TIG

Template Interactive Generator

USER'S GUIDE

(Version 1.0)

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Ω	Work frequencies set
ω_i	Frequency (in rad/s) belonging to the work frequencies set Ω
ω_w	Current work frequency (in rad/s)
ω_{min}	Minimum frequency which it is visualised in the frequency axis of the *Frequencies* zone
ω_{max}	Maximum frequency which it is visualised in the frequency axis of the *Frequencies* zone
$\Gamma(\omega_i)$	Template computed at ω_i. It is saved in the *Saved Templates* zone.
$\Gamma_w(\omega_w)$	Current work template computed at ω_w. It is shown in the *Work Template* zone.
d_1	Validation minimum frequency exponent 10^{d1} (rad/s)
d_2	Validation minimum frequency exponent 10^{d2} (rad/s)
L	Total number of plant uncertain parameters
L_d	Number of uncertain parameters in the plant denominator
L_n	Number of uncertain parameters in the plant numerator
N_ω	Number of work frequencies
$N_{\omega val}$	Number of frequencies in the validation stage
Nb	Bailey & Hui algorithm configuration parameter
N_c	Number of points belonging to the boundary of $\Gamma_w(\omega_w)$
Nf	Fu algorithm configuration parameter
N_{ID}	Number of plant integrators or derivators.
Nk	Kharitonov segments algorithm configuration parameter
Np_j	Number of equispaced values in the parameter $p_j \in [p_j^{min}, p_j^{max}]$
N_t	Number of points belonging to $\Gamma_w(\omega_w)$

p_j	j uncertain parameter of the plant
$p_j^{\min}$	Minimum value of p_j
$p_j^{\max}$	Maximum value of p_j
p_j^0	Nominal value of p_j
R	Percentage of $\Gamma_w(\omega_w)$ points which belongings to the boundary
T_c	Time which takes the ε-algorithm in computing the boundary of $\Gamma_w(\omega_w)$
T_t	Time which takes the current work algorithm in computing $\Gamma_w(\omega_w)$

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CHAPTER 1:
GENERAL CONSIDERATIONS

1.1 INTRODUCTION

A *plant template* is a set of number complex representing the frequency of an uncertain plant transfer function. A template can be drawn in a complex plane [Real part, Imaginary part], or alternatively in a Nichols chart [Phase (degrees), Magnitude (dB)].

The templates are used in different robust control techniques. For instance, they are used in the Quantitative Feedback Theory (QFT) which was developed by Issac Horowitz [Horowitz, 1963]. QFT is a robust control design methodology that uses frequency-domain concepts to satisfy performance specifications and handle plant uncertainty. QFT is based on the observation that feedback is needed mainly when the plant is uncertain and/or when there are disturbances acting on the input and/or the output of the plant. The design procedure using QFT has been described in a wide variety of articles and books ([Horowitz, 1992], [Horowitz, 2001], [Houpis et al., 1992], [Houpis et al., 2006], [Yaniv, 1999]).

The templates are used in QFT to compute the bounds associated to design specifications. The template boundary is really the only necessary part to compute the bounds. Template interior points only cause an unnecessary risen in the computation time.

In general, the control engineers that used QFT usually do not pay much attention in the template computation, and even less in eliminating the template interior points. Typically, they usually work with all the template points, and not only with the template boundary. Besides, QFT users usually used a *grid technique* on the uncertain plant parameter space to compute the templates. The grid technique is simple, but sometimes is not very efficient.

The most used and known software tool to implement the QFT methodology is the Matlab QFT toolbox [Borghesani et al., 1995]. This toolbox has not implemented any function or algorithm to compute templates. This fact shows the little interest of the QFT designers in this issue.

Since 2004, control engineers can also used QFTIT[1] (Quantitative Feedback Theory Interactive Tool) [Díaz et al., 2005] in order to implement the QFT methodology. QFTIT is easier and more interactive than Matlab QFT toolbox. Obviously, QFTIT version 1.0 has several limitations. The most important one is that it can only work with plant transfer function expressed in real factored form, i.e, the plant has to be factored in gain, real zeroes, real poles, complex zeroes and complex poles. QFTIT used the excellent algorithm proposed by Gutman et al. (1995) to compute the template boundary of this kind of plant transfer functions.

The interactive software tool TIG (Template Interactive Generator) has been development as a first step in order to increase the kinds of plant transfer functions which can be treated in QFTIT. TIG allows to compute template boundaries of interval plants and of plant transfer functions with affine parametric uncertainty in its coefficients. These kinds of plants are very usual in control problems. Besides, TIG can be also used to obtain the template boundaries associated to plants whose templates have been previously computed in Matlab.

Once the template boundaries have been obtained using TIG, they can be export to Matlab or QFTIT. Therefore, TIG has been designed to cooperatively work with these two software tools.

TIG has been developed in Sysquake [Pyguet, 1999]. TIG is available as a free distribution executable file for Windows and Mac.

The structure of this manual is the following: the main features of TIG are described in the rest of this chapter. Chapter 2 is dedicated to describe the items of the TIG window. The menus of the tool are described in Chapter 3. Finally, three illustrative examples of how TIG works are included in Chapter 4.

1.2 MAIN FEATURES

1.2.1 Kind of problems which can be solved using TIG

Let the uncertain parameters vector *p*

$$p = [p_1, p_2, ..., p_L]$$

[1] The readers interested in download QFTIT should visit `http://ctb.dia.uned.es/asig/qftit/`

where $p_j \in [p_j^{\min}, p_j^{\max}]$ j=1,2,..,L.

TIG can compute the template boundaries for plant transfer functions with the following structure

$$P(s,p) = \frac{b(s,p)}{a(s,p)} = \frac{\sum_{k=0}^{m} b_k(p)\cdot s^k}{\sum_{k=0}^{n} a_k(p)\cdot s^k} \tag{1.1}$$

where $b_k(p)$ y $a_k(p)$ are lineal combinations of the uncertain parameters:

$$b_k(p) = \beta_{k0} + \sum_{j=1}^{l_p} \beta_{kj}\cdot p_j \tag{1.2}$$

$$a_k(p) = \alpha_{k0} + \sum_{j=1}^{l_p} \alpha_{kj}\cdot p_j \tag{1.3}$$

It supposes that β_{kj} and α_{kj} are real constants.

TIG implements four algorithms for computing the template boundaries of this special kind of plants:

- *Bailey & Hui* algorithm [Bailey & Hui, 89]. This algorithm directly generates points of the template boundary if the numerator uncertain parameters are independent of the denominator uncertain parameters, i.e.,

$$P(s,q,r) = \frac{b(s,q)}{a(s,r)} = \frac{\sum_{k=0}^{m} b_k(q)\cdot s^k}{\sum_{k=0}^{n} a_k(r)\cdot s^k} \tag{1.4}$$

  where $q_h \in [q_h^{\min}, q_h^{\max}]$ h=1,2,..,L_n and $r_i \in [r_i^{\min}, r_i^{\max}]$ i=1,2,..,L_d, with L_n+L_d=L. Besides, $b_k(q)$ and $a_k(r)$ have also to present an affine structure similar to (1.2) and (1.3).

  If there is some dependency between numerator uncertain parameters and denominator uncertain parameters, this algorithm generates a conservative

template boundary. The total number of points N_c belonging to the template boundary generated for this algorithm is given for the expression:

$$N_c = 2 \cdot Nb \tag{1.5}$$

where *Nb* is the number of points which belong to the upper (or lower) template boundary. TIG allows users to configure *Nb*. Its default value is *Nb*=25.

- *Fu algorithm* [Fu, 90]. This algorithm considers $2^{L-1} \cdot L$ template edges[2], and it generates *Nf* points for each one. Therefore, the total number of generated points is

$$N_t = 2^{L-1} \cdot L \cdot Nf \tag{1.6}$$

TIG allows users to set *Nf*. Its default value is *Nf*=5.

- *Kharitonov segments algorithm* [Barlett et al., 93]. This algorithm must only be used for interval plants, i.e,

$$P(s,q,r) = \frac{b(s,q)}{a(s,r)} = \frac{\sum_{k=0}^{m} q_k \cdot s^k}{\sum_{k=0}^{n} r_k \cdot s^k} \tag{1.7}$$

where $q_k \in [q_k^{\min}, q_k^{\max}]$ and $r_k \in [r_k^{\min}, r_k^{\max}]$. It considers 32 template edges, and it generates *Nk* points for each one. Therefore, the total number of generated points is

$$N_t = 32 \cdot Nk \tag{1.8}$$

Users can set *Nf*. Its default value is *Nk*=5.

- *Grid algorithm*. It generates N_t points of a template, according to the following expression:

$$N_t = \prod_{j=1}^{L} Np_j \tag{1.9}$$

[2] A template edge can be external or internal. A *template external edge* forms part of the template boundary. On the other hand, a *template internal edge* is contained inside of the template boundary.

where Np_j is the number of equispaced values for the uncertain parameters $p_j \in [p_j^{\min}, p_j^{\max}]$ j=1,...,L which are considered for obtaining points of the template. Users can set Np_j. Its default value is Np_j=2.

Bailey & Hui algorithm, Fu algorithm and Kharitonov segments algorithm can only be used if $a(j\omega_i, p) \neq 0$, for any combination of the uncertain parameters values. The plant template $\Gamma(\omega_i)$ is not bounded if $a(j\omega_i, p)=0$. Besides, if the hiper-rectangle formed from q or r contains the complex plane origin, then Bailey & Hui algorithm cannot used either.

Bailey & Hui algorithm is the only one which directly generates the template boundaries. In case of working with any of three other algorithm, it is necessary to use and additional algorithm to obtain the template boundaries. TIG implements the algorithm proposed by F.M. Montoya [Montoya, 98]. In this manual, this algorithm will be called ε-*algorithm*. It works in the following way: It starts from a template boundary point, typically the template point with greater real part. It traces a circle of radius ε, and it looks for the template point with minimum phase contained inside the circle. This point also belongs to the template boundary. This procedure is repeated till located all of the template boundary points. For example, in Figure 1.1, the template point with greater real part is *p1*. *p2* is the template point with minimum phase inside of the circle with radius ε and center *p1*. The center of the next circle with radius ε must be *p2*.

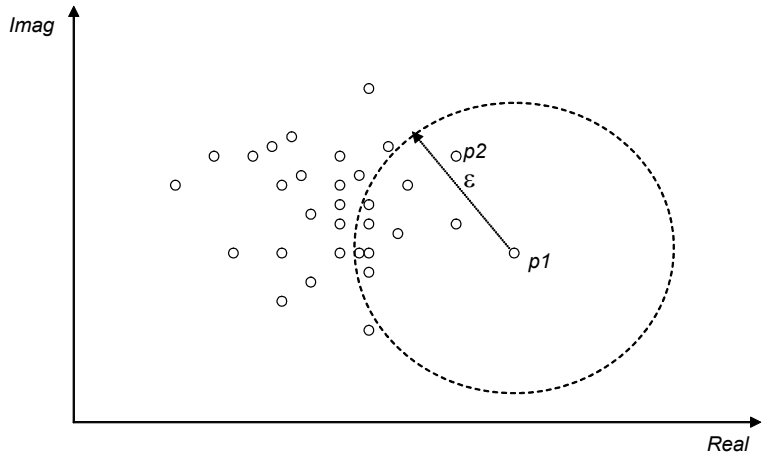

Figure 1.1. Template points ('o') and search circle of radius ε

The success of the ε-algorithm depends of two factors: the radius ε of the search circles, and the distribution of the template points in the complex plane. If the radius ε is very large, the number of template boundary points will be the minimum possible. In this case, the

algorithm obtains a conservative approximation of the template boundary, which is called "convex hull" in the literature.

If the radius ε is decreased, the number of template boundary points will rise. Besides, the template boundary will be more abrupt because the algorithm considers more template interior points as part of the template boundary. Obviously, if the radius ε is very little the algorithm will not find any template boundary point.

The ε-algorithm will find the template boundary if the distribution of the template points in the complex plane is homogeneous. Otherwise, it is necessary to scale the template points.

The ε-algorithm implemented in TIG has three parameters which can be tuned by users:

- *Weight*. It is a positive real number. It multiplies to the diagonal D of the rectangle which encloses all of the template points. The radius ε is related to the parameter *Weight* through the following expression:

$$\varepsilon = Weight \cdot D \tag{1.10}$$

  The default value of *Weight* is 1.

- *Factor X*. It is a positive real number which divides the coordenate x of the template points. *Factor X* =1, by default.

- *Factor Y*. It is a positive real number which divides the coordenate y of the template points. *Factor Y* =1, by default.

In conclusion, the ε-algorithm needs the visual supervision of the users. He must to check whether the algorithm generates the right template boundary. Otherwise, users will have to modify the parameter *Weight*. Likewise, if the distribution of the template points in the complex plane is not homogenous, users will have to scale the template points using the parameters *Factor X* or/and *Factor Y*. An example of the use of these parameters can be found in section 4.2.2.1.

1.2.2 TIG interactivity

The main features of TIG are its ease of use and strong interactivity. All that users have to do is to place the mouse pointer over the different items which the tool displays on the screen. Any action carried out on the screen is immediately reflected on all the graphs

generated and displayed by the tool. This allows users to visually perceive the effects of theirs actions. Some examples of the TIG interactivity are:

1) The work template $\Gamma_w(\omega_w)$ in the Nichols chart (or in the complex plane) is simultaneously modified if users change the configuration parameter of the template computation algorithm (*Nb* for Bailey & Hui algorithm, *Nf* for Fu algorithm or *Nk* for Kharitonov segments algorithm) or the work frequency ω_k.

2) The boundary of the work template $\Gamma_w(\omega_w)$ in the Nichols chart (or in the complex plane) is simultaneously modified if users change the configuration parameter (*Weight*, *Factor X* or *Factor Y*) of the ε-algorithm used for computing the boundary template.

3) The zeroes and poles of the nominal plant are simultaneously moved in the complex plane if users modify the nominal value of the plant uncertain parameters.

Obviously, the TIG interactivity depends of the computational load. It considers that the computational load is *heavy* if the following relation is verified:

$$T_t + T_c > 0.6\ s \tag{1.11}$$

where T_t is the time (in seconds) that the work template computation algorithm takes in computing $\Gamma_w(\omega_w)$, and T_c is the time (in seconds) that the ε-algorithm takes in computing the boundary of $\Gamma_w(\omega_w)$. In this case, the TIG interactivity decreased. There is a delay since users makes a change until the change is represented in all the figures of the TIG window.

Other TIG features are:

- The simultaneous visualization of the work templates computed for each one of the four templates computation algorithm implemented in TIG.
- The automatic selection and removing of all the interior points of $\Gamma_w(\omega_w)$
- The manual selection and removing of any point of $\Gamma_w(\omega_w)$.

