# INTEGRATED AND SEQUENTIAL DIAGNOSIS APPROACHES OF CLOSED LOOP SYSTEMS

**N.BARKAT*** **M.S. NAIT-SAID****

*Laboratory of electromagnetic induction and propulsion systems,
Department of Electrical Engineering ,Batna University, Email: n-barkat-ele2012@hotmail.com
**Department of Electrical Engineering, Batna University, Email: medsnaitsaid@yahoo.fr

**R.CHOUCHANE***
*Department of Electrical Engineering, Batna University, Email: Rebaichouchane@yahoo.fr

***Abstract:*** *This paper presents a comparison between the two diagnosis approaches of linear closed-loop systems; sequential approach and integrated approach.*

*An application of these two approaches for a DC motor will be introduced at the end to have the advantage and inconvenient one and the other for electrical entertainment.*

***Key words:*** *Integrated approach, sequential approach, closed loop (CL), diagnosis, parity space (PS), residual, direct synthesis.*

## 1. Introduction.

The essential task of diagnosis module is detection and localization of faults affect a system in the first stage moment of development in order to avoid its propagation and to undertake suitable actions to avoid a total loss of the system.

The use of a CL control law is essential in the majority of industrial applications, in order to reduce the sensitivity of the system compared to the internal or external changes which can affect it; so to ensure the stability of the systems function. On the other hand to improve these performances some are the influences of the systems environment (disturbances or faults).

The control in CL is often calculated in way to have a zero difference between the reference and the controlled output. On the contrary the residues generation methods are based exclusively on the calculation of difference between the reference and the controlled output; if the difference it is non-null, that affirms a fault is occurred. Sure enough, a small difference not reflects the absence of faults but rather an effective control [1]. So the detection and localization of faults in CL systems are more delicate.

Works treating the synthesis module diagnostic CL systems are relatively few. Of their formulations, they are classified in two categories; sequential and integrated approach. The first one is interested in the successive synthesis of the modules of control and diagnosis, while the second one consists in simultaneously synthesizing of the control and diagnosis modules.

The work presented in this paper concerns the definition of the two approaches of CL systems diagnosis. A method of each approach will be shown. In the end, an application of these two methods on a D.C motor will be exposed; to find the essential conclusions

## 2. Sequentially approach

### A. Principle of approach

In the sequential approach, the algorithm of diagnosis is set up after the synthesis of the control law. This approach was lately developed; it is based on the robust filter synthesis DLRD (Robust Detection and Location of Defects) of the monitoring filters of the complexes systems. It is based on modeling as LFT (Linear Fractional Transformation) which allows taking into account the uncertainties model, and the modern synthesis tools and robust analysis such as the use of the standard analysis $H\infty$ / $H$- and *LMI* (Linear Matrix Inequalities) [2].

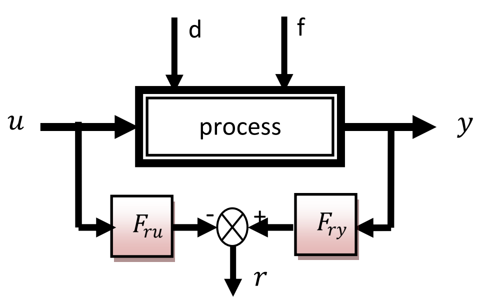


Fig.1: Principle of residue generation by direct synthesis method

## B. *Direct syntheses method*

A residue is a signal indicative of defects. It is defined by a filter F which connects the inputs and outputs of the process (Fig.1)

The residual signal has the following general structure:

$$r(s) = [F_{ry} \quad F_{rx}] \begin{bmatrix} y(s) \\ u(s) \end{bmatrix} \tag{1}$$

Or;

$$r(s) = F_{ry}(s)y(s) - F_{ru}(s)u(s) \tag{2}$$

Where $F_{ry}$ and $F_{ru}$ are respectively the transfer matrices of the input signal and the output, in order to ensuring a good property of detection and localization of the residue signal; so that in the absence of faults *f* and disturbances *d*, the residue *r* is zero

The state model of a nominal functioning of a dynamic system is described by the following relation:

$$\begin{cases} \dot{x}(t) = A(t)x(t) + B(t)u(t) \\ y(t) = c(t)x(t) + D(t)u(t) \end{cases} \tag{3}$$

The state model of a system subjected to different type of faults *f* (actuator, process and sensor) and disturbances *d* is described by the following relation:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + F_x f(t) + D_x d(t) \\ y(t) = cx(t) + F_y(t)f(t) + D_y(t) \end{cases} \tag{4}$$

Where *f* is the faults vector and *d* the disturbances vector on the inputs and outputs acting through the known matrices $F_X$, $F_y$, $D_X$ and $D_y$ respectively.

