ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA116

INITIAL EXPERIMENTAL TEST OF A MODIFIED ADRC ALGORITHM FOR MICROPHONICS REDUCTION*

A. Elejaga†, J. Jugo, University of the Basque Country, Leioa, Spain
P. Echevarria, A. Neumann, A. Ushakov, Helmholtz-Zentrum Berlin, Berlin, Germany

Abstract

In this article, the results obtained with a new designing approach for the active disturbance rejection control (ADRC) algorithm are presented, where loop shaping techniques are used in order to stabilize the controller and make it more resilient to delay. The objective of this work is to describe the experiment performed to test the microphonic reduction capability of the modified ADRC (MADRC), as well as to present and discuss the results obtained on the test system, which is a 9-cell super conducting radio frequency (SRF) cavity.

This is in response to the need of a precise microphonics control in SRF cavities that are operated with high quality factors. Due to the stochastic nature of microphonics and the relatively large delay of piezoelectric actuators, feedback controllers tend to destabilize the system before an acceptable control bandwidth is obtained and, therefore, are quite limited. The objective of this new approach is to modify the basic structure of the ADRC in order to enable the study of its frequency response and then make it more robust via loop shaping techniques.

INTRODUCTION

Microphonic detuning is a problem of particular relevance in SRF cavities operating with high loaded quality factors (Q_L) [1]. In these particular cases, the cavities have a bandwidth of only a few tens of Hertz, making them extremely sensitive to detuning. In this way, any mechanical disturbance can detune the device, increasing the power consumption of the system or even causing it to malfunction. Thus, it is necessary to have precise microphonics control systems to ensure the correct operation of the SRF cavities.

Due to the stochastic nature of microphonics and the relatively large delay of piezoelectric actuators, feedback controllers tend to destabilize the system before an acceptable control bandwidth is obtained and, therefore, are quite limited. This is also the case of the ADRC algorithm, which is a powerful controller in rejecting perturbations, but is specially sensitive to delay.

The ADRC algorithm has gained relevance in recent years, due to its effectiveness in controlling nonlinear systems and its relative simplicity [2]. In fact, one of the most important features of the algorithm is that it is not necessary to know the dynamics of the plant in order to design the controller. This algorithm has been used several times in the field of particle accelerators, especially in LLRF systems [3, 4].

However, as other control techniques, the ADRC algorithm has practical limitations. An important one arises from the presence of time delay, which reduces the stability margin of the system. Several works have dealt with the time delay effect by means of ADRC schemes and several methods have been proposed [5, 6]. In general, those methods improve the stability in presence of time delay, but reducing, at the same time, the disturbance rejection capability of the controller.

The main idea of this novel approach is to modify the basic structure of the ADRC algorithm , so it enables the frequency response analysis of its open loop in order to identify the range of frequencies where the instability occurs. Afterwards, a stabilization process can be done by adding different filters such as lead-lag compensators and notch filters [7].

CONTROLLER DESCRIPTION

The ADRC technique is based in four fundamental elements: a simple differential equation as a transient trajectory differentiator (TD), the nonlinear control laws and the use of the concept of total disturbance estimation and rejection. In this work, the reference tracking is not considered necessary, since the main objective of the controller is the disturbance rejection. For this reason, the use of a tracking differentiator is not considered hereinafter, simplifying the discussion. To further facilitate the design of the controller, the linear version of it is used (LADRC).