1.2.3 Cooperation with other software tools

TIG is designed to be able to cooperate with Matlab and QFTIT. There are three possible cooperation configurations (see Figure 1.2):

- *Configuration 1*. First, users use TIG to define the plant, and to compute the template boundaries. Second, they export all this information to QFTIT where they will continue doing the remaining stages of the QFT methodology.

- *Configuration 2*. First, users use Matlab to define the plant and to compute the templates. Second, they start TIG and import the templates. Third, they computed in TIG the template boundaries. Fourth, they export the boundaries to QFTIT where they will continue doing the remaining stages of the QFT methodology.

- *Configuration 3*. First, users use Matlab to define the plant and to compute the templates. Second, they start TIG and import the templates. Third, they computed in TIG the template boundaries. Fourth, they export the boundaries to Matlab where they will continue doing the remaining stages of the QFT methodology, or other control robust methodology.

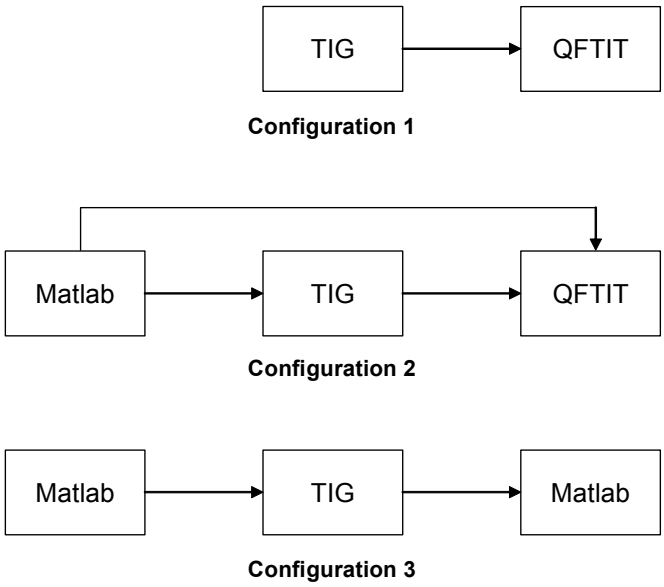

Figure 1.2. Possible cooperation configurations between *TIF, QFTIT and Matlab*

1.2.4 Limitations

TIG version 1.0 has the following limitations:

- The maximum value of the plant denominator grade is *n*=7. Therefore, the maximum value of the plant numerator will be m=6.

- The maximum number of plant integrators or derivators is N_{ID}=10.

- The maximum number of plant uncertain parameters is L=14.

- The maximum number of different uncertain parameters in the plant denominator is L_d=7. The plant numerator has the same restriction. Remind that $L=L_n+L_d$.

- The maximum number of work frequencies is N_ω= 10.

- The maximum frequency interval is $[10^{-3},10^{6}]$ (rad/s).

- The maximum value of the Bailey & Hui algorithm configuration parameter *Nb* is given for the following expression:

$$Nb_{\max} = \max\left\{\frac{25\times 120}{T_t(25)}, 5000\right\} \tag{1.12}$$

  where $T_t(25)$ is the time (in seconds) that this algorithm takes in computing the template if *Nb*=25.

- Fu algorithm is only available if L≤ 9. Table 1.1 shows the maximum value that *Nf* can take in function of *L*.

L	1	2	3	4	5	6	7	8	9
$\boldsymbol{Nf}_{max}$	5000	2500	1428	312	125	52	22	9	5

Table 1.1: Maximum value of Nf in function of L

- For the Kharitonov segments algorithm, the maximum value of its configuration parameter is *Nk*=312.

- The grid algorithm is only available if L≤13. Besides, the maximum number of template points, which this algorithm is able to computed, is N_t=10000.

Chapter 2:

DESCRIPTION OF THE TIG WINDOW ITEMS

2.1 TOOL LAYOUT

With TIG is possible to work in two different modes: *Configuration* and *Analysis*

- *Configuration Mode*. It consists of four sequential steps:
  - Step 1: Configuration of the plant uncertain parameters.
  - Step 2: Configuration of the plant transfer function denominator.
  - Step 3: Configuration of the plant transfer function numerator.
  - Step 4: Configuration of the work frequencies set Ω
- *Analysis mode*. In this mode, users can do the following actions:
  - See the saved templates $\Gamma(\omega_i)$ $\omega_i \in \Omega$ which have been computed by default using the Bailey & Hui algorithm with *Nb*=25.
  - Use different algorithms for computing $\Gamma_w(\omega_w)$, modify its configuration parameters, and compare the algorithms among them.
  - Obtain the boundary of $\Gamma_w(\omega_w)$, and modify the configuration parameters of the ε-algorithm in order to improve the boundary.
  - Add and remove points of $\Gamma_w(\omega_w)$.
  - See the change in the form of $\Gamma_w(\omega_w)$ in function of ω_w.
  - Change the elements of the set Ω.

- See the change in the form of $\Gamma_w(\omega_w)$ in function of plant parameters uncertainty.

In the following sections of this chapter, the items of the TIG window are described for each work mode. Analysis mode is described first because the tool always starts in this mode on a predefined example.

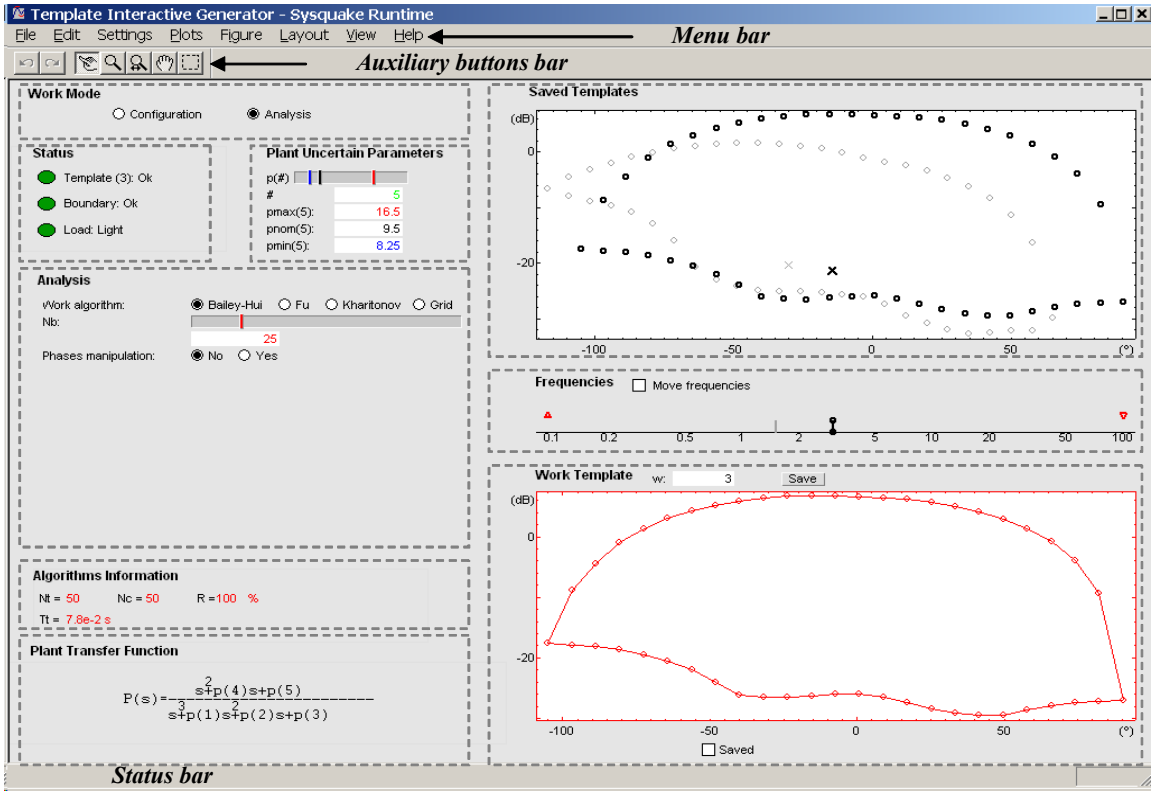

Figure 2.1. Initial aspect of the TIG window. The limits of each window zone have been drawn in broken line.

2.2 ANALYSIS MODE

Figure 2.1 shows the initial aspect of the TIG window when the tool is started. At the top of the window, the menu bar and the auxiliary buttons bar are located. At the bottom of the window, a grey horizontal bar is drawn. It is called *status bar*. It shows different information in function of where the mouse pointer is placed on the window. Likewise, a rectangle is drawn on the status bar right end. It shows the message "`Runnnig`" as the tool is computing.

In the area between the buttons bar and the status bar, there are six zones on its left side (*Work Mode*, *Status*, *Plant Uncertain Parameters, Analysis*, *Algorithms Information and*

Plant Transfer Function), and three zones on its right side (*Saved Templates*, *Frequencies* and *Work Template*). All of these zones are described in the following subsections.

2.2.1 Work Mode Zone

This zone allows to select the work mode. It consists of two radio buttons, one for each work mode: `Configuration` and `Analysis`. Users have only to click on the appropriate radio button in order to select a work mode.

When the tool starts, the radio button associated to the analysis mode is active, i.e, it contains a little black circle. In this work mode, if users click on the radio circle `Configuration`, then the `Save a work session` dialog box (see section 3.2.1) will appear. It allows to save the work session.

Likewise, if users click on the radio circle `Analysis` in the configuration mode, then a dialog box will appear with the message "`Configuration has not finished`". Users cannot force the transition from configuration mode to analysis mode. This transition is automatically done when they complete the last step of the configuration mode.

2.2.2 Saved Templates Zone

This zone has mainly an informative function. It contains a Nichols chart where the saved templates $\Gamma(\omega_i)$ $\omega_i \in \Omega$ are represented in different colours. A saved template is a valid template which can be exported to Matlab or QFTIT. Likewise, the template points are represented with '$\circ$' and its nominal value with 'x'. The points of the template saved at the work frequency ω_w are always drawn in black colour. Besides its width is usually greater[1] than the points of the other templates.

Users can easily know the frequency ω_i associated to a template. If they place the mouse pointer on some template point, ω_i will be shown in the status bar. They can also know the value of the template nominal point in a similar way. They have only to place the mouse pointer on the symbol 'x' which represents to the template nominal point.

Figure 2.1 shows two saved templates in this zone: $\Gamma(1.5)$ (grey colour) and $\Gamma(3)$ (black colour). Therefore, the work frequency is ω_w=3 rad/s.

[1] Users can turn off this option (see section 3.2.4).

Initially, the templates shown in this zone are computed by the Bailey & Hui algorithm[2] (with *Nb*=25), when the transition from configuration mode to analysis mode takes place. Users can save other templates in this zone throughout the work session. TIG only allows to save one template for each frequency ω_i.

2.2.3 Frequencies Zone

This zone allows users to do several actions: visualize and configure the work frequencies set Ω, and to select ω_w. It contains a horizontal axis which is graduated in radians per seconds using a logarithmic scale. On this axis, a vertical segment for each frequency $\omega_i \in \Omega$ is drawn in different colours. The code of colours is the same used in the *Saved Templates* zone. The segment associated to the current work frequency is drawn in black colour, and two '○' are placed on its ends to highlight it.

In order to change ω_w, users have only to click on the segment associated to the new work frequency which they want to choose. Although the axis is graduated, they can know the exact value ω_i placing the mouse pointer on the appropriate segment. The status bar shows the value of ω_i.

Moreover, if users click on the square box `Move frequencies`, a '`x`' appears on it, i.e., this feature is active. Then, they can horizontally move the vertical segments, i.e., they can modify the frequencies. In order to move a segment, users must follow the following steps: First at all, place the mouse pointer over the segment. Second, holding down the mouse left button, drag horizontally the segment till placed in the wanted position.

While users move the work frequency ω_i, the *Saved Template* zone simultaneously shows how the template $\Gamma(\omega_i)$ changes. Remind that $\Gamma(\omega_i)$ is obtained using the Bailey & Hui algorithm with *Nb*=25. Likewise, the *Work Template* zone shows how the work template $\Gamma_w(\omega_i)$ is modified. $\Gamma_w(\omega_i)$ is obtained using the current template computation algorithm. Such algorithm is selected in the Analysis zone. It is important to bear in mind that this TIG functionality is only available if the computational load is light.

In this zone, users can also add and remove frequencies $\omega_i \in \Omega$. If they click on the red triangular handler, which is located on the left side of the frequencies axis, then a new segment will appear on the axis. It is located 5 rad/s on the right from the greater frequency

[2] TIG uses the grid algorithm (with Np_j=2) whether the Bailey & Hui algorithm cannot be used.

$\omega_i \in \Omega$. In order to configure the accurate value of ω_w, users must write it in the field `w` of the *Work Template* zone. Then, they must pulse the key `[ENTER]`.

In order to remove a $\omega_i \in \Omega$, users must simply click on the red triangular handler located on the right side of frequencies axis. The removing order is sequential starting from the highest frequency $\omega_i \in \Omega$.

Figure 2.1 shows two segments in the *Frequencies* zone. One of them is at ω_1=1.5 rad/s (grey colour), and the another is at ω_i=3 rad/s (black colour). The square box `Move frequencies` is not activated. Therefore, users cannot move the segments. But, they can add or remove frequencies.

2.2.4 Work Template Zone

This zone contains a Nichols chart (or a complex plane) where the current work template $\Gamma_w(\omega_w)$ is drawn. Four different colours are used to distinguish the algorithm which is being used to compute the templates: red (Bailey & Hui algorithm), green (Fu algorithm), blue (Kharitonov segments algorithm) and brown (grid algorithm). Likewise, the black colour is reserved to draw the saved template $\Gamma(\omega_w)$.

The points of $\Gamma_w(\omega_w)$ are represented in this zone with the symbol '$\circ$'. The points of the $\Gamma_w(\omega_w)$ boundary are connected using a solid line (except in the case of $\Gamma(\omega_w)$ or whether the ε-algorithm has not able to obtain the boundary). If users locate the mouse pointer over it, they can read the accurate value of a $\Gamma_w(\omega_w)$ point in the status bar.

If users have tried different algorithms to compute $\Gamma_w(\omega_w)$, TIG allows to see in this zone one or all of the $\Gamma_w(\omega_w)$ computed. Users have only to click in the appropriate square box. Each algorithm has associated a square box which is placed at the bottom of this zone. There also is a square box labelled as `Saved` which is associated to $\Gamma(\omega_w)$.

At the upper part of this zone, It is located the field `w`. It always shows the current value of ω_w. In order to change the value of ω_w, users have first to write a new value for ω_w in this field, and then they have to press the key `[ENTER]`. The change of ω_w will have success depending on the new value of ω_w and the frequencies $\omega_i \in \Omega$. For instance, the field `w` in Figure 2.1 shows that ω_w= 3 rad/s. Because there is a ω_i=1.5 rad/s $\in \Omega$, users can only introduce $\omega_w \geq$ 1.5 rad/s in this field. In order to introduce ω_w< 1.5 rad/s, users must first click

on the segment associated to ω_1=1.5 rad/s in the *Frequencies* zone. Now, because ω_w=1.5 rad/s and there is a ω_i=3 rad/s $\in \Omega$, then users can only introduce ω_w< 3 rad/s in this field.