In Laplace domain (for zero initial conditions), the output y is expressed in terms of inputs u, f fault and perturbation as follows;

In Laplace domain (for the initial conditions are null), the output *y* is expressed in terms of inputs *u*, the faults *f* and disturbance *d* as follows;

$$y(s) = G_u(s)u(s) + G_f(s)f(s) + G_d(s)d(s) \tag{5}$$

Where the matrices $G_u$,, $G_f$ *and* $G_d$ *are defined as following :*

$$\begin{cases} G_u(s) = c(sI - A)^{-1}B + D \\ G_f(s) = c(sI - A)^{-1}F_x + F_y \\ G_d(s) = c(sI - A)^{-1}D_x \end{cases} \tag{6}$$

*s*; represents the complex Laplace variable

If one considered that *d* is a known entered, one can be adapted the following writing;

$$y(s) = G_\eta(s)u_\eta(s) + G_f(s)f(s) \tag{7}$$

And the residual signal relation is as following;

$$r(s) = M(s)f(s) + N(s)d(s) + P(s)u(s) \tag{8}$$

Where again;

$$r(s) = r_f(s) + r_d(s) \tag{9}$$

Where;

$$\begin{cases} M(s) = F_{ry}(s)G_f(s) \\ N(s) = F_{ry}(s) * G_d(s) \\ P(s) = F_{ry}(s)G_u(s) - F_{ru}(s) \end{cases} \tag{10}$$

And;

$$\begin{cases} r_f(s) = M(s) * G_f(s) * f(s) \\ r_d(s) = P(s) * u(s) + N(s) * d(s) \end{cases} \tag{11}$$

The basic idea is to break down the residue into two Terms; $r_f$ (the influence of faults on r) and $r_d$ (the knowledge entry).

The synthesis of the matrices $F_{ru}$ , $F_{ry}$ is carried out in a relevant way in order to maximize the sensitivity of the residue *r* to the faults *f* and to minimize its sensitivity to disturbances *d* for a detection and isolation of faults with a lower amplitude.

In the literature there are several methods about this subject such as synthesis tools $H_\infty$ [2].

In the context of this work, one will only search to minimize the transfer *u* to *r*, as the transfer of *d* to *r*. the transfer of *f* to *r* a priori it must be maximized.

The step which should be followed is as follows;

- One fixes *M(s)* entirely or partly, with the concern of facilitating the detection and the localization of the fault.
- Then one seeks, by an adequate optimization algorithm, the filter *F(s)* which makes it possible to have:

$$r(s) \approx r_f(s) \tag{12}$$

It is important to note that the structure of *M (s)* fixed the logic detection and localization of fault then performed the residue; it must be well thought out.

## 3. Integrated approach

### *A. Principle of the approach*

For this approach the control modules and diagnosis are synthesized simultaneously.

In this context, the authors of some works formulate the problem of *CL* systems diagnostic in a classical framework where the control law (obtained by pole placement by state feedback) is associated with the generation of residues used for the fault diagnosis.

The synthesis of the coupled control and diagnosis is performed by optimizing a criterion combining objectives increased control and diagnosis, using weighting factor according to the importance attached to either one or the other [5], [6].

In other work, the authors propose a diagnosis method of *CL* systems based on two techniques: in the one hand the algebraic estimation technique, which makes it possible to obtain the derivative of various orders of a disturbed temporal signal and thus a better estimate of the parameters.

On the other hand the uses of the flatness notion for the control synthesis of the closed loop system [7].

As against, in some work, there is a definition of a mixed module for both the synthesis of the control law and the generation of residues for the diagnosis of faults [8], [9].