Linear Active Disturbance Rejection Control

Consider a linear system described by the expression :

$$Y(s) = P(s)U(s) + \xi(s) \tag{1}$$

Where P(s) is the dynamic of the system that can be described as follows:

$$P(s) = \frac{b_m s^m + \cdots + b_1 s + b_0}{a_n s^n + \cdots + a_1 s + a_0} \tag{2}$$

ξ(s) is the external disturbance and U(s) the input to the system. The basic idea of the ADRC is to achieve the right control feedback law in order to convert the system in to a decoupled chain of integrators, so it can be easily controlled via proportional gains [2]. For that matter, the system to control is redefined as a decoupled chain of integrators of order n-m plus a total disturbance f as shown in 3. This total disturbance is unknown and includes every external disturbances plus the part of the system's dynamic that is different from the decoupled chain of integrators:

* WORK SUPPORTED BY HELMHOLTZ-ZENTRUM BERLIN AND THE UNIVERSITY OF THE BASQUE COUNTRY
† ander.elejaga@ehu.eus

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA116

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \vdots \\ \dot{x}_{n-m} = f(x_1, x_2, \cdots, \xi(t), t) + bu \\ y = x_1 \end{cases} \tag{3}$$

Where b=b_m/a_n. Note that the only information needed about the plant is its relative order *n-m* and its high frequency gain *b*.

Then, an extended state observer (ESO) is applied, which is a Luenberger type observer with an extra state. In the first *n-m* states the observer estimates the response of the desired chain of integrators and in the extra state, f is calculated. Thus, by feeding back the f signal, the plant is converted to a decoupled chain of integrators which is then controlled by proportional gains K. The classic representation of the ADRC is shown in figure 1.

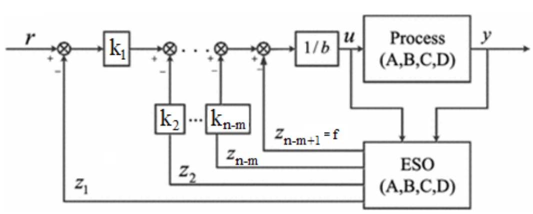

Figure 1: Standard structure of a LADRC

Modified Active Disturbance Rejection Control

Several modifications have been made to allow a simpler design and implementation, as well as to facilitate the study and correction of the system stability. This so-called MADRC is shown in figure 2.

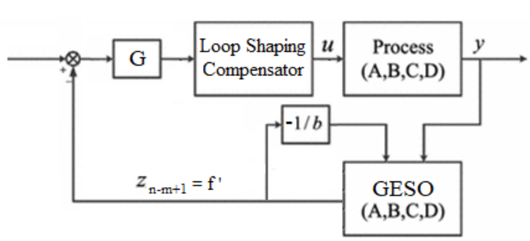

Figure 2: Standard structure of a MADRC

The first of which is the internalization of the proportional controller. In the MADRC, the desired dynamic is already included in the ESO, converting it in to what it is called a Generalized Extended State Observer (GESO) [8]. This makes the implementation and design of the controller much easier and allows us to control the plant just by feeding back the total disturbance f'.

In addition and taking into account that in this particular case the reference is always zero, the total perturbation has been directly fed back in to the GESO. This enables the frequency response analysis of the open loop of the system, so it is possible to identify in which frequency ranges the relative stability is the lowest.

Finally, a loop shaping compensator has been added in order to enhance the stability margin in those problematic ranges. The G parameter is the gain of the controller.

EXPERIMENTAL SETUP

In order to validate the feasibility of the controller, an experiment has been performed in a 9-cell tesla-type SRF cavity. It is located in the HobiCat test bench of the Helmholtz-Zentrum Berlin [9].

System Identification

The first step in the process was to identify the mechanical system to be controlled. For this purpose, the setup shown in Figure 3 was used.

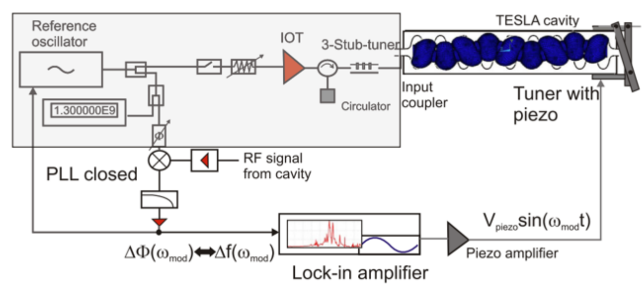

Figure 3: Experimental setup used for the identification of the system [10]

The control loop is closed with a phase-locked loop (PLL) so the injected RF signal is always tuned with the cavity. This device also approximates the detuning by comparing the phase of the incident and transmitted RF signals. A lock-in amplifier generates a reference signal with which the cavity is exited via a piezo tuner. The measured detuning is passed to the lock in amplifier in order to make a low noise measurement.

