Fig. 1), to filter the electrical signals (Filtering block in Fig. 1), and to scale the signals between the correct values (Signal shaping blocks in Fig. 1).
Signal shaping blocks are used in order to scale the microcontroller signals (0 V, +5 V) into the levels of the electronic card (-10 V, +10 V), and vice – versa. To make this, it is necessary to use a voltage reference which must be very accurate. This voltage reference is provided by the circuit REF 195 GP of Analog Devices, which gives an output of 5 Volts [2]. This 5 V reference is employed to obtain a new reference of 10 V by using a non inverting amplifier.
In Fig. 2 it is possible to see the necessary steps to scale the signals, and the intermediate voltage levels.

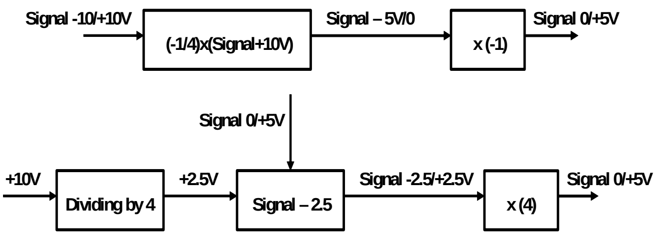

Fig. 2. Voltage levels in the system.

The filtering block is an anti-aliasing filter used before the signal sampler to restrict the bandwidth of the signal to approximately satisfy the Shannon sampling theorem. It is necessary to filter separately the three existing process (hydraulic, thermal and mechatronic), because of the different dynamics of each one. The dynamics of the process is directly related with the filter cut-off frequency. The three filters are hardware implemented and their outputs are connected to three analog inputs of the microcontroller. The analog input (so the filter) and the associated sampling time are selected in the program according to the desired dynamics.
The power block adapts the power supplying to the microcontroller, the operational amplifiers and provides specific voltages. The operational amplifiers supplying power is -12 / +12 V which is given by voltage regulators. The supply voltage for the microcontroller (+5 V) is given by a voltage regulator too. A 5 V voltage given by a precision voltage reference is amplified to obtain the desired 10 V reference.
LVCS12 is an easy applicable, credit card-sized Controller Module, based on the 16-bit HCS12 microcontroller family from Motorola. The LVCS12 has a 16 MHz crystal clock and it is equipped with a powerful MC9S12E128 microcontroller unit (MCU).
The microcontroller contains a 16-bit HCS12 CPU, 128 KB of Flash memory, 8 KB of RAM and a large amount of peripheral function blocks, such as SCI (3x), SPI, IIC, Timer, PWM, 10 bit ADC, 8 bit DAC and General-Purpose-I/Os. The MC9S12E128 has full 16-bit data paths throughout. An integrated PLL-circuit allows adjusting performance vs. current consumption according to the needs of the user application.
The LVCS12 module is also equipped with output amplifiers for the DAC channels and RS 232 transceivers for two serial interfaces (e.g. for PC connection) [3]. Students of ESTIA make practical works with LVCS12 module in Second Year in micro-programmed systems course, so, it is easy for them to use it.

3 Constraints in the output range of the operational amplifiers

At the beginning, we used the LM 358 operational amplifiers, which did not have the rail-to-rail feature [4]. When testing the system while running in normal conditions, it was not able to reach the expected maximum and minimum values of operation ranges. Wondering about the reason of this problem, most of the significant output voltages were measured and the data showed that the amplifiers could not give more than the power voltage, Vcc, minus a positive value, “b”, of some milivolts. When trying to give the “gnd” voltage, the same matter appeared, it was not possible to reduce from a positive value of “a”, similar to “b” (Fig. 3).

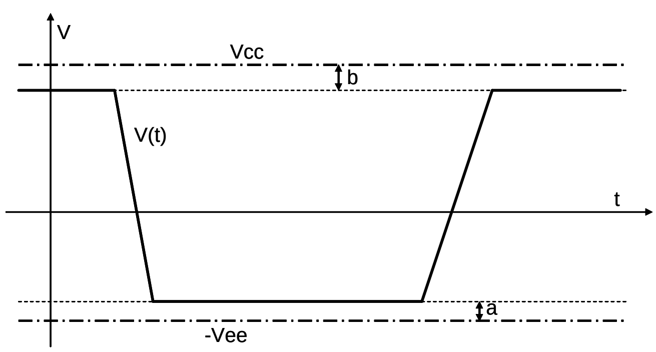

Fig. 3. Usual output range in an operational amplifier.

