ACTA tools as an integrated teaching assistant for the Design of Automatic Flight Control Systems

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Abstract: - ACTA I and ACTA II are two user friendly tools for teaching Automatic Control Systems, based on Matlab. ACTA tools greatly facilitate the design of Electronic Flight Control Systems. In this paper the ACTA tools and their functions are initially introduced; then a case study demonstrating how a typical modern aircraft control system may be analyzed and redesigned using the ACTA tools is presented. The paper concludes by summarizing the ACTA tools advantages, as well as, our future plans. The ACTA tools are available for free downloading through our wiki.

Key-Words: - Control systems, aircraft control, Electronic Flight Control systems, EFCS, ACTA tools, GUI, ACTA tools tutorial, Bloom's taxonomy.

1 Introduction

The Division of Automatic Control and Aerodynamic Systems offers an automatic control course to the Aircraft Engineering seniors of the Hellenic Air Force Academy of Greece (HAFA). The course is called "Aircraft systems, stability and control" [1], [2]. The average student population ranges from 25 to 30 cadets.

At the beginning of the course students have a background on mathematics, physics, mechanical, electrical and aeronautical engineering, electronics and programming. The introductory control systems course covers the following topics:

- Input-output and state space analysis of single-input single-output (SISO) control systems;
- Quantitative and qualitative analysis of MIMO control systems;
- The Root–Locus and frequency domain control design techniques;
- State space design method;
- Optimal control; and Adaptive control.

This course focuses on teaching and analysing dynamic stability and control of unstable multivariable dynamic systems, as well as, the design of Electronic Flight Control Systems (EFCS). In particular, emphasis is given on modern aircrafts and aerospace structures. These engineering systems demonstrate high structural instability.

The control systems course has the following objectives:

- To teach cadets the fundamentals of automatic control systems design and analysis, as well as the design methods of computer-aided control;
- To support learning by computer-aided control design and simulation examples;
- To minimize the gap between control theory and practice, by teaching control implementtation;
- To facilitate cadets to computer-aided design and testing of electronic flight control systems of modern aircrafts, used by the Hellenic Air Force;
- To enable students to design stable systems and to redesign existing systems for improved stability;
- Furthermore, to cultivate higher-order thinking such as analysis, synthesis and evaluation.

Automatic control courses are appropriate for higher education because they deal with the analysis, synthesis and evaluation of complex dynamic systems. A characteristic of automatic control courses is that they require extensive calculations. Only after a lot of tedious and error-prone calculations may a student decide on the stability of a system. Given that course duration, cadet study time and exam time are limited, it is rather impossible for students to study a modern, real EFCS in depth.

However, the goal of the course is not to give emphasis on calculations, but rather on engineering education, focused on the design of real systems. In order for cadets to cultivate the higher-order thinking mechanisms according to Bloom's taxonomy (Figure 1), they need to save time from calculations and spent it in the analysis, synthesis and evaluation of complex dynamic systems.

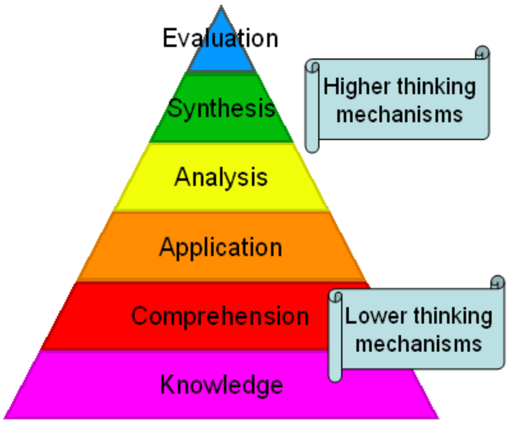

Fig. 1. Bloom's taxonomy and thinking mechanisms

Educational and research software such as Matlab and Simulink can alleviate this situation. Matlab is a widely used tool in education and research [3], [4]. The analysis of performance, stability and control characteristics of dynamic systems can effectively be done using appropriate Matlab models [5], [6], [7]. Computer-aided control system design and simulation improves the efficiency of learning the fundamental principles as well as the industrial practices of control theory.