### *B. Choice of feedback output gain*

The purpose of this section is finding a method which allows the realization of a certain decoupling between the control objective and the diagnostic on the one hand, the gain of the feedback loop is satisfied performance of the control and stability, and secondly, it would be desirable that optimizes the value of the residue having an easy detection of faults.

To achieve the desired objective, the parity space (PS) method is used. To do this, one must follow these steps;

- Write the system in its state form.

$$\begin{cases} \dot{x}\,(t) = Ax(t) + Bu(t) + F_x f(t) \\ y(t) = cx(t) + F_y\,(t) f(t) \end{cases} \tag{13}$$

- One derives out until the order from system in order to generated a residue by the parity space approach

$$\bar{y}(t) = O(k)x(t) + G(k)\bar{v}(t) + F(k)\bar{f}(t) \tag{14}$$

With;

$$\begin{cases} \bar{y}(t) = [y(t) \quad \dot{y}(t) \quad \ddot{y}(t)]^T \\ \bar{v}(t) = [v(t) \quad \dot{v}(t) \quad \ddot{v}(t)]^T \\ \bar{f}(k) = [f(t) \quad \dot{f}(t) \quad \ddot{f}(t)]^T, et\ f(t) = [f_a \quad f_c]^T \end{cases} \tag{15}$$

And;

$$\begin{cases} O(K) = \begin{bmatrix} C \\ C(A-BKC) \\ C(A-BKC)^2 \end{bmatrix} \\ G(K) = \begin{bmatrix} 0 & 0 & 0 \\ CB & 0 & 0 \\ C(A-BKC)B & CB & 0 \end{bmatrix} \\ F(K) = \begin{bmatrix} [0 \quad F_y] & [0 \quad 0] & [0 \quad 0] \\ C[F_x \quad -BKF_y] & [0 \quad F_y] & [0 \quad 0] \\ C(A-BKC)[F_x \quad -BKF_y] & C[F_x \quad -BKF_y] & [0 \quad F_y] \end{bmatrix} \end{cases} \tag{16}$$

- One writes the relation (14) in the form of;

$$\bar{y}(t) - G(k)\bar{v}(t) = O(k)x(t) + F(k)\bar{f}(t) \tag{17}$$

- To have a relation binding only the known quantities (the reference, output and their derivatives), we must eliminate the state x (t).

For this pre multiplying left and right of equation (17) by a matrix V (K) orthogonal to the observability matrix *O (K),* provided that this matrix should not belong to the orthogonal space of the faults matrix *F(K*). otherwise we may not detect some faults.
That is, *V (K)* must verify:

$$\begin{aligned} w(K)\ O(K) &= 0 \\ w(K)\ F(K) &\neq 0 \end{aligned} \tag{18}$$

- One chooses the elements of matrix *V(K*) in order to satisfy the condition (18); the idea here is to have a residue independent of the gain *K*, in order to have a large degree of freedom in the choice of the latter with an aim of satisfying the performances of the control. In fact, this gain can have like role the placement of poles of CL system in order to meet the requirements of control and stability.

$$r(t) = w(K)\left(\bar{y}(t) - G(K)\bar{v}(t)\right) = w(K)F(K)\bar{f}(K) \tag{19}$$

- In the range of allowable gains satisfying the constraints of the previous step, is chosen which optimizes the gain value of the residue. Among the values of *K* which satisfy the conditions of stability and fault detection, the gain is chosen which maximizes the influence of faults on the residue; or *k*, which verifies the following conditions

$$\begin{cases} w(k)F(k) \geq w(K)F(K), \quad \forall K \\ (A - BkC)\ \text{stable} \end{cases} \tag{20}$$

If *k* exists, then it carries out a double objective: ensures the stability of the system and a better detection of faults.

The elements of the vector $V(k)$ can be calculated according to the elements of the matrices $A$, $B$, $C$, $F_x$ and $F_y$.

## 4. Application

The aim required in this paragraph is the application of the two approach principles; sequential and integrated, which are exposed above, on a D.C. motor regulated in speed (fig.2).