For the identification, the cavity was excited by a sinusoidal signal of varying frequency, ranging from 1 to 800Hz. The frequency step was 0.2Hz and each frequency was maintained for 2.4 seconds.

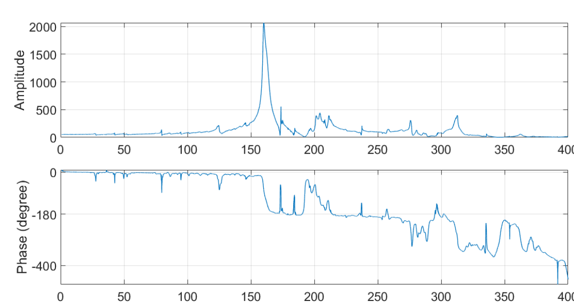

Figure 4: Mechanical response of the 9-cell Tesla cavity

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA116

As it is shown in figure 4, the phase of the system has a very abrupt change around 160 hertz due to the strong resonance mode, reaching almost -180 degrees. That means that the relative stability of the system in that area is extremely low.

Controller Validation and Results

The setup shown in Figure 5 was used to validate the controller.

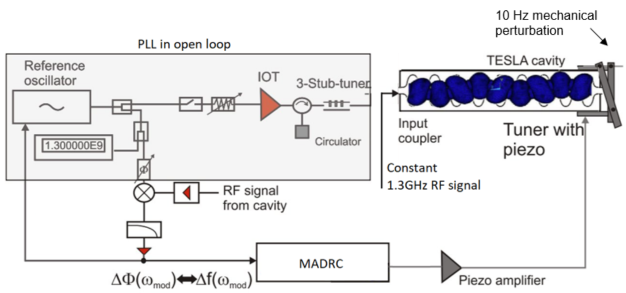

Figure 5: Experimental setup used for the validation of the MADRC

In this case, the PLL is connected in open loop and is only used to approximate the detuning. The cavity is fed with a constant 1.3GHz and 2Kw RF signal and excited with a 10 Hz mechanical perturbation created by one of the piezo actuators. The detuning estimated with the PLL is then fed into the controller, which actuates on the cavity via the other piezo actuator. The MADRC that was tested had an ESO bandwidth (ω_e) of 2 KHz and a controller bandwidth (ω_c) of 80 Hz [2].

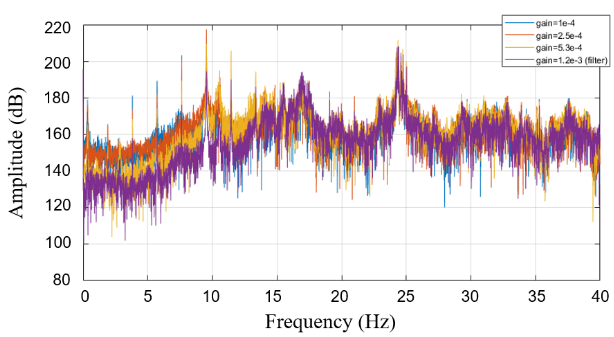

Figure 6: Frequency response of the controlled system in terms of different gains

Different gain values were tested until the system was destabilized with G=5.3e-4. As can be seen in Figure 6, the controller performance improves the higher the gain, achieving a maximum bandwidth of 11 Hz before loop shaping techniques were used. By implementing a notch filter centered in 160 Hz, it was possible to improve the relative stability of the system, thus allowing to increase the gain of the controller up to 1.2e-3 and achieving a control bandwidth of 17 Hz.