Unfortunately this solution is costly since it requires a lot of licenses. Fortunately, there are at least two alternatives:

a) The use of Free and Open Source Software (FOSS) Matlab substitutes such as Sage, SciLab, Octave and EngLab [8].
b) The development of Matlab-based software tools supporting engineering education (see for instance [9]-[14]).

This paper presents two comprehensive and user-friendly tools called the Automatic Control Teaching Assistants (abbreviated as **ACTA**) **I** and **II**, which perform complex Automatic Control Systems calculations and graphs in a user-friendly fashion. In fact, ACTA II was firstly presented in ref. [1] in 2009; also ACTA I tool was presented in ref. [2] in 2010; since then, new features have been added to both tools, which will be presented in this paper.

Using these two tools, instructors and students can design and optimize aircraft control systems in minutes; students can also use these tools in order to study the impact of various parameters in system stability and performance, and compare the different stability criteria.

Next, a case study referring to a real EFCS is presented; this case study, which is rather complex compared to previously presented [1], [2], calls for repetitive use of the ACTA I and II tools. The case study demonstrates: a) the features of the ACTA tools; b) their usage; c) that a complex system may be solved in a few minutes, saving time and effort and preventing from possible errors in calculations. ACTA tools enable the students to evaluate the effect of various parameters on the performance, stability and control of modern supersonic airplanes, cultivating the higher-order thinking mechanisms according to Bloom's taxonomy.

2 Brief presentation of the ACTA I tool

The ACTA I tool accepts the block diagram of a control system as a series of transfer functions (in fractional format); then, it computes the open-loop and closed-loop transfer functions of the overall system.

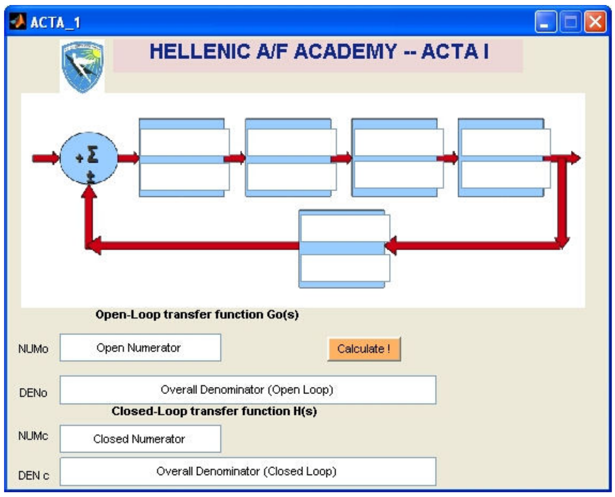

Fig. 2. Introductory screen of the ACTA I tool

As we can see from Figure 2, ACTA I allows the user to enter the coefficients of a control system consisting of up to four blocks in the forward path and one block in the feedback path. By entering the coefficients as Matlab matrices and pressing the "Calculate" button, ACTA I calculates the numerators and denominators of the overall transfer function of the whole system, both open-loop and closed-loop. The user can then take these results (i.e., the open-loop numerator and denominator) and enter them manually in the ACTA II tool for further calculations. Thus the tools can be used in combination.

In case the system has less than four blocks in the forward path, the empty boxes must be filled with 1's, as shown in Fig. 6 below. Should a system need more than four blocks, two or more of them must be combined in one.

The ACTA I tool consists of 600 lines of code approximately, including comments.

3 Brief presentation of the ACTA II tool

The purpose of the ACTA II tool is to facilitate the design of aircraft control systems by evaluating and displaying classic control system stability criteria quickly, easily, graphically and accurately. This is done by exploiting the powerful computational and graphical functions of Matlab [4]-[7]. It is constructed using the embedded Matlab tool for building GUIs, called "Guide" [15].

Figure 3 shows the start-up window; the user is prompted to enter the numerator and denominator polynomial coefficients of an open-loop control system in the appropriate boxes. Then he/she can select a pull-down menu under the label "**Select diagram type**" (Fig. 3). The name of each item gives information on the actions carried out. The following options are available [1], [2]: Bode diagrams; Nyquist diagram; Nichols chart; root-locus diagram; root-locus with a coordinate finder tool and root-locus with a coordinate finder tool and zoom capability. The latter is a new feature added recently (see below).