The button `Save` is another element places in the upper part of this zone. It is used to save $\Gamma_w(\omega_w)$ in the *Saved Templates* zone, in other words, if users click on it then $\Gamma(\omega_w)$= $\Gamma_w(\omega_w)$. It is important to clarify that TIG saved the $\Gamma_w(\omega_w)$ computed with the current templates computation algorithm, which it is selected in the *Analysis* zone.

2.2.5 Status Zone

The *Status* zone has simply an informative function. Users cannot interactuate with it. In the *analysis* mode, this zone contains three circular indicators labelled with short text messages. These items inform about different aspects of the work session.

The circular indicator placed at the top of this zone can take three different colours: red, yellow or green. Red colour means that the current work algorithm has not able to compute $\Gamma_w(\omega_w)$, because some uncertain parameters combination does the denominator equal to zero. In this case, the circular indicator is labelled with the text "`Template(`ω_w`): Error!`". Yellow colour for this circle indicator means that the current templates computation algorithm may not be properly working due to different reasons. In this case, the text message, which labelled the circular indicator, is "`Template(`ω_w`): Check!`". Users must try to use another algorithm. In any another case, this circular indicator takes the green colour, and it is labelled with the text "`Template(`ω_w`): OK`".

The circular indicator placed at the centre of this zone can also take three colours: red, yellow or green. If the ε-algorithm is not able to obtain the boundary of $\Gamma_w(\omega_w)$ with the current values of *Weight*, *Factor X* and *Factor Y*, then this circular indicator will take red colour. The message "`Boundary: Error!`" will also appear labelling the indicator. It takes yellow colour if users must visually verify the boundary computed by the ε-algorithm. The message "`Boundary: Check!`" appears labelling the indicator. This is the most usual case. On the other hand, it takes green colour if the Bailey & Hui algorithm is the current template computation algorithm. Remind that this algorithm directly computed points of the template boundary. In this case, the text message is "`Boundary: Ok`".

Finally, the circular indicator placed at the bottom of this zone can only take two colours: yellow or green. If the computational load is heavy, this indicator will take yellow colour and it will be labelled with the text "`Load: Heavy`". Remind that in this case the TIG interactivity

decreases. Otherwise, this indicator will take green colour. Likewise, the message "`Load: Light`" will labelled it.

In the *configuration* mode, the *Status* zone only contains a red circular indicator labelled with the text "`Configuration has not finished`".

2.2.6 Plant Uncertain Parameters Zone

This zone allows to configure the maximum, nominal and minimum values of the plant uncertain parameters. It contains five interactive elements: one slider and four text fields.

The field `#` allows to set the number associated to the uncertain parameter. Thus, 1 is associated to the parameter p_1, 2 to p_2, etc. Users have only to write the number in this field, and then pulse the key `[ENTER]`.

The fields `pmax(#)`, `pnom(#)` and `pmin(#)` allow to set the maximum $p_j^{\max}$, nominal p_j^0 and minimum $p_j^{\min}$ values of the parameter p_j, respectively. The performance of this three fields is similar to the field `#`. For instance in Figure 2.1, the *Plant Uncertain Parameters* zone shows that $p_5^{\max}$=16.5, p_5^0=9.5 and $p_5^{\min}$=8.25.

The slider `p(#)` consists of three vertical segments (blue, black and red) associated to $p_j^{\min}$, p_j^0 and $p_j^{\max}$, respectively. Users can horizontally move these segments; they have only to follow the following steps: First at all, place the mouse pointer over the segment. Second, holding down the mouse left button, drag horizontally the segment till placed in the wanted position.

If users drag the black segment associated to p_j^0, the template nominal values ('`x`') will simultaneously move in the *Saved Templates* zones. Besides, if the *Nominal Poles-Zeroes Map* (see section 3.2.4) was visible on the TIG window, the poles ('`x`') and the zeroes ('`o`') of the nominal plant transfer function would also be moved.

On the other hand, if users dragged the blue segment or the red segment (associated to $p_j^{\min}$ and $p_j^{\max}$, respectively), then they would be modifying the uncertainty range of the parameter p_j. Therefore, it is necessary to recompute the templates. In order to avoid heavy computational load situations, all of the frequencies $\omega_i \in \Omega$ are removed except the work frequency ω_w. Besides, all of $\Gamma(\omega_i)$ except $\Gamma(\omega_w)$ disappear in the *Saved Templates* zone.

While users drag one of these segments, they can simultaneously visualise the changes of $\Gamma(\omega_w)$ in this zone, and the changes $\Gamma_w(\omega_w)$ in the *Work Template* zone.

In conclusion, the slider `p(#)` is very useful to visualise as the uncertainty of a certain plant parameter affects to the template shape.

2.2.7 Analysis Zone

Users can do several actions in this zone: select the $\Gamma_w(\omega_w)$ computation algorithm, configure the parameters of the selected algorithm and the parameters of the ε-algorithm, select and remove $\Gamma_w(\omega_w)$ points, and correct the phase jumps of $\Gamma_w(\omega_w)$. The colour code used in this zone is similar to the used in the Work Template zone (see section 2.2.4).

At the top of this zone, the radio buttons `Work Algorithm` allow to select the algorithm for computing $\Gamma_w(\omega_w)$. There are four available algorithms: `Bailey-Hui`, `Fu`, `Kharitonov` and `Grid`. However, the number of available algorithms decreases if the number of plant uncertain parameters is high. In order to select a certain algorithm, users have only to click on the radio button associated to the algorithm.

The slider and the field associated to the configuration parameter of the work algorithm are located below of the radio buttons `Work Algorithm`, This parameter takes different names in function of the selected algorithm: `Nb` (Bailey & Hui algorithm), `Nf` (Fu algorithm) and `Nk` (Kharitonov segments algorithm). Users can set this parameter of two different ways. One way is horizontally to move the slider. Another alternatively way is to write its value in the text field. Because of the high computational cost, the configuration parameters associated to the grid algorithm can only be set using the `Settings` menu (see section 3.2.5).

If the work algorithm is not the Bailey & Hui algorithm, then three sliders (`Weight`, `Factor X` and `Factor Y`) will appear below of the field associated to the work algorithm configuration parameter (see Figure 2.2). These three sliders are associated to the ε-algorithm configuration parameters. A text field is located below of each one of these sliders, which allows to visualise and configure the value of such parameter.

The text `X:Y` appears below of the field associated to the parameter `Factor Y`. `X:Y` is the result of dividing `Factor X` between `Factor Y`. This amount informs about how much the X coordinate of the $\Gamma_w(\omega_w)$ has been increased or decreased with respect to its Y coordinate.

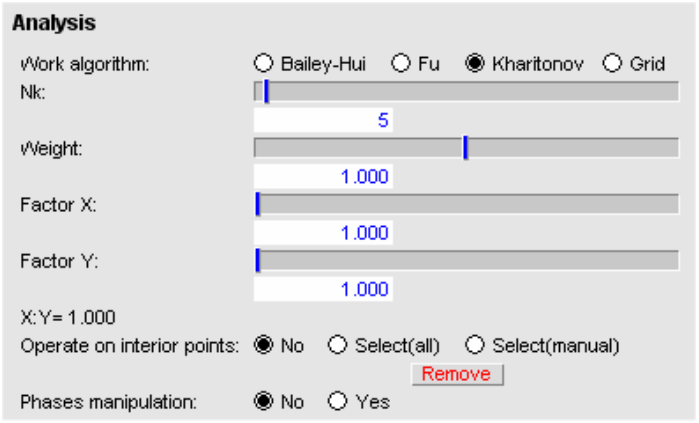

Figure 2.2: Typical aspect of the Analysis zone if the selected work algorithm is not the Bailey & Hui algorithm

The radio buttons `Operate on interior points` appear below of `X:Y`. They allow to remove points of $\Gamma_w(\omega_w)$. There are three possible options: `No`, `Select (all)` and `Select(manual)`. The option selected by default is `No`, i.e., users cannot remove point of $\Gamma_w(\omega_w)$. If they select the option `Select (all)` then all the points of $\Gamma_w(\omega_w)$ located inside of the boundary will be removed as they click on the button `Remove`. This button is placed below of the radio buttons `Operate on interior points`. The option `Select (manual)` allows to draw a square in the *Work Template* zone. The points of $\Gamma_w(\omega_w)$ enclosed inside of this rectangle will be remove as users click on the button `Remove`. In order to draw this rectangle, they must hold down the mouse left button.

Other available items in the *Analysis* zone are the radio buttons `Phases Manipulation`, the folding list `Phases range` and the buttons `-360°` or `360°`. All of this items can be used for users in order to remove the possible discontinuities in the phase of $\Gamma_w(\omega_w)$.

The radio buttons `Phases Manipulation` have two options: `No` or `Yes`. The selected option is `No` by default. If users select the option `Yes` then the folding list `Phases range` and the buttons `-360°` or `360°` will appear in this zone below of the radio buttons.

The folding list `Phases range` allows to select the points of $\Gamma_w(\omega_w)$ in function of the quadrant which they belong, The available options in this list are: `All`, `First Cuadrant`, `Second Cuadrant`, `Third Cuadrant` and `Fourth Cuadrant`. In order to select a element of the list, the following steps must be done: place the mouse pointer over the list, press the mouse left button, and, holding down the mouse left button vertically move the

mouse pointer till placed in the wanted option. In the *Work Template* zone, the selected points of $\Gamma_w(\omega_w)$ are drawn in blue colour (except for the option `All`). Users can add or subtract 360º to the phase of the $\Gamma_w(\omega_w)$ points if they pulse the button 360º or -360º, respectively.

Finally, it is important to take in mind that any modification done on a slider or a field of the *Analysis* zone are instantaneously (if the computational load is light) reflected in the *Work Template* zone.

2.2.8 Algorithms Information Zone

This zone shows the following information[3] about $\Gamma_w(\omega_w)$: N_t, N_c, R, T_t and T_c. it is important to take in mind that TIG rounds off to 0 the times T_t and T_c if they are lower or equal to 10^{-2} s.

2.2.9 Plant Transfer Function Zone

This zone shows the symbolic expression of the plant transfer function. Two red triangular handlers are also shown in both sides of this zone if the expression length is greater than the zone length. Users can use these handlers to move the expression to the right or to the left in order to see all of its terms.

2.3 MODE CONFIGURATION

Figure 2.3 shows the initial aspect of the TIG window in the *configuration* mode. Remind that to enter in this mode; users must click on the radio button `Configuration` in the *Work Mode* zone. There are six zones on the left of the TIG window (*Work Mode*, *Status*, *Configure Plant Uncertain Parameters, Configuration Steps*, *Algorithms Information and Plant Transfer Function*), and three zones on the left of the TIG window (*Table of Plant Uncertain Parameters*, *Frequencies* and *Work Template*).

Users mainly must work in the *Configuration Steps* zone to configure the number of the plant uncertain parameters, its values (minimum, maximum and nominal), and the work frequencies set Ω.

The upper part of this zone contains four text lines associated to each one of the four sequential steps of this mode. The current step is always highlighted in red colour.

[3] R is the percentage of points of $\Gamma_w(\omega_w)$ which belongs to the template boundary.

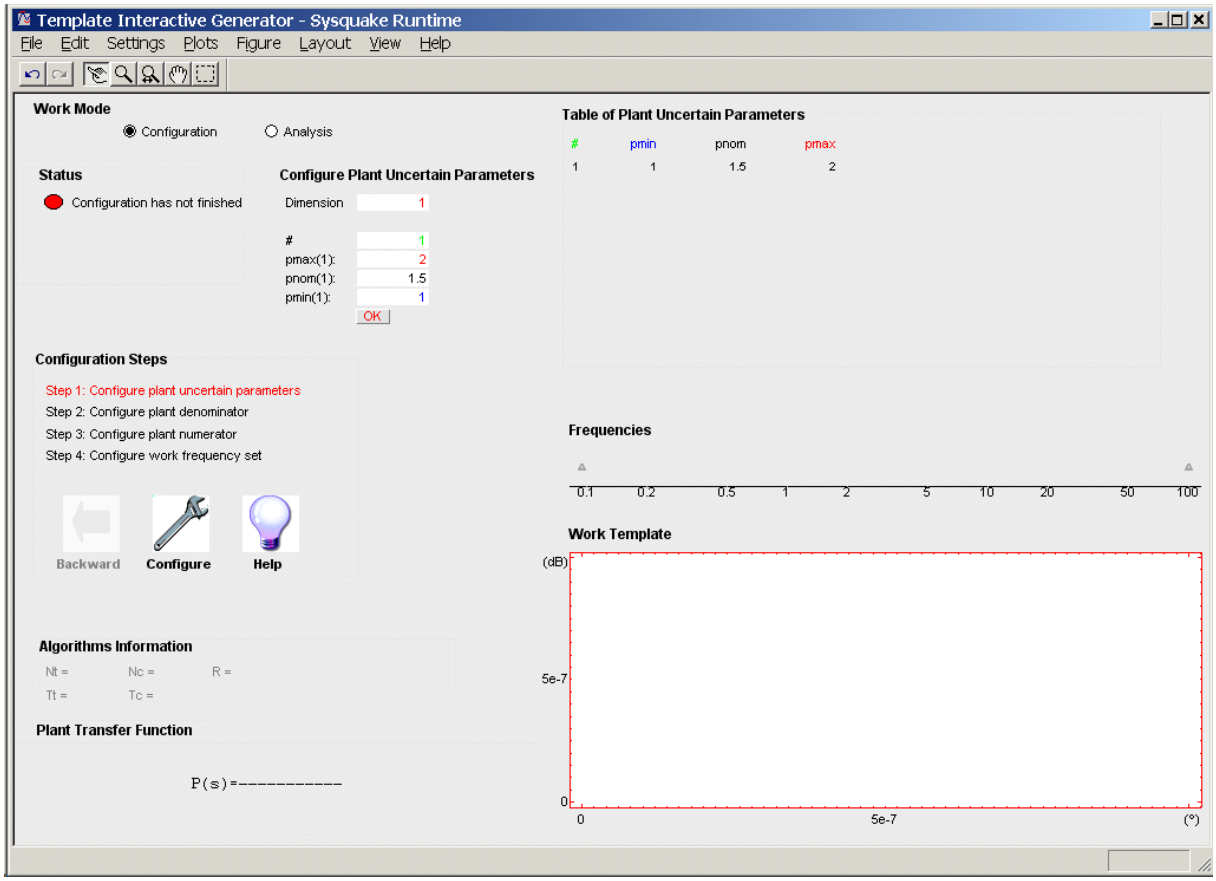

Figure 2.3. Initial aspect of the TIG window in the configuration mode

On the other hand, the lower part of this zone contains three buttons: `Backward`, `Configure` and `Help`. `Backward` allows to go back to the previous configuration step. If users click on `Configure`, a dialog box will appear on the window. They have to write different data in the dialog box depending on the configuration step. The button `Help` links to the TIG web site (`http://ctb.dia.uned.es/asig/tig/`). In this web site, users can download this manual.