3.1 The rail-to-rail feature

A simple operational amplifier cannot usually reach at the output its theoretical maximum and minimum values, i.e. Vcc and –Vee when powered

symmetrically and Vcc and ground when asymmetrically [5].
Fig. 4 and Fig. 5 show this feature: an operational amplifier working in a non inverting configuration. In this case, the power supplying is asymmetrical with values 5 V, 0 V, and it is possible to see that the output voltage Vo can not reach the value of Vee (5 V). The operational amplifier is the LM 158, of the same family as LM 358.

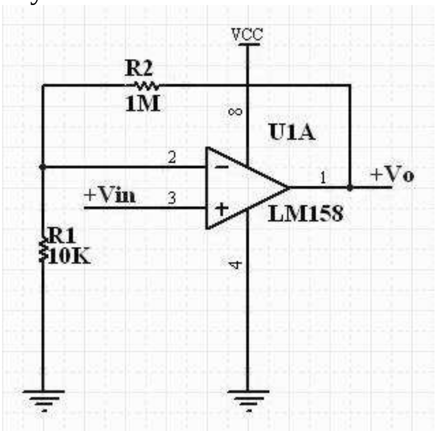

Fig. 4. Non inverting amplifier with asymmetrical power supply.

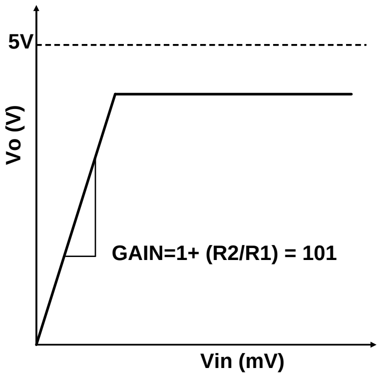

Fig. 5. Output characteristic of amplifier in Fig. 4.

The reason of this limitation can be explained by looking at the output stage of conventional amplifiers (Fig. 6). Most of the times this stage includes a transistor (BJT or MOSFET) with a serial resistor at the collector or drain.

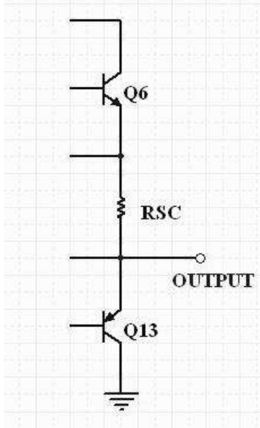

Fig. 6. Output stage of LM 358 operational amplifier.

So, although the transistor voltage dropout may be insignificant, if the output current has a usual value, the voltage dropped in the resistor must be taken into consideration [6].
In order to resolve this problem many manufactures offer rail-to-rail operational amplifiers, i.e., those that can give +Vcc and –Vee at the output [7], [8], because the serial resistor has been eliminated (Fig. 9).

3.2 Troubles in the initial circuit

Fig. 7 and 8 depict the electronic schematic of the circuits that suffer the worst consequences of the not-rail-to-rail capacity. The "10V" input should be very accurate and never lower than 10 V. Nevertheless, because of the limitation in the output range of previous amplifiers, this voltage was nearly 9 V and the circuits depicted in Fig. 7 and 8 did not work properly.

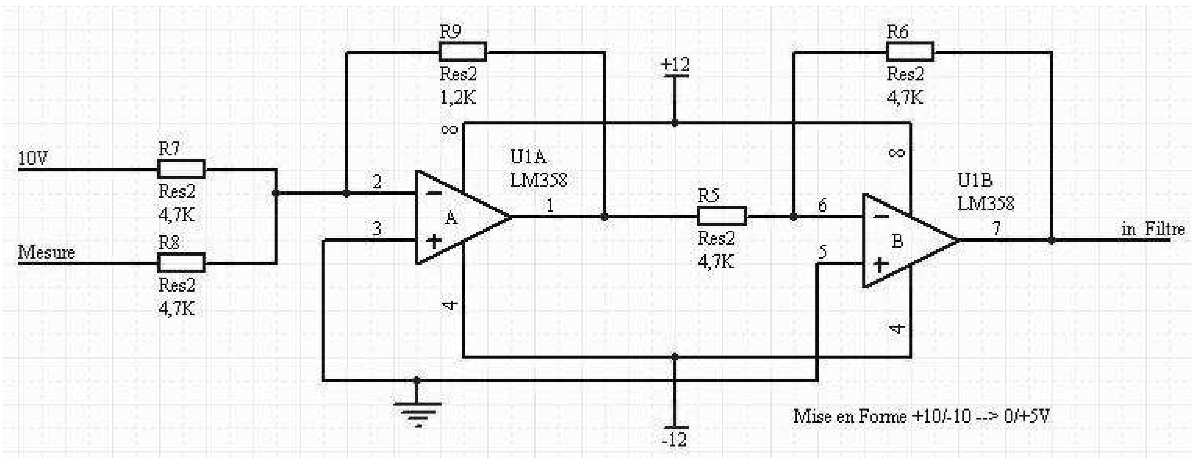

Fig. 7. The first circuit that cannot work properly because of the not accurate voltage.