Option "root-locus" allows users to check the gain, coordinates, damping factor, overshoot and frequency, by moving the mouse pointer on the curves (see [2], paragraph 5). Finder tool options enable users to click on a specific point on the root locus curves and get the step response at that particular point; in this way users can check system stability [1].

After selecting an option, the user must press the "**Calculate**" button to see the corresponding diagram. This can be done repeatedly with different diagram types, in order for the user to cross-check stability using various criteria. Also, button "**Grid**" toggles the grid.

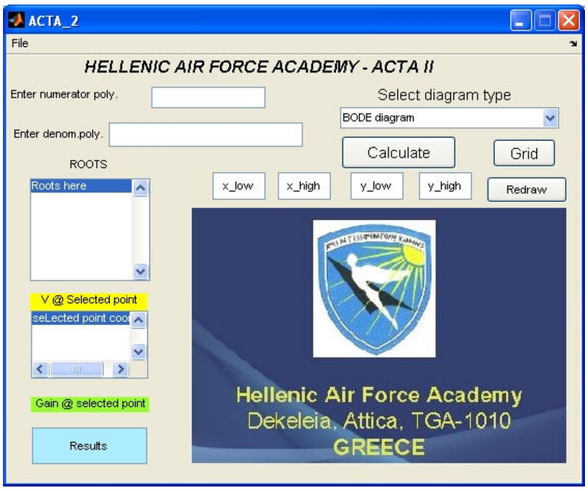

Fig. 3. Introductory screen of the ACTA II tool

During summer 2010, a new feature (not existed in [2]) was added in ACTA II: a zoom function; the user can insert the desired rectangular coordinates in four "edit boxes" and press the "**Redraw**" button in order to view a larger area (zoom out) or a detail (zoom in). This has resulted in a new option in the diagram type called "Root-locus with zoom and finder". In fact, this option gives the user the possibility to zoom-in before clocking on a particular point (to get the step response there), with increased accuracy. The zoom capability is very useful when the poles are very close to point (0,0), as is the case of Figure 7 for instance. In the tutorial below we shall see how useful this zoom-in feature is.

ACTA II tool was demonstrated in class in mid-February, at the first lesson of the spring 2010 semester (February 2010), right after the final exam [2]. It took five minutes for the instructor to solve one the final exam problems using ACTA II, whereas the students took 1h 15' (estimated time) by using calculators! Student assessment of ACTA II performed in March 2010 was very positive and this encouraged us to work more on this subject, developing the companion tool ACTA I. These two tools can be used in combination in order to solve a great number of automatic control problems.

ACTA II tool consists of 650 lines of code approximately, including comments.

4 ACTA tools tutorial

Let us now demonstrate a full example of an aircraft control system design by using the two ACTA tools. We shall examine a typical design problem of a supersonic aircraft steering system (see Fig. 4) from the bibliography [16], [17], [18].

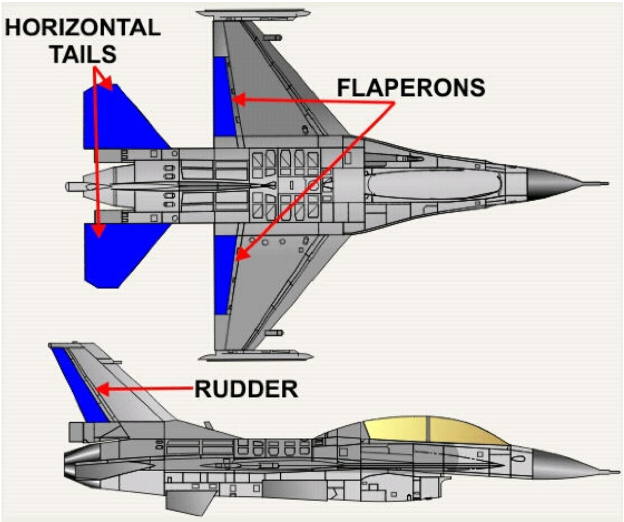

Fig. 4. Modern supersonic aircraft steering system

Assume that the open-loop transfer function consists of the following four terms (Figure 5):

$$\mathbf{Go = Ga(s)Ge(s)Gb(s)F(s)} \quad (1)$$

Where: Ga(s) is the Amplifier transfer function, Ge(s) is the Elevator Servo transfer function, Gb(s) is the aircraft transfer function and F(s) =1 is the vertical gyroscope (gyro) transfer function. The system uses negative feedback.