In this work mode, other useful zones are: *Configure Plant Uncertain Parameters*, *Table of Plant Uncertain Parameters* and *Plant Transfer Function*. The first zone offers an alternative way of configuring the plant uncertain parameters. The other two zones has an informative function. Thus, the *Table of Plant Uncertain Parameters* zone shows a table which contains $p_j^{\min}$, p_j^0 and $p_j^{\max}$ (j=1,..,L). The `Plant Transfer Function` zone shows the expressions of the denominator and the numerator. In the step 4, the field N_{ID} also appears in this zone. It allows to configure the number of plant integrators or derivators.

2.3.1 Step 1: Configuration of the uncertain plant parameters

In the step 1 of the *configuration* mode, if users click on the button `Configure` then the `Plant Uncertain Parameters` dialog box will appear on the window (see Figure 2.4). This dialog box shows the minimum, maximum and nominal values of the plant uncertain parameters according to the following format:

$$[p_1^{\min}, p_1^{\max}, p_1^0; p_2^{\min}, p_2^{\max}, p_2^0; ...; p_L^{\min}, p_L^{\max}, p_L^0]$$

Each value associated to a certain parameter has to be written separated by comma. Likewise, each uncertain parameter has to be written separated by semicolon. Besides, the relation $p_j^{\min} \leq p_j^0 \leq p_j^{\max}$ (j=1,..,L) must be verified. Remind that L cannot be greater than 14.

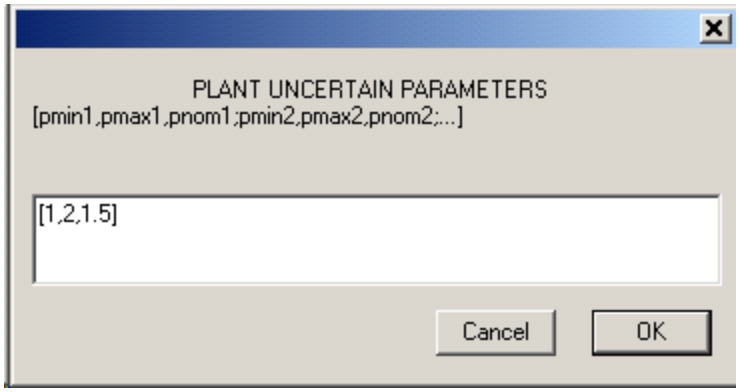

Figure 2.4. `Plant Uncertain Parameters` *dialog box*

In order to configure this dialog box, users have to do the following actions: First, write the plant uncertain parameters in the correct format. Then, click on the button `OK`. If no format error has been made, TIG will automatically go to the step 2 of the configuration mode. The zone *Table of Uncertain Parameters* will show the plant uncertain parameters.

TIG considers the existence of an only uncertain parameter $p_1 \in [1, 2]$ by default. Its nominal value is 1.5.

Users can also done this step configuration using the zone *Configure Plant Uncertain Parameters*. This zone is very similar to the zone *Plant Uncertain Parameters* (see section 2.2). However, there are two differences between these two zones. The first difference is that the field `Dimension` replaces to the slider `p(#)`. This field allows to configure the number L

of plant uncertain parameters. The second difference is the button `OK` placed at the bottom of the zone *Configure Plant Uncertain Parameters*. The function of this button is equal to the function of the button `OK` in the *`Plant Uncertain Parameters`* dialog box.

2.3.2 Step 2: Configuration of the plant denominator

In the step 2 of the *configuration* mode, if users click on the button `Configure` then the `Plant denominator` dialog box will appear on the window (see Figure 2.5). This dialog box shows a text string associated to plant denominator coefficients. They have to follow several rules in order to correctly write the text string.

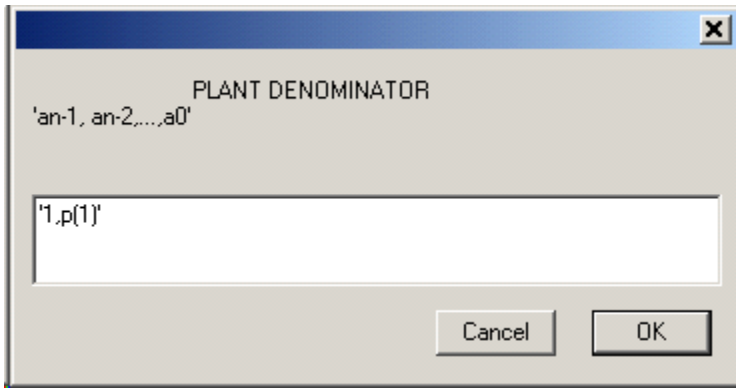

Figure 2.5. `Plant Denominator` dialog box

These writing rules are:

- The plant denominator coefficients must be written in descending order separated by commas. Therefore, the coefficient, which is placed in the left end of the text string, is associated to the higher power (s^n). Remind that $n \leq 7$.

- The coefficient associated to the lower power (s^0) cannot be 0, i.e., the denominator must be written without integrators. This kind of elements can be added in the step 4.

- Each uncertain parameter is represented by the symbol `p(j)`, where `j` is the number associated to the uncertain parameter. For example, `p(1)` is associated to the uncertain parameter p_1, `p(2)` is associated to the uncertain parameter p_2, and so on.

- A coefficient can be a linear combination of the uncertain parameters.

$$c_1p_1+ c_2p_2+...+ c_Lp_L+c_0$$

For instance, the text string `'2.3, -p(1)+3.5p(2)+5, 1.6p(2)+3.5p(3)'`, which is the same as the polynomial $2.3\cdot s^2+(-p_1+3.5\cdot p_2+5)\cdot s+(1.6\cdot p_2+3.5\cdot p_3)$, is correct. Another example of a correct text string is `'-2.1e-10,e-3p(1)+p(3)-2p(2)'`, which is the same as the polynomial $-2.1\cdot10^{-10}\cdot s+(10^{-3}\cdot p_1+\cdot p_3-2\cdot p_2)$. An example of a invalid text string is `'1, p(1)*p(3),p(3)^3'`.

- The independent term of the linear combination associated to a certain coefficient must be writen at the end of the linear combination. If it is written in the middle or in the end of the linear combination, an error message will appear in the windows. For instance, the string `'2.3, 5-p(1)+3.5p(2)'` is invalid. The correct string would be: `'2.3,-p(1)+3.5p(2)+5'`.

- A certain uncertain parameter can appear only one time at the linear combination associated to a coefficient. For example, the text string `'1, p(1)+3p(1)'` is invalid because p_1 is repeated. The correct string would be `'1, 4p(1)'`.

- The powers $r\cdot10^n$ or $r\cdot10^{-n}$ must be written in the text string as `ren` and `re-n`, respectively. For instance, the polynomial $4\cdot10^2\ s-2.5\cdot10^{-5}p_1$ would be equivalent to the text string `'4e2, -2.5e-5p(1)'`.

This dialog box contains the text string `'1,p(1)'` by default which is equivalent to the denominator $s+p_1$.

In order to configure this dialog box, users have to write the text string and then click on the button `OK`. If there is no error in the text string format, TIG will automatically go to the step 3 of the configuration mode. The plant denominator is shown in the zone *Plant Transfer Function*.

2.3.3 Step 3: Configuration of the plant numerator

In the step 3 of the *configuration* mode, if users click on the button `Configure` then the `Plant numerator` dialog box will appear on the window. The configuration of this dialog box is very similar to the `Plant denominator` dialog box. It is very important to remind that the numerator order must be lower or equal to the denominator order. Besides, the numerator must be written without derivators. This kind of elements can be added in the step 4.

2.3.4 Step 4: Configuration of the work frequencies set

In this step, users can configure the number N_{ID} of integrators or derivators associated to the plant. First, they must simply write such number in the field `Ni`. It is located at the top of the `Plant Transfer Function` zone. Then, they must click on the `[ENTER]` key. If N_{ID} is a positive (negative) integer then N_{ID} integrators (derivators) are added in the plant. N_{ID} is equal to 0 by default. Remind (see section 1.2.4) that TIG only allows to add 10 integrators or derivators as maximum.

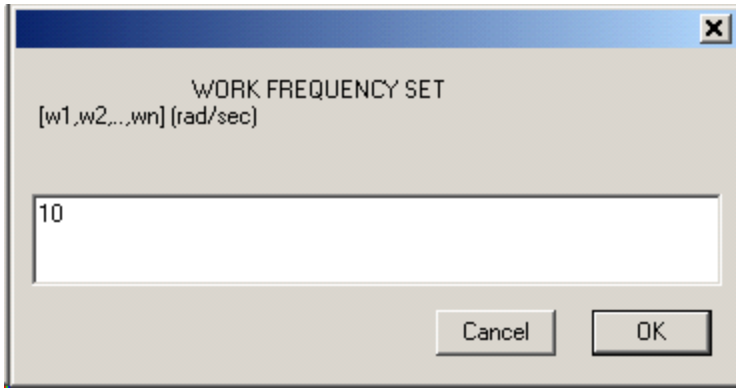

Figure 2.6: `Template Frequency Vector` dialog box

In this step 4, users must configure the work frequencies set Ω, i.e., the frequencies which are going to be used to compute the templates. If they click on the button `Configure` then the `Plant Work Frequency set` dialog box will appear on the window (see Figure 2.6). It shows the frequencies $\omega_i \in \Omega$ i=1,2,...,N_ω according to the following format:

$$[\omega_1, \omega_2 .., \omega_{N_\omega}]$$

N_ω can never be greater than 10. TIG initially considers the existence of an only frequency (ω_1=10 rad/s $\in \Omega$ by default).

In order to configure this dialog box, users have to do the following actions: First, write the frequencies. Then, click on the button `OK`. If no format error has been made, TIG will automatically computed the templates $\Gamma(\omega_i)$ using the Bailey & Hui algorithm with Nb=25 (or the grid algorithm with Np_j=2 whether the first one cannot be used). Once the computation has finished, TIG will automatically go to the analysis mode.

TIG will show a dialog box if the computational load is heavy. It contains a text message: "`The computation of the templates may take some seconds`" or "`The computation of the templates may take some time (maximum 10 seconds for each frequency)`".

If a template cannot be computed then TIG will show the message: "`Templates computation algorithms can not work at [wj] (rad/s) some uncertaint parameter does P=oo`". TIG will not automatically go to the analysis mode in this case.

2.4 AUXILIARY BUTTONS BAR

The auxiliary buttons bar (see Figure 2.7) is located at the top of the TIG window below of the menu bar. It contains 7 buttons:

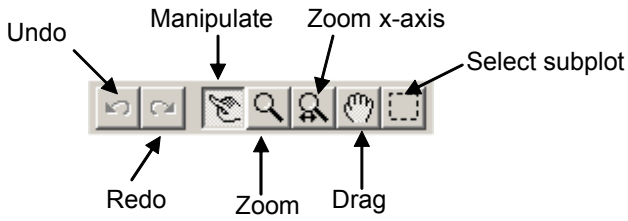

Figure 2.7: Auxiliary buttons bar

- `Undo`. It allows to undo the last action.
- `Redo`. It allows to redo the previously undone action.
- `Manipulate`. It allows to drag graphical elements in one of the zones; and see the effect this has on other figures.
- `Zoom`. It allows to click in a figure to double the scale in both x and y directions, or select the area that they want to display by holding down the mouse button. To revert to the default scale, hold down the `Shift` key, and click on the diagram.
- `Zoom x-axis`. It works in similar way to `Zoom` In this case, the scale is only doubled in the x direction.
- `Drag`. It allows to drag the items of a diagram to move it in its own limits.
- `Select`. It allows to drag and change the zones size. Thus, the aspect of the TIG window can be reconfigured according to the user preferences.

CHAPTER 3:
DESCRIPTION OF TIG MENUS BAR

3.1 INTRODUCTION

All software tools implemented with Sysquake have in the top of window a bar with the following menus (figure 2.1): `File`, `Edit`, `Settings`, `Figure`, `Layout`, `View` and `Help`. This is the case of TIG. Only the `Settings` and `Figure` menus are different for each tool. The most important menu is the `Settings` menu. This chapter is dedicated mainly to this menu.

3.2 SETTINGS MENU

Clicking in `Settings` a menu with the following entries is shown:

- `Load/Save`. Users can load or save a work session. Furthermore they can generate a report about the work session.
- `Import/Export`. Users can import templates from Matlab and export the save templates $\Gamma(\omega_i)$, shown in *Saved Templates* zone, to Matlab or QFTIT.
- `Frequency range`. It allows to configure the scale of the *Frequencies* zone, and the frequencies range where it is necessary to calculate the templates for the validation stage in QFTIT.
- `Options plot`. Users can choose different options for templates representation.
- `Grid algorithm configuration`. Configuration of parameters values Np_j associated to the grid algorithm.

Next subsections show the `Settings` menu inputs with more detail.

3.2.1 Load/Save entry

A work session is defined as the values of TIG local variables in a time instant. Users can save and load a work session in any time. A work session is saved in an ASCII file with `.ses` extension.

Furthermore, with TIG is possible to generate and save a report with the main data of a work session. The report is saved in an ASCII file with `.txt` extension.

The steps to load or save work session are: click on `Settings` menu, move the mouse on `Load/Save` input, and click on one of the following options:

- `Load work session`. Clicking on this option a dialog box is open, where users can select the `.ses` file of a previous work session.
- `Save work session`. Clicking on this option a dialog box is opened, users can write the `.ses` file name for this work session. The name is `session.ses` by default.
- `Save report`. Clicking on this option a dialog box is opened, where users can write the `.txt` file name of the work session report. For omission, the name is `report.txt` by default.

The difference between a work session file (`.ses`) and a report file (`.txt`) is that a `.ses` file is a sequence of numbers associated to TIG variables, no text message, and a `.txt` file has the main variables with explanatory message.

3.2.2 Import/Export entry

We saw in section 1.2.3 that TIG can cooperatively work with Matlab and QFTIT. Users can import templates from Matlab to TIG, and export templates $\Gamma(\omega_i)$ from the *Saved Templates* zone of TIG to Matlab or QFTIT.

For doing these actions, users must click on `Settings` menu, place the mouse on `Import/Export` input and click over some entry of the new menu that is shown:

- `Import templates from Matlab`. Clicking on this entry a dialog box is shown. The users must choose the file with Matlab templates. Previously, the templates was calculated in Matlab and saved to an ASCII file with extension `.tmp` by the function `mat2tig.m`. This function is distributed together with TIG.