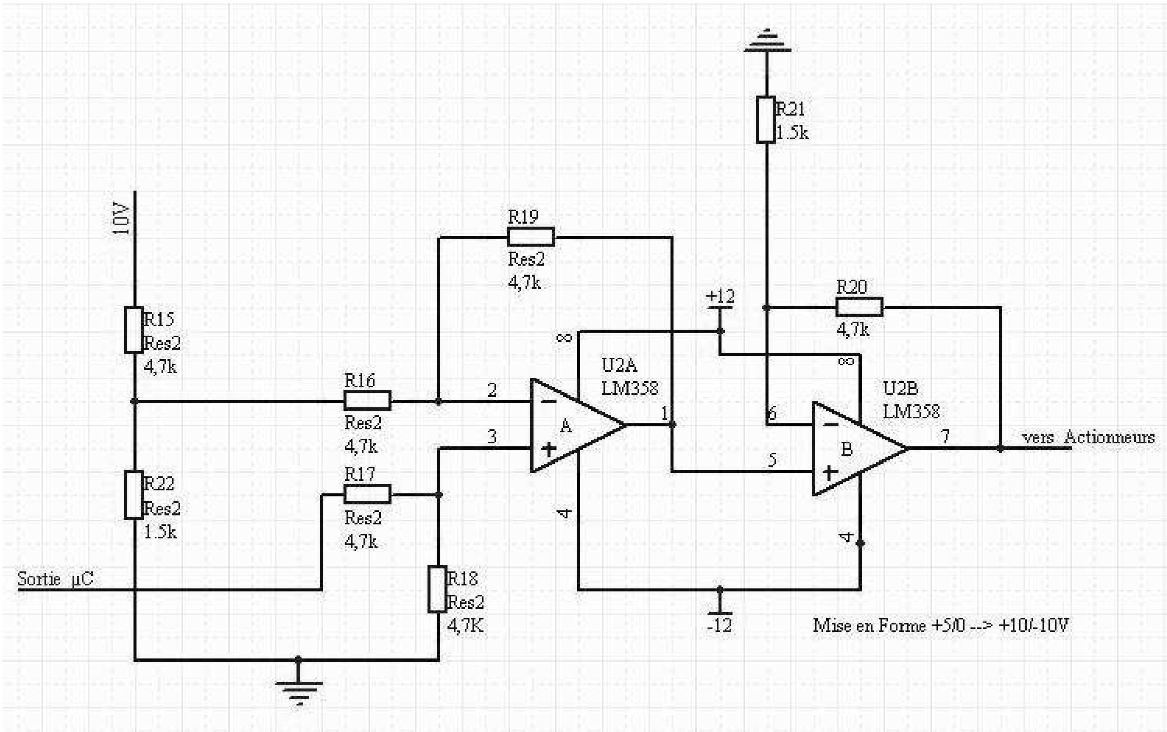

Fig. 8. The second circuit that cannot work properly because of the not accurate voltage.

It was not possible to obtain the correct voltage levels. This is, 5V – *x* and 0V + *x* instead of +5V/0V in the output *in Filtre* of Fig. 7, or 10V – *x* and -10V + *x* instead +10V/-10V in the output *vers Actionneurs* of Fig. 8. *x* always took a value of several milivolts.

4 The Solution: New operational amplifiers with rail-to-rail capability

As soon as the problem was identified and in order to fix it, all the amplifiers were substituted by LF353 which has the rail-to-rail feature [9].

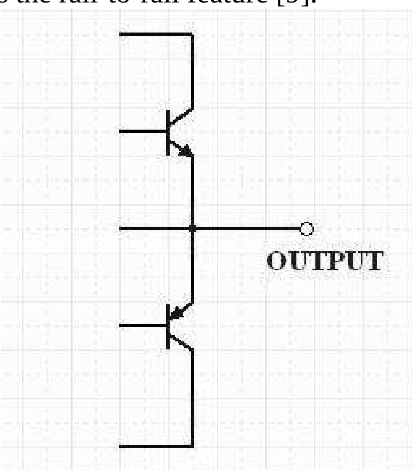

Fig. 9. Output stage of LF353 operational amplifier.