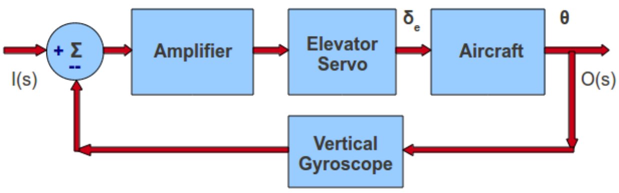

Fig. 5. Longitudinal control block diagram of an airplane

This feedback control system is commonly used for maintaining the command pitch angle of the airplane in a desired reference value.

The elevator servo controls the position δ_e of the elevator control surfaces. The airplane responds to this elevator position to produce an airplane pitch angle θ(s).

Typical transfer functions for an elevator servo and a high-performance aircraft are:

$$Ge(s) = \frac{K}{s+10} \quad (2)$$

$$Gb(s) = \frac{10(s+0.4)}{s(s^2+0.7s+5)} \quad (3)$$

After the calculations we get the following formula:

$$Ga(s)Ge(s)Gb(s) = \frac{10K(s+0.4)}{s(s+10)(s^2+0.7s+5)} \quad (4)$$

Where we have also assumed that Ga(s) = 1 for simplicity. Our mission is to check system stability using classic control methods and the ACTA tools and redesign the system in order to improve its stability.

By entering the above terms in the ACTA I boxes and pressing the “Calculate” button we get that (see Fig. 6):

$$Go(s) = \frac{10s+4}{s^4+10.7s^3+12s^2+50s} \quad (5)$$

Or, in Matlab vector format, Numerator = [10, 4] and Denominator = [1, 10.7, 12, 50, 0], where 0 stands for the constant term.

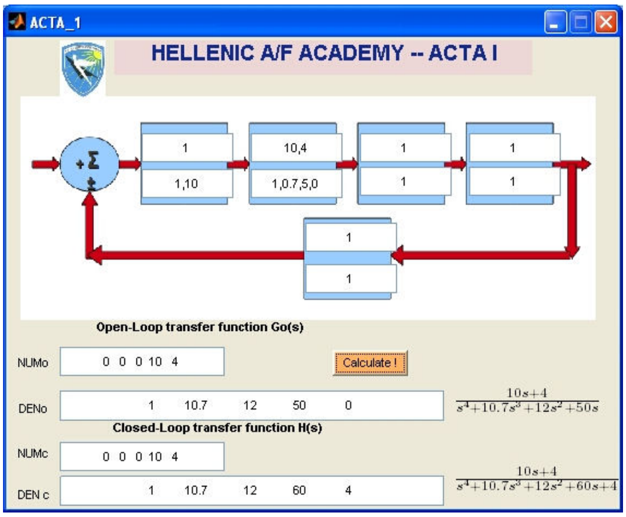

Fig. 6. Transfer function evaluation with ACTA I

ACTA I evaluates both the open and closed-loop transfer functions; it also displays them in the bottom right corner as well (Fig. 6).

The open-loop numerator and denominator polynomial coefficients are exactly in the format required by ACTA II.

The next step is to check system stability using various classic control methods with the ACTA II tool. By entering the evaluated Numerator and Denominator and selecting method (diagram type), we get the following results shown in Figures 7 and

8. The results match that of [16], paragraph 6.3.

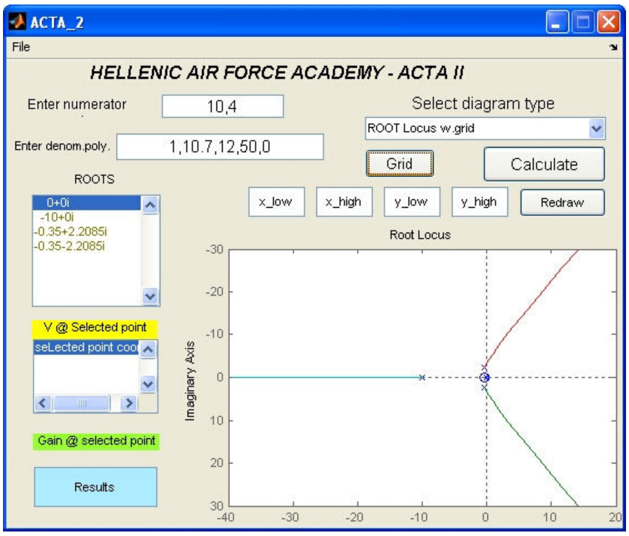

Fig. 7. Root locus diagram

As we can observe, the roots of Go(s) are displayed in the textbox "ROOTS" of ACTA II. Using the new zoom-in functionality (button "Redraw") we can get a better picture of the root locus, displayed in Figure 8.