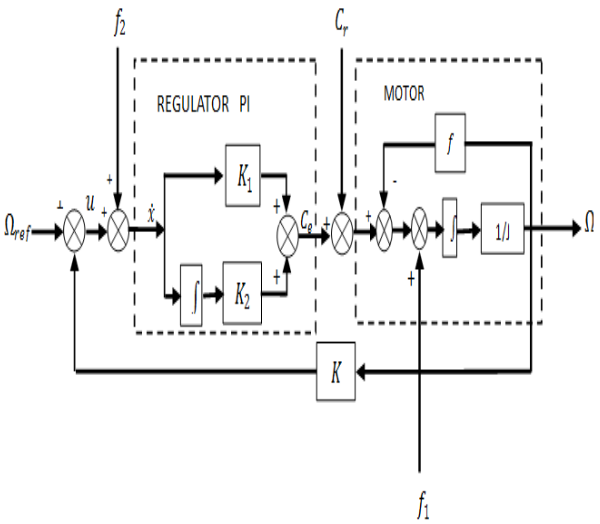


Fig.2: The block diagram of the speed loop of the D.C. motor.

This motor is governed by the following system of equations;

$$\begin{cases} \dot{x} = (u - K\Omega) + f_2 \\ J\dot{\Omega} = -f\Omega + (Ce - Cr) - f_1 \\ Ce = K_1\dot{x} + K_2 x \end{cases} \quad (20)$$

*A. The application of the analysis direct method*

The system of equations (20) can be written as:

$$\begin{cases} \dot{x}(t) = Ax + B\Omega_{réf}(t) + D_x d(t) + F_x f(t) \\ y(t) = cx(t) \end{cases} \quad (21)$$

By using the transformation of Laplace, while considering that the initial conditions are null, one can write;

$$y(s) = G_u(s)\Omega_{réf}(s) + G_f(s)f(s) + G_d(s)d(s) \quad (22)$$

Such as $G_u(s)$, $G_d(s)$ and $G_f(s)$ are respectively the transfer of the entry $\Omega_{réf}(s)$, the disturbance $D(s)$ and the fault $F(s)$.

It is proposed to generate the residue by the direct analysis approach, in the two cases; without and with the disturbance, then we obtain the following results (Fig.3).