The template is saved as a matrix of real numbers in a file `.tmp`. Each pair of columns is the real and imaginary part of a template. Besides, the following information is saved: a row vector with the frequencies of each template, a positive integer number that is the row of the template matrix with the nominal point, a row vector with numerator coefficients of nominal plant and a row vector with the denominator coefficients of the nominal plant.

- `Export templates to Matlab`. A dialog box is opened. There users must write the file name `.tmo` where the templates $\Gamma(\omega_i)$ of *Saved Templates* zone are saved. The file name is `toMATLAB.tmo` by default. The data of a `.tmo` file is loaded to Matlab by the function `tig2mat.m`. This function is distributed together with TIG.

$\Gamma(\omega_i)$ $\omega_i \in \Omega$ are saved as a matrix of real numbers in a `.tmo` file. Each pair of columns is the real part and imaginary part of a template. $\omega_i \in \Omega$ are saved in the next-to-last row. Likewise, a positive integer number is saved in the last row. It informs about the row which contains the template nominal point.

This menu entry is not available in the configuration mode.

- `Export templates to QFTIT`. A dialog box is opened where users must write the file name (`.tqf`) where the templates $\Gamma(\omega_i)$ of *Saved Templates* are going to be saved. The file name is `toQFTIT.tqf` by default.

  The following data are saved in a `.tqf` file: a row vector with the numerator coefficients of nominal plant, a row vector with the denominator coefficients of nominal plant, a row vector with Ω, N_ω matrices with two columns (phase (º) and magnitude(dB)) associated to each $\Gamma(\omega_i)$, a two columns matrix with nominal points of the N_w templates, a row vector with $N_{\omega val}$ validation frequencies, a character string with the name of algorithm used to calculate the validation templates, the value of configuration parameter of algorithm, $N_{\omega val}$ two columns matrices (phase (º) and magnitude(dB)) associates to each validation template. If a template can not be calculated, the string `vempty` replace to matrix.

  If the templates are imported from Matlab, and the nominal plant numerator and denominator are not defined, then this menu entry will not be shown.

3.2.3 Frequency range entry

This menu entry allows to configure the *Frequencies* zone scale and the frequencies range where is necessary to calculate the templates for the validation stage in QFTIT.

Clicking on this entry, a menu is folded with two entries: `Template frequency range` and `Frequency range for QFTIT validation stage`

3.2.3.1 Template frequency range entry

Clicking on `Template frequency range` entry, the dialog box of Figure 3.1 is shown.

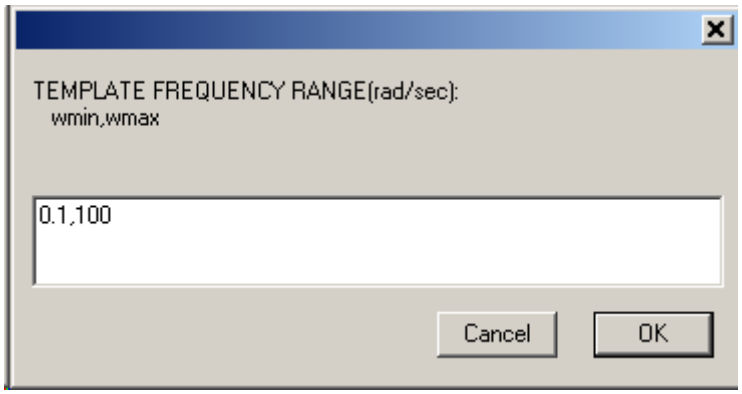

Figure 3.1. `Template Frequency vector` dialog box

It shows the minimum ω_{min} and maximum ω_{max} values of the frequencies axis according to the following format:

$$\omega_{min},\omega_{max}$$

The values of this frequencies are ω_{min}=0.1 rad/s and ω_{max}=100 rad/s by default. Users can write the values of this frequencies and then click on the `OK` button.

3.2.3.2 Frequency range for QFTIT validation stage entry

When the plant is defined in Matlab or TIG, then it is necessary an additional set of $N_{\omega val}$ templates in the frequencies range [10^{d1}, 10^{d2}] (rad/s) for the validation stage in QFTIT.

If the plant is defined in Matlab, this set of templates is computed with the function `mat2qftitval.m`. This function is distributed together with TIG.

If the plant is defined in TIG, this set of templates is computed automatically when is created the file `.tqf` by the `Export templates to QFTIT` option. This set is saved in this file. The algorithm used to compute these templates is the algorithm marked as `Work Algorithm` in the *Analysis* zone. The configuration parameter is the same that the parameter indicated in the *Analysis* zone if the computational load is light. Otherwise, the parameter values are: *Nb*=25, *Nf*=5, *Nk*=20 y Np_i=2.

The dialog box of Figure 3.2 is shown when users click on `Frequency range /Frequency range for QFTIT validation stage` entry associated to the `Settings` menu.

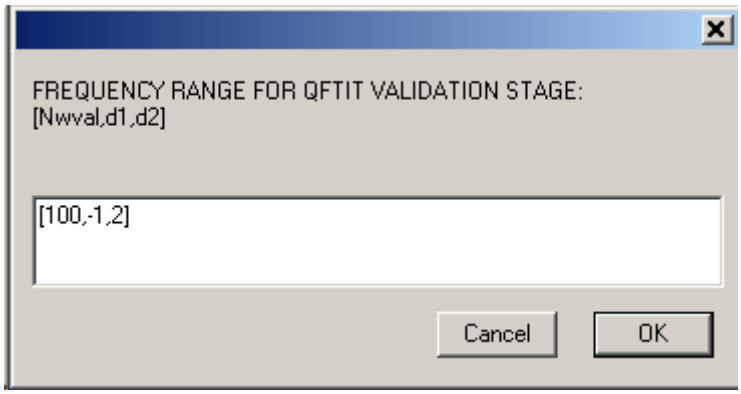

Figure 3.2. `Frequency range for QFTIT validation stage` *dialog box*

The number of validation frequencies $N_{\omega val}$, the exponent d_1 of minimum validation frequency 10^{d1} rad/s and the exponent d_2 of maximum validation frequency 10^{d2} rad/s are displayed in the dialog box with the following format:

$$[N_{wval},d1,d2]$$

The values are: N_{wval}=100, d_1=-1 and d_2=2, by default. Users can change these values writing the new values for $N_{\omega val}$, d_1 y d_2 and clicking on `OK` bottom.

An estimation of the template computation time is done by TIG. If this time is greater than 4 minutes, the number of validation templates is decreased.

3.2.4 Options plot entry

If users click on the `Options plot` entry belonging to the `Settings` menu, another menu will appear. It contains the following options:

- Diagram kind of the *Work Template* zone. There are two kinds of diagrams: `Nichols diagram` and `Complex plane`. The selected option is `Nichols diagram`, by default.

- Scale kind in *Work Template* zone:

  - `Automatic scale`. The axes are automatically scaled in order to display all templates. This is the option by default.

  - `Fix scale`. The axes range is fixed. Users can change it using four black triangle manipulators located at the axis end. If they click on a manipulator the scale is shifted.

- Show the poles-zeros map in the tool window. If users click on `Show nominal poles-zeroes map` option, the *Work Template* zone is replace for the *Nominal poles-zeroes map* zone. `Hide nominal poles-zeroes map` option is activated by default.

- To emphasize the work template in the `Saved templates` zone. `Highlight work template` option is activated by default.

3.2.5 Grid algorithm configuration entry

If users click on `Grid algorithm configuration` entry of `Settings` menu, the dialog box of Figure 3.3 is shown.

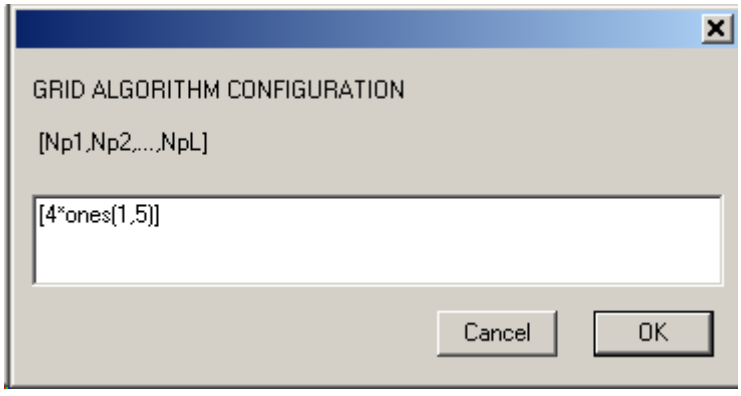

Figure 3.3. `Grid algorithm configuration`. dialog box

The parameter Np_j of grid algorithm is displayed in the dialog box, its format is:

$$[Np_1,Np_2,...,Np_L]$$

The initial value is `[4*ones(1,5)]`, that is equivalent to `[4,4,4,4,4]`. Users must write the values of Np_j and click on `OK` bottom.

3.3 OTHER TOOL MENUS

Other menus in the TIG menu bar are:

- `File`. Users can do the following actions with this menu: restart the application (`Reset Data` input), print the tool window (`Print` input), and exit of application (`Exit` input).
- `Edit`. Options of this menu are: `Undo`, `Redo`, change the line type (`Preferences/Thick lines` input), change the font, size and style of character (`Preferences/Figure Font` input), and change the colour of tool window (`Preferences/Background Color` input).
- `Plots`. Display the different zones of tool window, and change a zone for another zone.
- `Figure`. Options of this menu are: `Manipulate`, `Zoom`, `Zoom X`, `Drag`, and `Select`. These modes were comments in section 2.4.
- `Layout`. Layout the zones of tool window.
- `View`. Hide the auxiliar bottoms bar (`Toolbar` input) and status bar.
- `Help`. There is a link to web page `http://www.calerga.com/` of Calerga.

Users can see the Sysquake manual (in `http://www.calerga.com/`) for more information.

CHAPTER 4:
ILLUSTRATIVE EXAMPLES

4.1 EXAMPLE 1

This section is dedicated to describe the example implemented in TIG by default. Let the following plant

$$P(s,p)=\frac{s^2+p_4\cdot s+p_5}{s^3+p_1\cdot s^2+p_2\cdot s+p_3} \tag{4.1}$$

which contains 5 uncertain parameters:

$$p_1\in[2.3,\ 19],\ p_2\in[13.51,\ 147],\ p_3\in[11.025,\ 490],\ p_4\in[7,\ 9.5]\ ,\ p_5\in[8.25,\ 9.5] \tag{4.2}$$

Its nominal values are:

$$p_1^0=10,\ p_2^0=100,\ p_3^0=25,\ p_4^0=8,\ p_5^0=9 \tag{4.3}$$

The work frequencies set is:

$$\Omega=\{1.5,\ 3\}\ \text{(rad/s)} \tag{4.4}$$

The problem consists in obtaining the boundaries of $\Gamma(1.5)$ and $\Gamma(3)$.

In the transfer function (4.1), the numerator uncertain parameters are independent of the denominator uncertain parameters. Therefore, the Bailey & Hui algorithm is a good selection in order to compute these boundaries. Likewise, the grid algorithm can be used to check that the computed boundaries are correct. Thus, this first illustrative example is going to be used for learning to do the same actions in TIG:

- Compute and study the template boundaries using the Bailey & Hui algorithm.
- Compute the templates using the grid algorithm.

- Graphically study how the template shape changes as the frequency or the plant uncertain parameters are modified.

- Graphically study how the location of the template nominal point changes as the nominal values of the plant parameters are modified.

4.1.1 Configuration

In order to enter in TIG all the information about the plant, the tool has to be in configuration mode. For going to this work mode, users have to click on the radio button `Configuration` in the *Work Mode* zone. The `Save work session` dialog box will appear on the TIG window. If users want to save the current work session, they have to write the file name (with `.ses` extension) and click on `OK`. Otherwise, they have to click on `Cancel`. In both cases, TIG will go to the *configuration* mode. Figure 2.3 shows the initial aspect that the TIG window takes in this mode.

4.1.1.1 Step 1: Configuration of the plant uncertain parameters

When TIG is in the first step of the configuration mode, the `Configuration Steps` zone has the message `Step 1: Configure plant uncertain parameters` highlighted in red.

A possible way of doing this step is clicking on the `Configure` button in the *Configurations Steps* zone. The `Plant uncertain parameters` dialog box will appear on the TIG window. Remind that this dialog box allows to configure the minimum, nominal and maximum values of the uncertain plant parameters. According to (4.2) and (4.3), users have to fill the dialog box with:

```
[2.3 19.8 10; 13.51 147 100; 11.025 490 25; 7 9.5 8; 8.25 16.5 9.5]
```

and then click on `OK`. TIG automatically goes to the step 2. The *Table of Plant Uncertain Parameters* zone shows the entered values.

Users can easily check that these values are correct. If they detect some wrong value, they can change it doing the following actions: First, pulse the `Backward` button in the *Configuration Steps* zone to go back to step 1. Second, pulse the `Configure` button to see again the `Plant uncertain parameters` dialog box. Third, change the wrong value. Finally, click on `OK`.

Another way of doing the step 1 is to work with the fields of the *Configure Plant Uncertain Parameters* zone. Fist at all, users have to write the number of uncertain plant parameters in the field `Dimension`. Then, they have to pulse the `[ENTER]` key.

Second, users have to write in the field `#` the number of the uncertain parameter that they want to configure. For instance: 1 for the parameter p_1, 2 for the parameter p_2, and so on. Then, they have to pulse the `[ENTER]` key. The *Table of Plant Uncertain Parameters* zone highlights in black colour the values associated to the selected parameter.

Third, users have to write the maximum, nominal and minimum values of the selected parameters in the fields `pmax(#)`, `pnom(#)` and `pmin(#)`, respectively. For instance, suppose us that the selected parameter is p_1. In order to configure its maximum, nominal and minimum values, users have to do the following actions:

1) Write 19.8 in the field `pmax(1)`, and then pulse `[ENTER]`.

2) Write 10 in the field `pnom(1)`, and then pulse `[ENTER]`.

3) Write 2.3 in the field `pmin(1)`, and then pulse `[ENTER]`.

The configuration of p_2, p_3, p_4 and p_5 can be done in a similar way. When users finish the configuration of all the plant parameters, they have to click on the button `OK`. It is located at the bottom of the *Configure Plant Uncertain Parameters* zone.

4.1.1.2 Step 2: Configuration of the plant denominator

When TIG is in the second step of the configuration mode, the `Configuration Steps` zone has the message `Step 2: Configuration of the plant denominator` highlighted in red.

In order to configure the plant denominator, users have to pulse the button `Configure` in the zone *Configuration Steps*. The `Plant denominator` dialog box will appear on the TIG window. According to (4.1), users have to write

```
'1,p(1),p(2),p(3)'
```

and click on `OK`.

4.1.1.3 Step 3: Configuration of the plant numerator

When TIG is in the third step of the configuration mode, the `Configuration Steps` zone has the message `Step 3: Configuration of the plant numerator` highlighted in red.