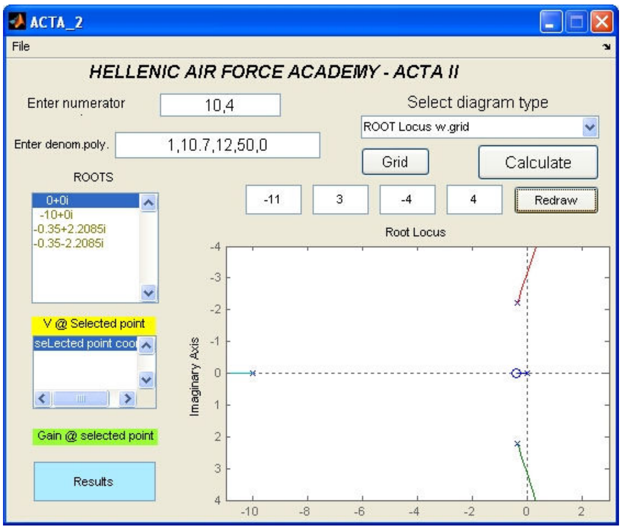

Fig. 8. Getting a zoom-in root locus diagram

From Fig. 8 we can observe that the airplane has a small damping ratio in pitch and as the amplifier gain increases, the closed–loop damping ratio reduces and very soon the airplane becomes dynamically unstable.

Typically, a modern high-performance aircraft has this characteristic, as it is intentionally designed unstable for better performance. Therefore, one has to design a pitch stabilization system to make the airplane closed-loop stable in pitch.

A well-known procedure to obtain a feedback stability augmentation system (SAS) is to connect a Rate Gyroscope in an inner feedback loop as shown in Fig. 9; then, to select the gain of the rate gyro so that the overall system has adequate damping. Let us assume that the transfer function of the rate gyro is 1.

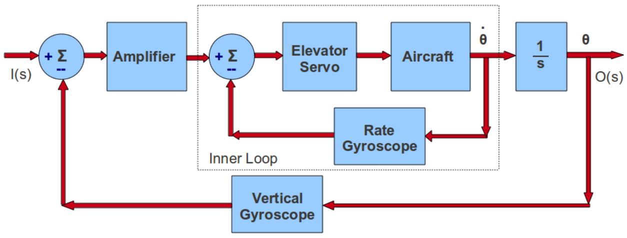

Fig. 9. Pitch displacement with stability augmentation system

Now we use ACTA I to get the transfer function of the inner loop in order to simplify the overall system block diagram (Fig. 10):

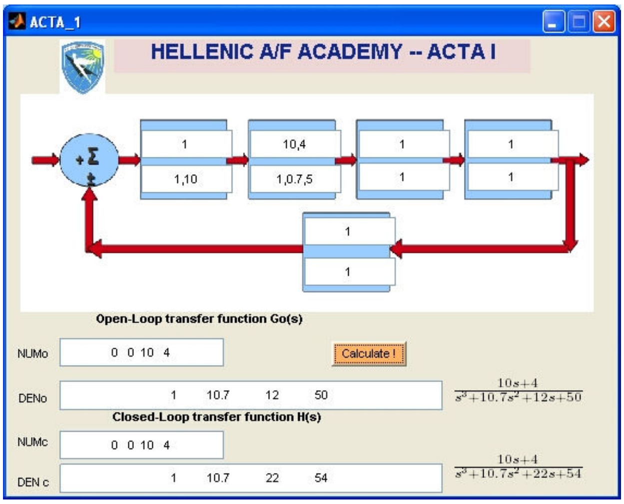

Fig. 10. Evaluation of the transfer function of the inner loop

From ACTA I we get the transfer function of the inner loop which was found to be (Fig. 10):

$$H_{inner} = \frac{10s + 4}{s^3 + 10.7s^2 + 22s + 54} \quad \textbf{(6)}$$

Now we can substitute the inner loop by its closed-loop transfer function and use ACTA I again in order to evaluate the overall system of Figure 9.