It is important to mention that due to a failure in the cavity pick-up antenna, it was impossible to perform the calibration of the data, so the results obtained are qualitative. However, the controller was able to reduce the detuning in more than 20dB over almost the entire bandwidth.

CONCLUSION

As the results obtained show, the validity of the loop shaping method applied to the ADRC can be confirmed, since, by implementing a notch filter, it has been possible to re-stabilize the system and improve the bandwidth of the controller from 11 to 17 Hz.

Based on theoretical studies we have conducted, it is possible to further improve the bandwidth of the controller by implementing more filters, but there is a physical limit that cannot be exceeded by feedback controls.

Even so, the performance obtained is far better than that of a PID. In addition, it is possible to add feedforward (FF) algorithms to this controller to handle higher frequency constant disturbances [10, 11]. In this way, the MADRC would control low frequency stochastic disturbances, such as those caused by fluctuations in cavity temperature, and the FF would control constant disturbances such as those caused by motors, etc.

In addition, the MADRC algorithm is really effective in ramping fields in CW versus Lorentz Force detuning when changing the field setpoint.

ACKNOWLEDGEMENTS

We thank S. Klauke, H. Plötz, M. Schuster and A. Frahm for installing and preparing the experimental setup.

REFERENCES

[1] M. Liepe *et al.*, “Pushing the limits: Rf field control at high loaded q,” in *Proceedings of the 2005 Particle Accelerator Conference*, IEEE, 2005, pp. 2642–2644.

[2] J. Han, “From pid to active disturbance rejection control,” *IEEE transactions on Industrial Electronics*, vol. 56, no. 3, pp. 900–906, 2009.

[3] Z. Zheng, Z. Liu, J. Wei, S. Zhao, and Y. Zhang, “Adrc control for beam loading and microphonics,” *Proc. of LINAC2012, Tel-Aviv, Israel, TUPB061*, p. 615, 2012.

[4] Z. Geng, “Superconducting cavity control and model identification based on active disturbance rejection control,” *IEEE Transactions on Nuclear Science*, vol. 64, no. 3, pp. 951–958, 2017.

[5] Q. Zheng and Z. Gao, “On active disturbance rejection for systems with input time-delays and unknown dynamics,” in *2016 American control conference (ACC)*, IEEE, 2016, pp. 95–100.

[6] L. Castañeda, A. Luviano-Juárez, G. Ochoa-Ortega, and I. Chairez, “Tracking control of uncertain time delay systems: An adrc approach,” *Control Engineering Practice*, vol. 78, pp. 97–104, 2018.

[7] J. Jugo, A. Elejaga, and P. Echevarria, “Modified active disturbance rejection control scheme for systems with time delay,” *IET Control Theory & applications*, in press 2023.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA116

[8] J. She, K. Miyamoto, Q.-L. Han, M. Wu, H. Hashimoto, and Q.-G. Wang, "Generalized-extended-state-observer and equivalent-input-disturbance methods for active disturbance rejection: Deep observation and comparison," *IEEE/CAA Journal of Automatica Sinica*, 2022.

[9] O. Kugeler, A. Neumann, W. Anders, and J. Knobloch, "Adapting tesla technology for future cw light sources using hobicat," *Review of scientific instruments*, vol. 81, no. 7, p. 074 701, 2010.

[10] A. Neumann, W. Anders, O. Kugeler, and J. Knobloch, "Analysis and active compensation of microphonics in continuous wave narrow-bandwidth superconducting cavities," *Physical Review Special Topics-Accelerators and Beams*, vol. 13, no. 8, p. 082 001, 2010.

[11] R. Rybaniec *et al.*, "Fpga-based rf and piezocontrollers for srf cavities in cw mode," *IEEE Transactions on Nuclear Science*, vol. 64, no. 6, pp. 1382–1388, 2017.