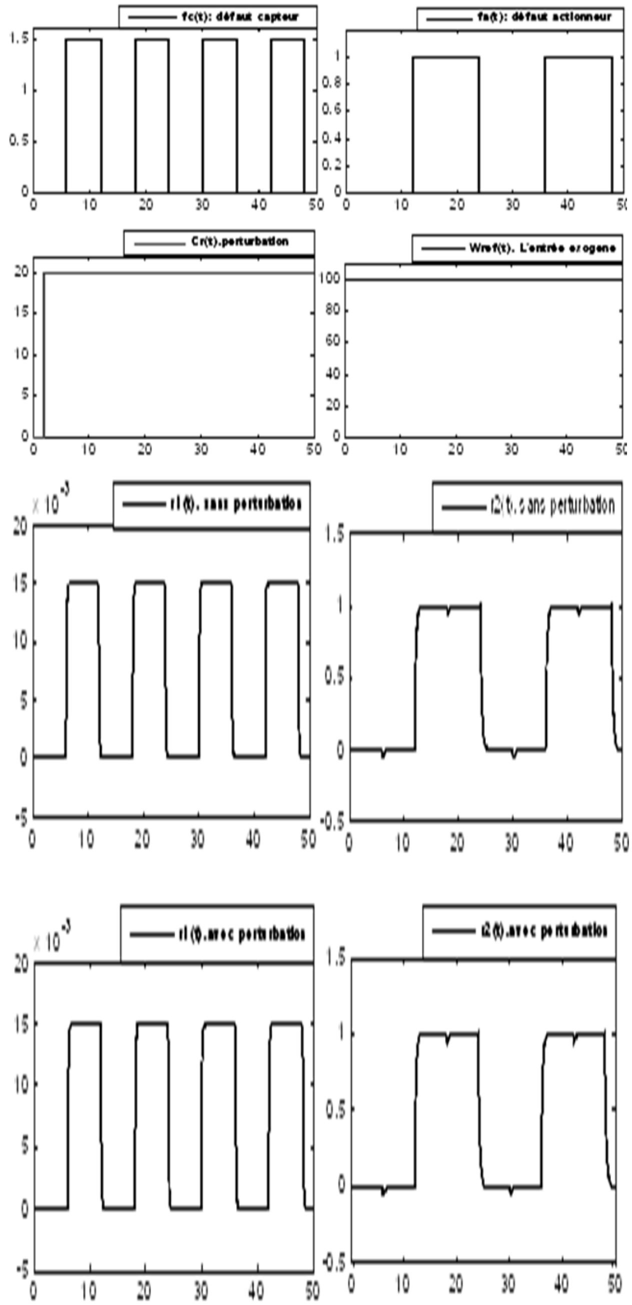


Fig.3: Residues by the direct approach, with and without disturbance.

One notices that by the directed analysis method, one could obtain two residues; $r_1(t)$ which is sensitive to the sensor fault and $r_2(t)$ which is sensitive to the actuator faults.

These results show that the use of the direct analysis method for diagnosis a *D.C.* motor subjected to actuator and sensor faults is very effective, since by this method one obtained residues which are not only sensitive opposite to the faults but also robust opposite the disturbances.

*B. Application of the integrated approach principle*

From Fig. 2, we can write:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + F_x f_a(t) \\ y(t) = cx(t) + F_y(t) f_{c(t)} \end{cases} \quad (23)$$

With;

$$u(t) = v(t) - K\Omega(t) = v(t) - Kcx(t) - KF_y f_c(t) \quad (24)$$

Then the equations system (23) is written:

$$\begin{cases} \dot{x}(t) = (A - BKc)x(t) + Bv(t) + [F_x \quad -BKF_y] f(t) \\ y(t) = cx(t) + [0 \quad F_y] f(t) \end{cases} \quad (25)$$

The system is of second order, then one derives left twice, we obtain the equation (18).

The definitions of the various matrices are given by the following equations;

To meet condition (18), the elements of the vector *V(K)* are selected as polynomials of degree *1* in *K:*

$$V(K) = [(V_{10} + V_{11}K) \quad (V_{20} + V_{21}K) \quad (V_{30} + V_{31}K)] \quad (26)$$

Let us pose;

$$v = [V_{10} \quad V_{11} \quad V_{20} \quad V_{21} \quad V_{30} \quad V_{31}] \quad (27)$$

So;

$$V(K)O(K) = [(V_{10} + V_{11}K) \quad (V_{20} + V_{21}K) \quad (V_{30} + V_{31}K)] \begin{bmatrix} c \\ c(A - BKc) \\ c(A - BKc)^2 \end{bmatrix} \quad (28)$$

With

$$\begin{cases} \theta_0 = \begin{bmatrix} c \\ O_{1\times2} \\ cA \\ O_{1\times2} \\ cA^2 \\ O_{1\times2} \end{bmatrix}, \quad \theta_1 = \begin{bmatrix} O_{1\times2} \\ c \\ -cBA \\ cA \\ -c(ABc + BcA) \\ cA^2 \end{bmatrix} \\ \theta_2 = \begin{bmatrix} O_{1\times2} \\ O_{1\times2} \\ O_{1\times2} \\ -cBA \\ c(Bc)^2 \\ cA^2 \end{bmatrix}, \quad \theta_3 = \begin{bmatrix} O_{1\times2} \\ O_{1\times2} \\ O_{1\times2} \\ O_{1\times2} \\ 0_{1\times2} \\ c(Bc)^2 \end{bmatrix} \end{cases} \quad (29)$$

Solving system of equations (18) gives:

$$V(K) = [(-1 + K) \quad (2 + K) \quad 1] \quad (30)$$

So we obtained a residue which is defined by the following relation:

$$w(K)F(K) = [(-1 + K) \quad (2 + K) \quad 1] \begin{bmatrix} 0 & 0 \\ CF_x & 0 \\ C(A - BKC)F_x & CF_x \end{bmatrix} \quad (31)$$

Although;

$$V(K)f(K) = [1 \quad 2] \quad (32)$$

The residue will be defined by;

$$r(t) = [1 \quad 2] \begin{bmatrix} f(t) \\ \dot{f}(t) \end{bmatrix} \quad (33)$$

So for this example the residue is independent of the gain *K*, what makes it possible to choose a value for this last with an aim of satisfying the performances of the control, without degrading those of the diagnosis.