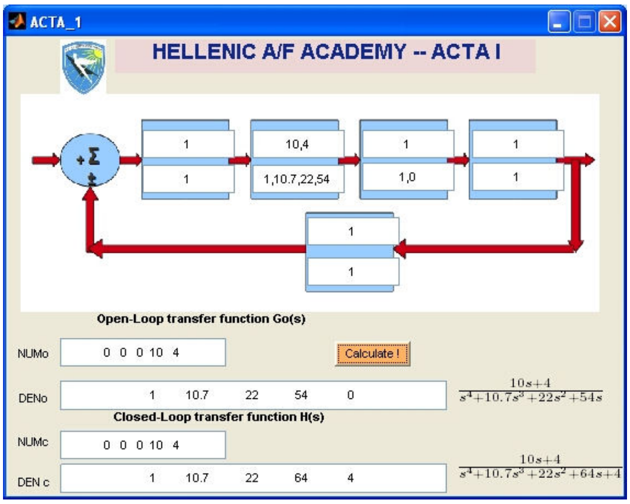

Fig. 11. Evaluation of the transfer function of the overall system

Next we input the open-loop transfer function of the overall system of Figure 9 in ACTA II in order to check its stability.

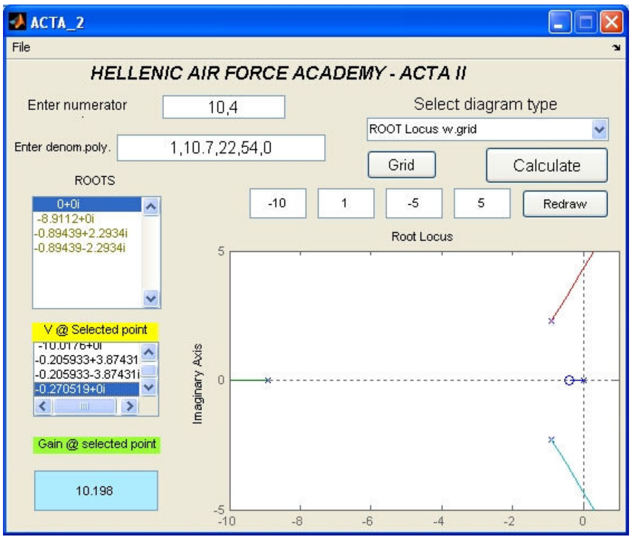

Fig. 12. Root locus of pitch displacement control system with pitch rate feedback

Figure 12 shows the closed loop root locus diagram of the Longitudinal Stability Augmented Dynamic System of the airplane. We can see that the system has an adequate damping rate in order to obtain a satisfactory longitudinal flying quality, when the outer loop is closed.

However, as we can see in Fig. 12, there is a real root near 0. Scrolling down in the middle listbox of ACTA II we find that the root is at -0.270519 (Fig. 12). This root produces a transient pitch response with a long settling time; more compensation must be added if the performance is to be improved.

The introduction of a pole on the negative real axis can improve time response. So we replace the amplifier by a cascade lag compensator [6], [16], [17], [18] with a transfer function of:

$$Gc(s) = \frac{Kc}{s + 0.4} \tag{7}$$

Using ACTA I once more and taking Kc = 1 we evaluate the modified compensated overall system (Fig. 13):

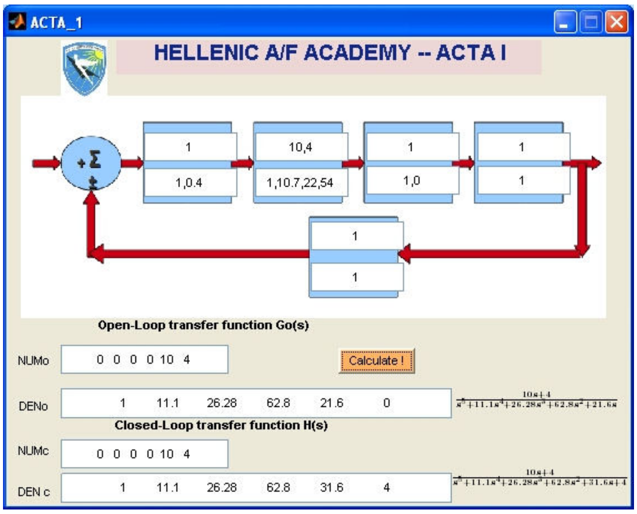

Fig. 13. Evaluation of the transfer function of the compensated system

Fig. 14 shows the modified root locus of the compensated automatic longitudinal flight control system.