In order to configure the plant numerator, users have to pulse the button `Configure` in the zone *Configuration Steps*. The `Plant numerator` dialog box will appear on the TIG window. According to (4.1), users have to write

```
'1,p(4),p(5)'
```

and click on `OK`.

4.1.1.4 Step 4: Configuration of the work frequency set

When TIG is in the fourth step of the configuration mode, the `Configuration Steps` zone has the message `Step 4: Configure work frequency set` highlighted in red. Remind that in this step, users can also configure the number of plant integrators or derivators. In this example the plant (4.1) has no integrators and no derivators. Therefore, users have not to enter any value in the field `Ni` of the *Plant Transfer Function* zone.

In this point of the configuration mode, users should save the work session. For doing this action, they have only to click on the `Save work session` option (which belongs to the `Load/Save` entry of the `Settings` menu), and write the file name where they wants to save the work session. For example, `example1_conf.ses`.

In order to configure the work frequency set Ω, users must click on the `Configure` button located in the *Configuration Steps* zone, write the elements of Ω (see (4.4))

```
[1.5, 3]
```

in the dialog box `Template frequency vector`, and finally click on `OK`.

4.1.2 Analysis

4.1.2.1 Obtaining and studying of the template boundaries

Once the users have completed the step 4 of the configuration mode, TIG automatically goes to the analysis mode (see Figure 2.1). $\Gamma(1.5)$ (grey colour) and $\Gamma(3)$ (black colour) are drawn in the *Saved Templates* zone. These two templates have been computed by the

Bailey & Hui algorithm with *Nb*=25. It is easy to know that the current work frequency is ω_w=3 rad/s. Users have only to see the field `w` located in the `Work Template` zone.

The *Analysis* zone shows that the Bailey & Hui algorithm is the work algorithm, and that its configuration parameter is *Nb*=25. Therefore, the work template $\Gamma_w(3)$ drawn in black colour in the *Work Template* zone is identical to $\Gamma(3)$. Users can easily check this fact. They have only to click on the square box `Saved` which is located at the bottom of this zone. In such case, the points of $\Gamma(3)$ are drawn in black colour in the Nichols chart. As it can be observed, these points are located in the same position that the points of $\Gamma_w(3)$, which are drawn in red colour.

In the *Status* zone, the three circular indicators are in green colour. The two firsts indicate that $\Gamma_w(3)$ and its boundary have successfully been computed using the current work algorithm. The third indicates that the computational load is light.

The *Algorithms Information* zone contains the following information[1] associated to $\Gamma_w(3)$: N_t=50, N_c=50, R=100% and T_t=3.2·10^{-2} s. Remind that the Bailey & Hui algorithm directly computed points belonging to the template boundary. This is the reason for obtaining R=100%.

We are going to study if it is necessary to increase *Nb* for improving the boundary of $\Gamma_w(3)$, or if it is possible to decrease *Nb* without significantly changing the boundary shape. Users must to drag the slider `Nb` in the *Analysis* zone to do this study.

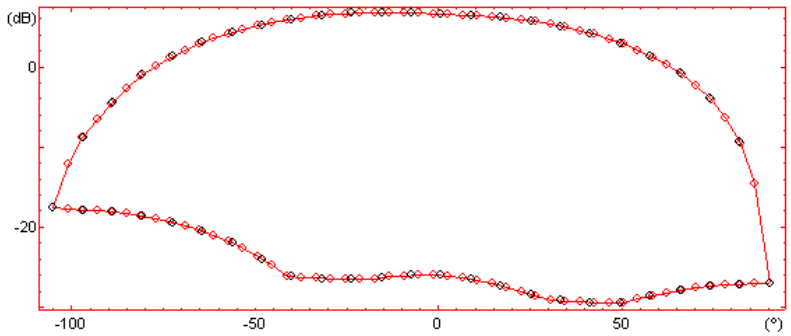

Figure 4.1. $\Gamma_w(3)$ (red colour) computed by the Bailey & Hui algorithm with Nb=50, and $\Gamma(3)$ (black colour) computed by the same algorithm with Nb=25.

It can be observed in the *Work Template* that if the users increase *Nb*, the boundary of $\Gamma_w(3)$ will have more points. However, the boundary shape will not significantly change. Perhaps, a good value is *Nb*=50 to better define the boundary ends (see Figure 4.1). The work template obtained with this value must be saved in the *Saved Templates* zone. For that, users have to pulse the `Save` button. It is located at the top of the *Work Template* zone.

If the computational load is heavy, the sliders will disappear of the TIG window. In this case, users must use the field *Nb* to change the value of this parameter. For this example, the computational load is heavy[2] if *Nb*>414.

In order to check that the Bailey & Hui algorithm generates a non-conservative boundary of $\Gamma_w(3)$, the grid algorithm is going to be used to compute $\Gamma_w(3)$. Users must to click on the `Grid algorithm configuration` entry of the menu `Settings`. A dialog box appears with the following content

```
[2*ones(1,5)]
```

This means that Np_j=2 for j =1,...,5. According to (1.9), TIG will only compute $N_t=2^5$= 32 points of $\Gamma_w(3)$. This amount is clearly insufficient to do a good checking. Therefore a greater value of Np_j must be considered. For example, if Np_j=6 then $N_t=6^5$= 7776. To configure this value, users have to write

```
[2*ones(1,5)]
```

or alternatively

```
[6,6,6,6,6]
```

in the dialog box. Then, they have to click on `OK`. A new dialog box appears on the TIG toolbox which contains the following message

```
The approximate time to compute 7776 points is less than 1 minute
```

After pulsing on OK, TIG starts to compute $\Gamma_w(3)$ using the grid algorithm. When the computation finishes, the points of $\Gamma_w(3)$ are drawn in brown colour in the *Work Template* zone. Besides, the points of the $\Gamma_w(3)$ boundary are connected with brown solid line. Remind that the boundary points are obtained by the ε-algorithm. The distribution of computed points

[1] The values of T_t or T_c, which appears in this chapter, can change in function of the computer characteristic where TIG was run.
[2] This situation also depends on the computer where TIG was run.

suggest that a heap should appear in the upper part of $\Gamma_w(3)$. It probably would appear if *Nb* was increased.

The *Algorithms Information* zone contains the following information associated to $\Gamma_w(3)$: N_t=7776, N_c=94, R=1.22%, T_t=21.547 s and T_c=1.063 s.

In order to visualise the boundary of $\Gamma_w(3)$ that was obtained using the Bailey & Hui algorithm with *Nb*=50, users have to click on the square box `Bailey`. Remind that it is located at the bottom of the *Work Template* zone. Figure 4.2 shows the aspect that takes this zone. It can be observed that the template boundary obtained by the Bailey & Hui algorithm with *Nb*=50 is correct.

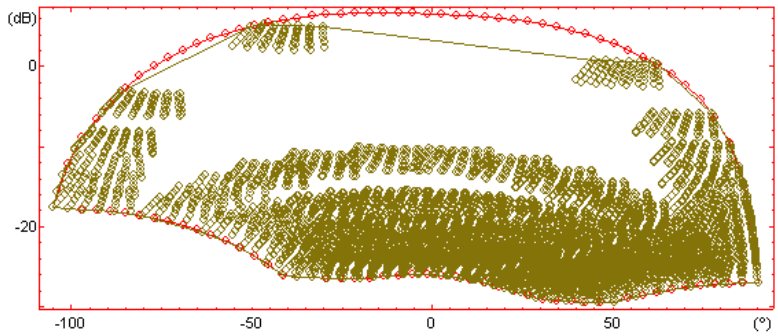

Figure 4.2. $\Gamma_w(3)$ (red colour) computed by the Bailey & Hui algorithm with Nb=50 and $\Gamma_w(3)$ (brown colour) computed by the grid algorithm with Np_j=6.

Once the comparison has been done, users must select the Bailey & Hui algorithm as the current work algorithm. They have only to select the `Bailey-Hui` option associated to `Work Algorithm` in the *Analysis zone* for getting that.

The work frequency is now going to be changed to ω_w=1.5 rad/s. Users must to click on the grey segment in the *Frequencies* zone. $\Gamma(1.5)$ is now drawn in black colour in the *Saved Templates* zone. Remind that $\Gamma(1.5)$ was computed by the Bailey & Hui algorithm with *Nb*=25. Likewise, the *Work Template* zone shows $\Gamma_w(1.5)$ with *Nb*=50. Users can also represent $\Gamma(1.5)$ in this zone to compare with $\Gamma_w(1.5)$. They have only to click on the square box `Bailey`. Figure 4.3 shows that $\Gamma(1.5)$ and $\Gamma_w(1.5)$ are very similar. Therefore it is not necessary to modify $\Gamma(1.5)$.

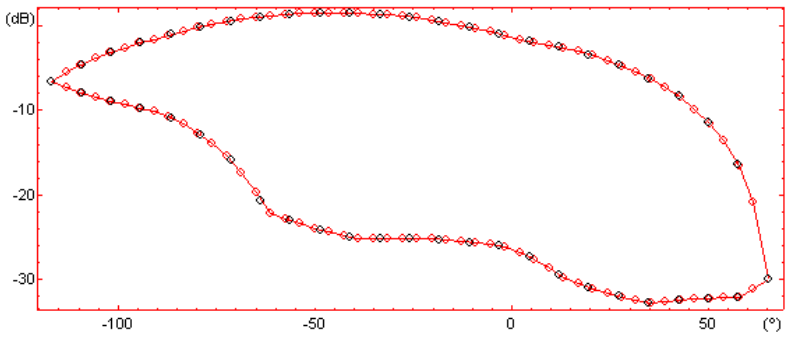

Figure 4.3. $\Gamma_w(1.5)$ *(red colour) computed by the Bailey & Hui algorithm with Nb=50 and* $\Gamma(1.5)$ *(black colour) computed by the same algorithm with Nb=25*

Once the wanted boundaries have been obtained, users should save the work session. Perhaps in the future they wanted to modify the template boundaries, or obtain boundaries at new frequencies. Remind that the `Save work session` entry of the `Settings menu` must be used for getting that.

Likewise, users can export the template boundaries, which are saved in the *Saved Templates* zone, to QFTIT or Matlab. They must use the corresponding entries of the `Settings` menu.

4.1.2.2 Studying of the template shape in function of the frequency

A basic rule of the QFT methodology says: "The bound associated to a certain specification will change if the template shape changes". Therefore, it is only necessary to consider those frequencies where the template shape appreciably changes. Thus, the studying of the template shape in function of the frequency can be very useful in order to select the proper work frequency set.

The TIG interactivity easily allows to do this studying. Users have only to do the following steps:

1) Click on the square box `Move frequencies`. It is located at the upper part of the *Frequencies* zone. Remind that this square box will only be visible if the computational load is light

2) Locate the mouse pointer over a vertical segment in the frequencies axis which is associated to a certain work frequency.

3) In order to increase or decrease ω_w, drag the associated vertical segment to the left or the right, respectively. Remind that the *Saved Templates* zone and the `Work Template` zone simultaneously show $\Gamma(\omega_w)$ and $\Gamma_w(\omega_w)$, respectively.

For this example, the template shape is going to be analysed at the frequency range [0.001, 1000] (rad/s). As the current frequency range is [0.1,100] (rad/s), this must be changed. Users have to select the `Template frequency range` option in the `Frequency range` entry belonging to the `Settings` menu. A dialog box will appear. Users have to write `0.001,1000`, and then click on OK.

Once the new frequency range has been configured, users must click on the square box `Move frequencies` in order to be able to drag the segments associated to the work frequencies in the *Frequencies* zone. If users drag the segment located at ω=1.5 rad/s to the left till 0.001 rad/s, they will see in the *Saved Templates* zone that the $\Gamma(\omega_w)$ shape tends to a vertical line located at 0º (see Figure 4.4). However, the *Work Template* zone shows the real shape of $\Gamma_w(0.001)$. It has a width lower than 1º.

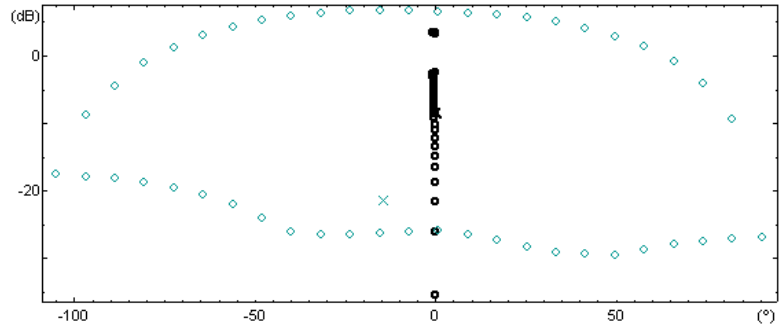

Figure 4.4. $\Gamma(0.001)$ (black colour) and $\Gamma(3)$ (blue colour) computed by the Bailey & Hui algorithm with Nb=25

Besides, if users drag the segment located at ω=3 rad/s to the right, They will observe that TIG is not able to compute $\Gamma(\omega_k)$ in the range [3.7,12.2] (rad/s). Some values combinations of the uncertain plant parameters make the plant denominator equal to 0, i.e, the template is not bounded. Users are easily aware of this situation because the upper indicator of the *Status* zone is in colour red, and it shows the message `Template: Error!`. Likewise, the *Work Template* zone is empty.

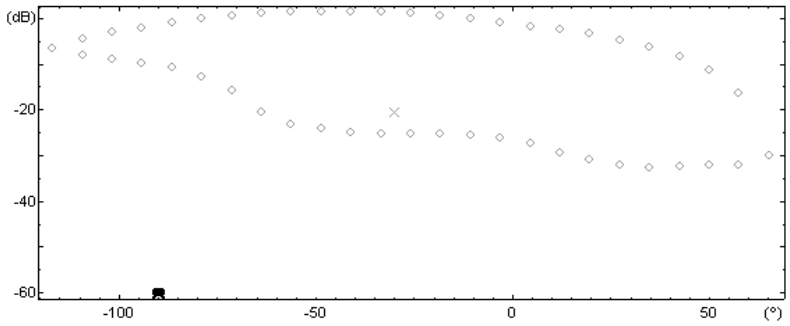

Figure 4.5. $\Gamma(1.5)$ (grey colour) and $\Gamma(1000)$ (black colour) computed by the Bailey & Hui algorithm with Nb=25

Finally, if users move the segment toward frequencies greater than ω=12.1 rad/s, the width and length of the template will decrease. The template looks like a small point at ω=1000 rad/s in the *Saved Templates* zone. In fact, $\Gamma_w(1000)$ has a small area in the *Work Template* zone. Its magnitudes and phases are contains in the range [-60.00, -59.99] dB and [-90.41º, -89.27º], respectively. Remind that the coordinate of a template point can be read in the *status bar* after placing the mouse pointer over it.