The results of simulation are represented on figure (4) which represents the variation of exit return gain K which influences only the exit y(t), on the other hand the evaluation of the residue r(t) is invariant in the two cases.

The change of the exit return gain influences only the speed and no influence on the indicator of faults r(t). This last is sensitive to the faults and also robust opposite the disturbances which are represented by the resistive torque *Cr(t)*.

By this method, one could carry out decoupling between the objective of control and that of the generation of the residues for the diagnosis of a *D.C.* motor which it is subjected to actuator and sensor faults.

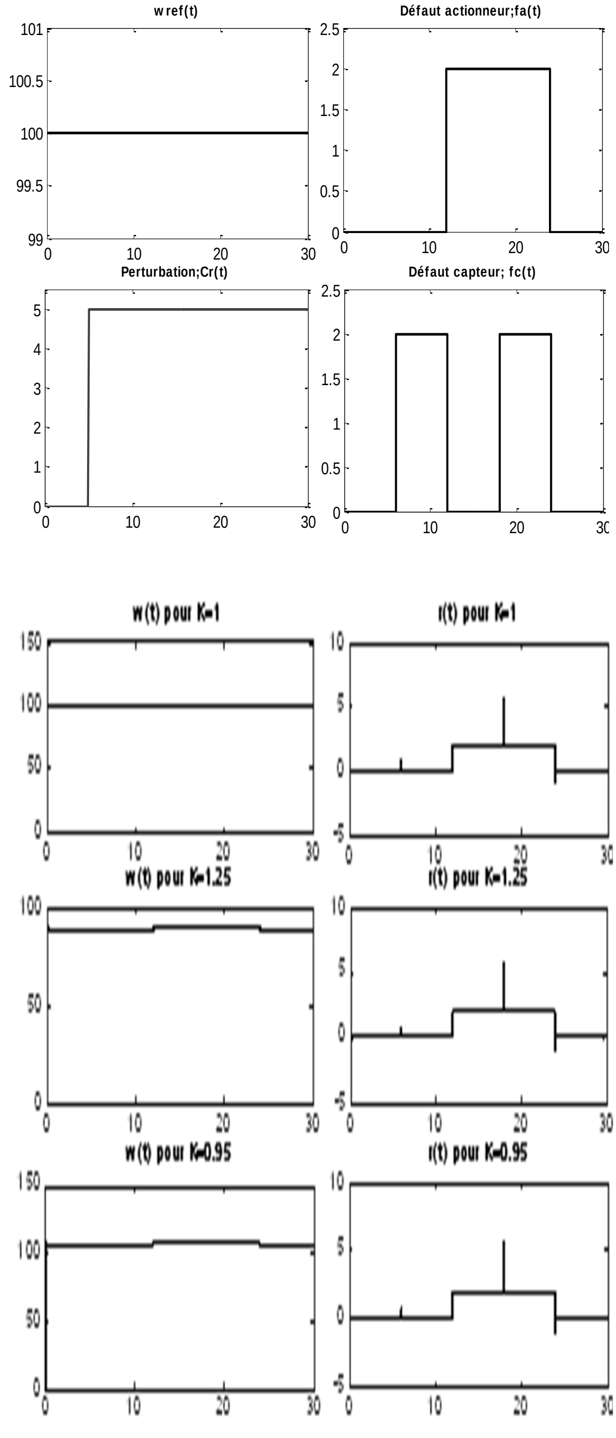


Fig.4: The influence of the output feedback on the control and residue generator for DC motor.

## 4. Conclusion

can conclude that the sequential approach has the advantage of simplifying to a significant degree the synthesis of the diagnosis module, it does not propose to manage the existing compromise between the performances of the control and those of the diagnosis since it consists in imposing the performances of the control then, thereafter, to optimize the performances of the diagnosis what has as a consequence a loss in degree of freedom for the synthesis of the generator of residues. On the other hand, the integrated approach leaves a certain degree of freedom for the choice of the performances of module of diagnosis which is used for detection and the localization of defects, in spite of its complexity

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