LF353 output stage is depicted in Fig. 9.
In this way, the entire system worked properly and it is being used successfully in the Control courses for engineers, in the second and third academic years of ESTIA. The experimental setups were selected in order to teach control in several engineering fields with different dynamics such as in hydraulic, thermal and mechatronic process.

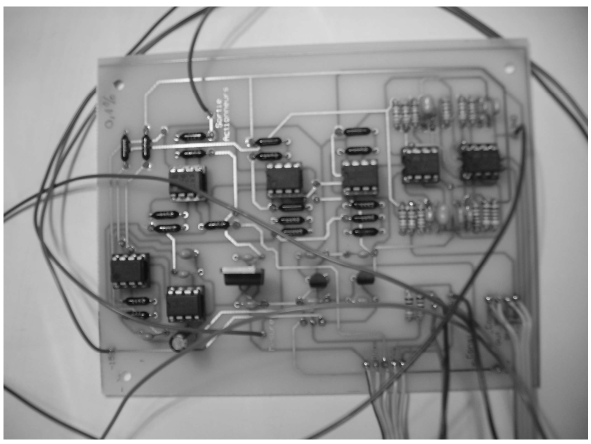

Fig. 10. Electronic card described in Section 2, where it is possible to see all the operational amplifiers.

5 Conclusions

The "rail-to-rail" capacity is seldom among the most important features of an operational amplifier (symmetry of the power, offset, CMMR, gain, input impedance, output impedance, frequency response, polarization currents, etc.). It means that the output range is equal to the power voltages (positive and negative or zero) without any offset.

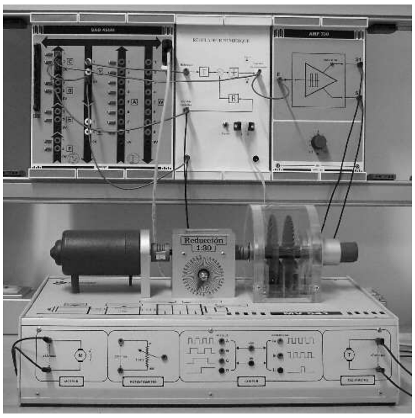

Fig. 11. Discrete Time Control didactical setup made in ESTIA.

The performance of the system sometimes does not depend on that feature, since it operates far enough from the limits of the output range or the offsets are negligible.
On the other hand, the rail-to-rail capability is crucial in accurate systems, like instrumentation ones, not to degrade the performance.
In our case, a circuit to perform some discrete time control algorithms needed a maximum output range for the system to work properly. With the initial operational amplifiers, the performance was not adequate. After setting rail-to-rail ones the problem has been resolved.

6 Acknowledgment

The work described in this paper has been supported by the Regional Council of Aquitaine (France), and the Government of the Basque Country (Spain), in the frame of Cooperation Commons Funds Euskadi-Aquitaine.

References:

[1] Y. Yutaka and H. Kobayashi, Low-Voltage Rail-To-Rail CMOS Operational Amplifier Design, *Electron Communications JPN 2 89 (12)*, 2006, pp. 1-7.

[2] *Precision Micropower, Low Dropout, Voltage References REF19x Series*, Analog Devices, 1999.

[3] *LVCS12 Hardware Version 1.10 User Manual*, MCT Elektronikladen GbR, 2004.

[4] *LM158/LM258/LM358/LM2904 Low Power Dual Operational Amplifiers,* National Semiconductor, 1994.

[5] P.R. Gray and R.G. Meyer, *Analysis and Design of Analog Integrated Circuits,* John Wiley & Sons, 1984.

[6] W. Aloisi, G. Giustolisi and G. Palumbo, Design and Comparison of Very Low-Voltage CMOS Output Stages, *IEEE T Circuits-I 52 (8)*, 2005, pp. 1545-1556.

[7] P. Aguirre and F. Silveira, Design of a Reusable Rail-To-Rail Operational Amplifier, *16th Symposium on Integrated Circuits and Systems Design, SBCCI Proceedings,* 2003, pp. 20-25.

[8] L. H. C. Ferreira and T. C. Pimenta, An Ultra-Low-Voltage Ultra-Low-Power CMOS Miller OTA With Rail-To-Rail Input/Output Swing, *IEEE T Circuits-II 54 (10),* 2007, pp. 843-847.

[9] *LF353 Wide Bandwidth Dual JFET Input Operational Amplifier,* National Semiconductor, 2003.