4.1.2.3 Studying of the template nominal point in function of the plant uncertain parameters nominal values

TIG allows to study the positions of the template nominal point and the poles and zeros of the nominal plant in function of the plant uncertain parameters nominal values.

In order to do this studying, the *Nominal Poles-Zeroes map* must be shown in the TIG window. Remind that this zone can be visualised selecting the `Show nominal poles-zeroes map` option associated to the `Options plot` entry of the menu `Settings`.

Users first must write the number *j* of the uncertain parameter p_j in the field `#` belonging to the *Plant Uncertain Parameters* zone. Second, they have to drag the black vertical segment (associated to p_j^0) in the slider `p(#)` to left or right. The field `pnom(#)` simultaneously shows the nominal value that it is being configured by the users. The nominal point of each template (represented with the symbol '`x`') is also simultaneously moved in the *Saved Templates* zone. Likewise, the poles ('`x`') and the zeroes ('`o`') of the nominal plant are displaced in the *Nominal Poles-Zeroes map* zone.

Let us suppose that the tool has been restarted pulsing the keys [ctrl]+[n], and that users have set the value 1 in the field # belonging to *Plant Uncertain Parameters* zone. In this case, the other fields of this zone show the maximum, nominal and minimum values of the plant parameter p_1: 19.8, 10 and 2.3, respectively. Remind that TIG starts with the plant (4.1) by default.

If users place the mouse pointer over the nominal point of a certain template in the *Saved Templates* zone, its coordinates are shown in the status bar: [-30.16º,-20.39 dB] for $\Gamma(1.5)$ and [-14.58º,-21.35 dB] for $\Gamma(3)$.

Likewise, it can be observed in the *Nominal Poles-Zeroes Map* that the nominal plant has two real zeroes (s=-6.55, s=-1.45), a real pole (s=-0.26) and a pair of complex poles (s=-4.87$\pm$ j·8.59). These values can also be read in the status bar following a similar procedure to the previously explained for the template nominal point

In the slider p(#), if users drag the black segment (associated to p_1^0=10) to the left till the blue segment (associated to $p_1^{\min}$=2.3), they will observe how the nominal points of $\Gamma(1.5)$ and $\Gamma(3)$ move to the right approximately following a straight line. Their new coordinates are [-23.44º,-20.47 dB] and [0.29º,-21.18 dB], respectively. The complex poles has also been moved to the right, now s=-1.02$\pm$ j·9.92.

On the other hand, if users drag the black segment (associated to p_1^0=10) to the right till the red segment (associated to $p_1^{\max}$=19.8), they will observe how the nominal points of $\Gamma(1.5)$ and $\Gamma(3)$ move to the left. Their new coordinates are [-38.73º,-20.46 dB] and [-30.49º, -22.31 dB], respectively. The complex poles have also been moved to the left. Now, they have been transformed in two real poles s=-10.52 and s=-9.015.

Similar analysis can be done with the other plant uncertain parameters.

4.1.2.4 Studying of the template shape in function of the plant parameters uncertainty

TIG allows to study the template shape variation in function of the plant parameters uncertainty.

Let us suppose that the tool has been restarted pulsing the keys [ctrl]+[n]. Remind that TIG starts with the plant (4.1) by default.

If users place the mouse pointer over the extremes points of $\Gamma_w(3)$, they can check that $\Gamma_w(3)$ has a width of 195.41º and a length of 36.16 dB.

If users want to study how the $\Gamma_w(3)$ shape changes in function of p_5, they have to do the following actions: First, set the value `1` in the field `#`. Second, change the Nichols chart scale to fix mode (`Fix scale` option of the `Settings/Options plot` menu). Finally, drag the blue segment (associated to $p_5^{\min}$) and the red segment (associated to $p_1^{\max}$) till located over the black segment (associated to p_5^0). The difference between these three values is about 0.0001. Therefore, the parameter uncertainty is negligible. Users can observed in the *Work Template* zone that the $\Gamma_w(3)$ width has been reduced to 174.07, while the $\Gamma_w(3)$ length has been lightly modified to 35.4.

Similar analysis can be done with the other plant uncertain parameters.

4.2 EXAMPLE 2

This second example considers the plant originally proposed in [Fu, 90]:

$$P(s,p)=\frac{s^2+(0.4\cdot p_1+0.2\cdot p_2+4)\cdot s+(p_1-p_3+20)}{s^3+(0.5\cdot p_1-0.5\cdot p_2+0.5\cdot p_3+9.5)\cdot s^2+(2.0\cdot p_1+p_2+27)\cdot s-p_1+p_3+22.5} \tag{4.5}$$

It has three uncertain parameters

$$\{p_1, p_2, p_3\} \in [-3,3] \tag{4.6}$$

whose nominal values are:

$$p_1^0=1.5,\ p_2^0=-1.5,\ p_3^0=1.5 \tag{4.7}$$

The work frequencies set is

$$\Omega=\{0.2, 1, 3\}\ \text{(rad/s)} \tag{4.8}$$

The problem consists in obtaining the boundaries of $\Gamma(0.2)$, $\Gamma(1)$ and $\Gamma(3)$.

The numerator and denominator of the transfer function (4.5) have the same uncertain parameters. In this case, the Bailey & Hui algorithm generates conservative template boundaries. Therefore, another algorithm must be used. Users can check that the best

selection is the Fu algorithm. Thus, this second example is going to be used for learning to do the same actions in TIG:

- Compute and study the template boundaries using the Fu algorithm.
- Tune the configuration parameters (*Weight*, *Factor X*, *Factor Y*) of the ε-algorithm.
- Remove template points

4.2.1 Configuration

All the information about the problem has to be entered in TIG by users. Thus, first the tool must be started doing double click on the file `tig.exe`. Then, they must click on the Configuration radio button of the *Work Mode* zone in order to TIG goes to the configuration mode.

4.2.1.1 Step 1: Configuration of the plant uncertain parameters

A possible way of doing this step is click on the `Configure` button in the *Configurations Steps* zone. The dialog box `Plant uncertain parameters` will appear on the TIG window. Remind that this dialog box allows to configure the minimum, nominal and maximum values of the plant uncertain parameters. According to (4.6) and (4.7), users have to fill the dialog box with:

```
[-3 3 1.5; -3 3 -1.5;-3 3 1.5]
```

and then click on `OK`. TIG automatically go to the step 2.

4.2.1.2 Step 2: Configuration of the plant denominator

In order to configure the plant denominator, users have to pulse the button `Configure` in the zone *Configuration Steps*. The dialog box `Plant denominator` will appear on the TIG window. According to (4.5), users have to write

```
'1,0.5p(1)-0.5p(2)+0.5p(3)+9.5,2.0p(1)+p(2)+27,-p(1)+p(3)+22.5'
```

and click on `OK`. TIG will automatically go to the step 3.

The *Plant transfer function* zone shows the plant denominator. Two red triangular handlers also appear at the bottom of the zone, because the denominator expression width

is greater than the zone width. Users can click on the triangular handler to move the denominator expression to left or right. Thus, they can see all the denominator terms.

4.2.1.3 Step 3: Configuration of the plant numerator

In order to configure the plant numerator, users have to pulse the button `Configure` in the zone *Configuration Steps*. The dialog box `Plant numerator` will appear on the TIG window. According to (4.5), users have to write

```
'1,0.4p(1)+0.2p(2)+4,p(1)-p(3)+20'
```

and click on `OK`. TIG will automatically go to the step 4.

4.2.1.4 Step 4: Configuration of the work frequencies set

The plant (4.5) has no integrators and no derivators. Therefore, users have not to enter any value in the field `Ni` of the *Plant Transfer Function* zone.

In this point of the configuration mode, users should save the work session. They have only to click on the `Save work session` option (which belongs to the `Load/Save` entry of the `Settings` menu), and write the file name where they wants to save the work session. For example, `example2_conf.ses`.

In order to configure the work frequency set Ω, users must click on the `Configure` button located in the *Configuration Steps* zone, write the elements of Ω (see (4.8))

```
[0.2,1,3]
```

in the dialog box `Template frequency vector`, and finally click on `OK`.

4.2.2 Analysis

4.2.2.1 Obtaining and studying of the template boundaries

Once the users have completed the step 4 of the configuration mode, TIG automatically goes to the analysis mode (see Figure 4.6). $\Gamma(0.2)$ (grey colour), $\Gamma(1)$ (bluish green colour) and $\Gamma(3)$ (black colour) are drawn in the *Saved Templates* zone. These three templates have been computed by the Bailey & Hui algorithm with *Nb*=25. The current work frequency is ω_w=3 rad/s (see the field `w` located in the `Work Template` zone).

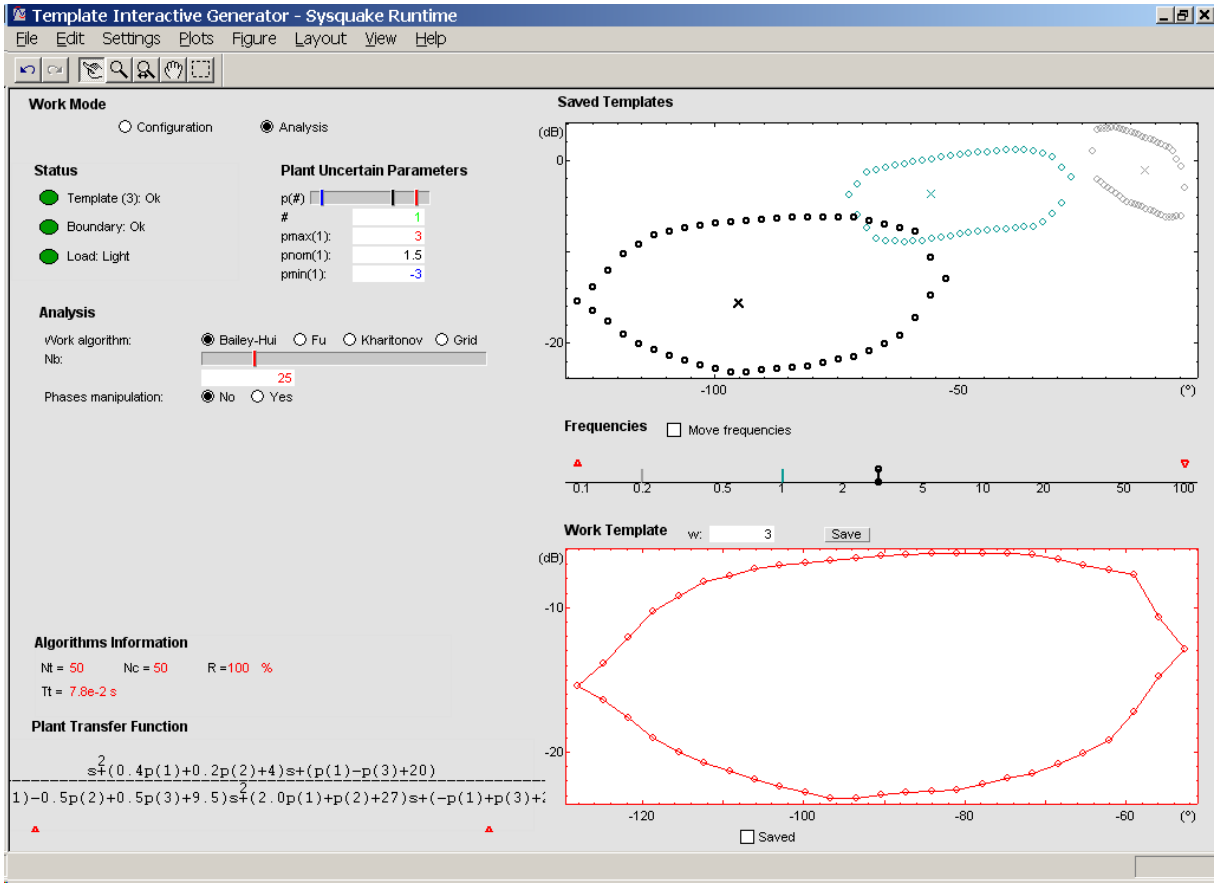

Figure 4.6: Initial aspect of the TIG window in the analysis mode for this example

For computing $\Gamma_w(3)$ by the Fu algorithm, users have to click on the `Fu` radio button of `Work Algorithm` in the *Analysis* zone. Instantaneously, the $\Gamma_w(3)$ points (green 'o') are drawn in the *Work Template* zone. The $\Gamma_w(3)$ boundary (green solid line) is also drawn. The used configuration parameters are the default values, i,e, *Nf*=5, *Weight*=1, *Factor X*=1 and *Factor Y*=1. Users can observed that the obtained $\Gamma_w(3)$ boundary is not correct, because it is not include all the points belonging to the $\Gamma_w(3)$ right side. They can check that doing *Weight*=0.16 and *Factor X*=5, the correct $\Gamma_w(3)$ boundary is obtained.

In the *Algorithms Information* zone, users can read the following data: N_t=60, N_c=21, *R*=35 %, T_t=0 s[3] and T_c=0 s

A analysis of the $\Gamma_w(3)$ boundary is going to be done. The goal is knowing whether it is necessary to increase or whether it is possible to decrease the number of points belonging to the $\Gamma_w(3)$ boundary. To do this analysis, users have to follow these steps:

[3] T_t=0 s (or T_c= 0s) is only a notation which means that $T_c<10^{-2}$ s (or $T_t<10^{-2}$ s).

1) Pulse the `Save` button to save $\Gamma_w(3)$. Remind that this button is located at the top of the *Work Template* zone.

2) Click on the `Saved` square box located at the bottom of *Work Template* zone. The $\Gamma(3)$ points are drawn in black colour in the Nichols chart.

3) Drag the `Nf` slider, which is located in the *Analysis* zone, to the right to increasing *Nf*. Users can simultaneously observed that N_t and N_c increase. However, the boundary shape does not significantly change. *Nf*=8 is perhaps a good value. It do N_t=96 and N_c=36.

Once users have finished the analysis, they have to click on the `Saved` square box. Thus, $\Gamma(3)$ is not drawn in the *Work Template* zone. In order to remove the interior points of $\Gamma_w(3)$, users first must to click on the `Select(All)` radio button of `Operate on interior points` in the Analysis zone, and then click on the `Remove` button. Therefore, now only the $\Gamma_w(3)$ boundary is drawn in the *Work Template* zone. It must be saved in the *Saved Templates* zone. Users have only to pulse the button `Save`.

Moreover, it is easy to check that the Bailey & Hui algorithm generates at conservative boundary if the numerator uncertain parameters are dependent of the denominator uncertain parameters. The plant (4.5) is an example of this situation. Users have only to click on the `Bailey` square box located at the bottom of the *Work Template* zone. Thus, the points of the $\Gamma_w(3)$ computed by the Bailey & Hui algorithm, and the $\Gamma_w(3)$ boundary computed by the Fu algorithm and the ε-algorithm are represented in the Nichols chart (see Figure 4.7).

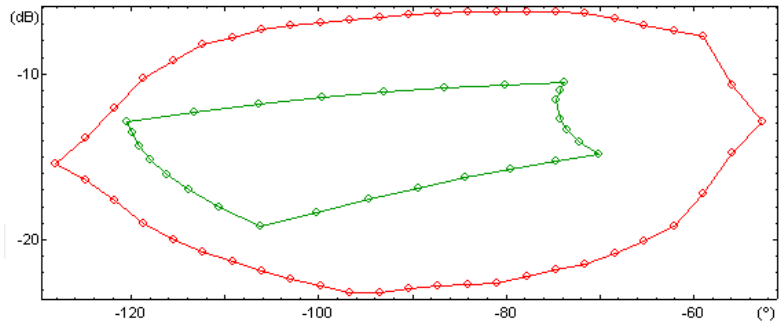

Figure 4.7. $\Gamma_w(3)$ (red colour) computed by the Bailey & Hui algorithm (Nb=25), and $\Gamma_w(3)$ (green colour) computed by the Fu algorithm (Nf=8) and the ε-algorithm (Weight=0.16, Factor X=0.16)

In order to change the work frequency to ω_w= 1 rad/s, users have to click on the blue segment in the *Frequencies* zone. The Saved Templates zone now shows $\Gamma(1)$ in black colour. Likewise, the *Saved Templates* shows $\Gamma_w(1)$ in green colour. Remind that $\Gamma(1)$ and $\Gamma_w(1)$ was computed by the Bailey & Hui algorithm (with *Nb*=25) and the Fu algorithm (with *Nf*=8). However, the $\Gamma_w(1)$ boundary has not been drawn. This means that the ε-algorithm has not been able to find the boundary with *Weight*=1, *Factor X* =1 and *Factor Y*=1. Therefore, these values must be suitably tuned.

For example, a boundary appears if *Weight* is decreased to 0.37.However, the $\Gamma_w(1)$ points placed at the right lower extreme do not belong to this boundary. Users can try to improve the boundary decreasing *Weight* even more, but no improvement will be obtained. In fact, the boundary will disappear. Another option is to increase Factor X, i.e., to bring nearer the template points in the x-axis. users can check that a good boundary appears if *Factor X* is increased to 4.

Users can analyse if it is possible to decrease the number of points belonging to the $\Gamma_w(1)$ boundary, without changing its shape. To do this studying, they have to do the following actions: First, pulse on the `Save` button. Second, click on the `Saved` square box. $\Gamma(1)$ will been drawn in black colour in the *Work Template* zone. Third, drag the `Nf` slider to the left in order to decrease `Nf`. Users can check that *Nf*=5 is a good value.

Once users have finished this analysis, the interior points of $\Gamma_w(3)$ must be removed. The way to do this action has been previously explained in this section. Figure 4.8 shows the $\Gamma_w(1)$ boundary. It must be saved in the *Saved Templates* zone.

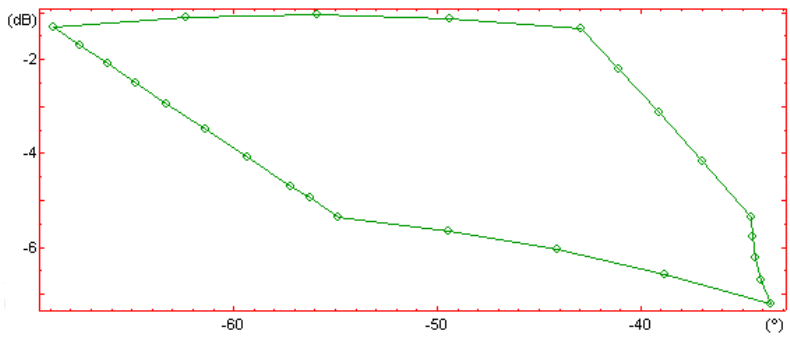

Figure 4.8. $\Gamma_w(1)$ boundary computed by the Fu algorithm (Nf=5).

Finally, users have to obtain the $\Gamma(0.2)$ boundary. In order to change the work frequency to ω_w= 0.2 rad/s, users have to click on the grey segment in the *Frequencies* zone. They can check that the wanted boundary (see Figure 4.9) is obtained with *Nf*=5, *Weight*=1, *Factor X*=1 and *Factor Y*=1.

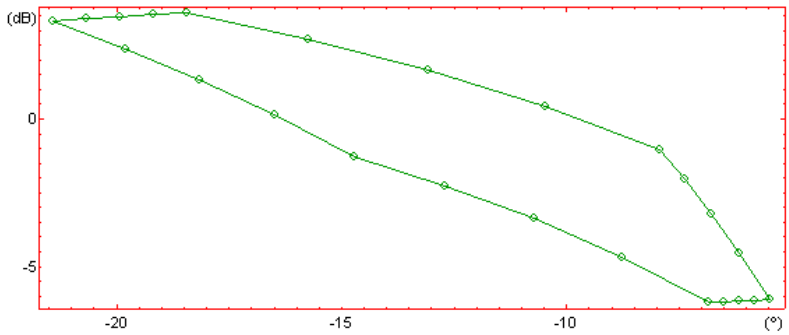

Figure 4.9. $\Gamma_w(0.2)$ boundary computed by the Fu algorithm (Nf=5).

Once the wanted boundaries $\Gamma(0.2)$, $\Gamma(1)$ and $\Gamma(3)$ have been obtained, users should save the work session. Remind that the `Save work session` entry of the `Settings menu` must be used for getting that.

Likewise, users can export the template boundaries, which are saved in the *Saved Templates* zone, to QFTIT or Matlab. They must use the corresponding entries of the `Settings` menu.

4.3 EXAMPLE 3

In this example, we can see the following actions with TIG:

- Import templates from Matlab
- Calculate the boundaries of these templates
- Export the obtained boundaries to Matlab.

4.3.1 Import templates from Matlab to TIG

When the templates are calculated in Matlab, the following variables are in the Matlab workspace:

- `P`. Complex matrix (real and imaginary part of a point in the complex plane), each column is associated to a template.
- `w`. Row vector with the frequencies $\omega_i \in \Omega$ (in rad/s) of each templates.
- `nompt`. Integer number that it is the row of matrix `P` with the points of the templates associated to nominal plant.

Furthermore, if users want export the templates from TIG to QFTIT, the following variables are additionally necessary:

- `numP0`. Row vector with the numerator coefficients of the nominal plant.
- `denP0`. Row vector with the denominator coefficients of the nominal plant.

To export this information to TIG, it is necessary a `.tmp` file with all variables in the format described in the section 3.2.2. This file can be created by the function `mat2tig.m` that is distributed together with TIG. The directory `/tig/fmat` with this function must be added to Matlab path.

For example, supposing that TIG is located in the hard disk `F:` inside of the `tig` directory, this function can be invocated in the following way:

```
» mat2tig('F:\\tig\data',P,w,nompt)
```

or

```
» mat2tig('F:\\tig\data',P,w,nompt,numP0,denP0)
```

The file `data.tmp` is created in the directory `tig`.

Now, this file can be load into TIG. For this, select `Import templates from Matlab` in the `Import/Export` entry of `Settings` menu. A dialog box is shown to select the file to load into TIG, in this example is `data.tmp`.

Figure 4.10 shows the TIG window *after importing* *`data.tmp`*. Users can see that some items have been removed from the TIG window. Thus, the upper circular indicator associated to the templates has been removed from the *Status* zone. The `Work Algorithm` radio buttons and the slider (and the field) associated to the work algorithm configuration have been also removed from the *Analysis* zone. Likewise, the computing time T_t of the work

template is not showed in the *Algorithm Information* zone is not displayed. Finally, the message "`TF is not available`" is shown in the *Plant Transfer Function* zone. Obviously, all of these elements are not necessary yet, because the templates were calculated in Matlab.

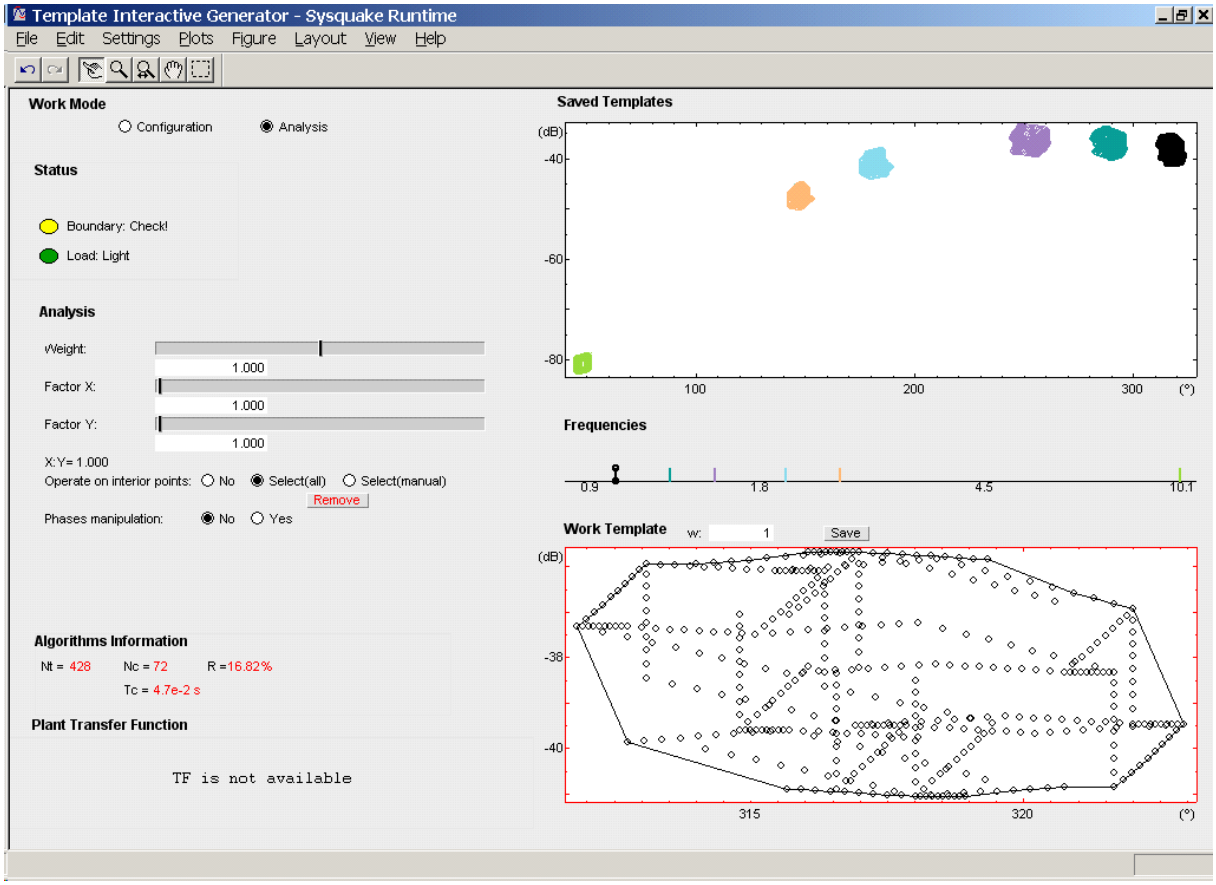

Figure 4.10. Aspect of the TIG window after importing `data.tmp`

Users must bear in mind that when the templates are imported from Matlab, the frequencies in the *Frequencies* zone are fixed, and it is not possible to write values in the box `w` of *Work Template* zone.

4.3.2 Calculate the boundaries of imported templates

According to the *Saved Templates* zone in Figure 4.10, six templates have been imported. In the *Work Template* zone, the points of $\Gamma_w(1)$ are marked in black, and the boundary of $\Gamma_w(1)$ is drawn in black solid line.. The following information is shown in the *Algorithm Information* zone: N_t=428, N_c=72, R=16.82 % y T_c=4.7·10^{-2} s.

The boundary obtained by the ε-algorithm (considering the default values of *Weight*, *Factor X* and *Factor Y*) is correct. Therefore, it is not necessary to tune the configuration parameters. Now, the interior points must be removed. Users have to do the following actions: select the `Select(all)` option of `Operate on interior points` of *Analysis* zone, and click on `Remove` bottom. In the *Work Template* zone, the points of the $\Gamma_w(1)$ boundary are only drawn.

Users can see that some sides of the $\Gamma_w(1)$ boundary can remain defined using a fewer number of point. TIG allows to manually remove some template boundary points. Users have to do the following actions: First, select the `Select(manual)` option of `Operate on interior points` in the *Analysis* zone. Second, holding down the mouse left button, draw a rectangle which enclose the points. Finally, click on the `Remove` button. Following this procedure, a boundary with N_c=18 (see Figure 4.11) can be obtained.

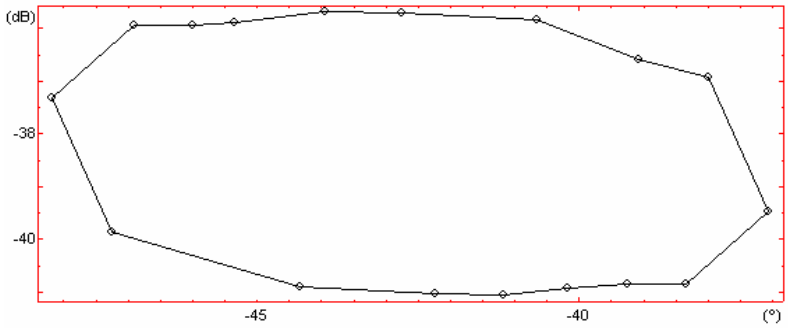

Figure 4.11.Boundary of $\Gamma_w(1)$

It can be observed that that the template boundary phase range [310º, 325º] is out of the usual Nichols range [-360º, 0º]. TIG allows to add or subtract 360º to the template points. Users have to click on `Yes` of `Phases manipulation` option of *Analysis* zone and click one time on -360º button. The phase range is move to [-50º, -35º].

The boundary must be saved in the *Saved Templates* zone. For this, users have to click on the `Save` button.

A similar procedure can be followed to obtain the boundaries of the other five templates.

The work session should be saved for use in the future. For this, click in `Save work session` option of `Settings` menu.

4.3.3 Export template boundaries from TIG to Matlab

In order to export the boundaries to Matlab, users have to do the following actions: First at all, a `.tmo` file must be create which contains the boundaries saved in the *Saved Templates* zone. To create this file, users must click on the `Export templates to Matlab` option belongings to the `Import/Export` entry of the `Settings` menu, write the file name in the dialog box (for example `templates.tmo`), select the directory, and click `OK`.

Second, load the boundaries into the Matlab workspace from the `templates.tmo`. Users can use the function `tig2mat.m` to load this file in Matlab.

For example, supposing that TIG is located in the hard disk `F:` inside of the `tig` directory, this function can be invocated in the following way:

```
>>[P,w,nompt]=tig2mat('F:\\tig\templates');
```

The meaning of `P`, `w` and `nom` was explained in section 4.3.1.