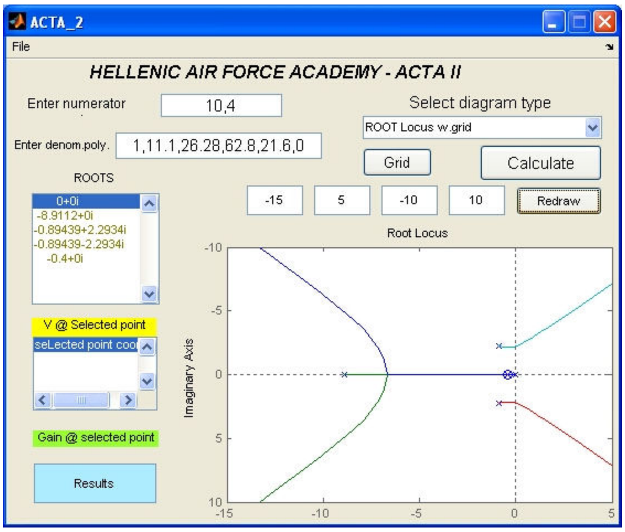

Fig. 14. Root locus of compensated and stability augmented longitudinal flight control system

Possible complex roots obtained from this figure, give the two distinct oscillatory motions of longitudinal response of statically stable airplanes. Thus, the designed longitudinal automatic flight control system with cascade compensation and stability augmentation gives the conventional short–period and phugoid modes with level 1 flying qualities.

To check the design, we can get the step response from within ACTA II, by selecting "Root locus with zoom & finder" from the "Select diagram type" drop down menu; this is shown in Fig. 15. We have selected the zoom option in order to achieve better accuracy. We observe that we have zero steady–state error and the system response is satisfactory.

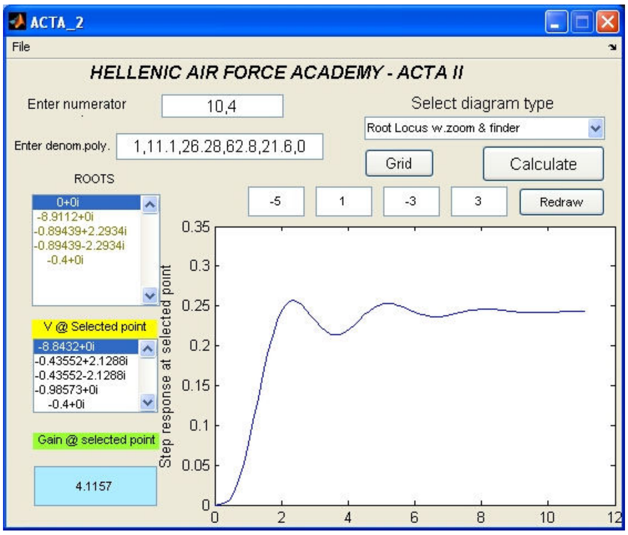

Fig. 15. Step response of the compensated system

This concludes the tutorial. It is obvious that students would have to perform a lot of calculations if they had to solve the problem by hand. This is a major reason for using the ACTA tools.

5 Conclusion

In this paper we have presented the ACTA I and ACTA II tools, which have been developed for teaching automatic control systems and especially EFCSystems, at the HAFA. The major advantages of the ACTA tools are the following:

- They enable the evaluation of control systems in seconds, thus saving time;
- They provide several classic control stability criteria;
- They facilitate the design of optimal control systems;
- They support learning by experimentation, trial-and-error and learning by discovery;
- They use a simple, user-friendly GUI environment;
- They are appropriate for Engineering Education problems, where there is no unique solution but many good solutions;
- They are cost-effective because they can operate as stand-alone applications (see below); otherwise, we would need to buy a number of licenses for our students.

ACTA II was used during the spring 2010 semester for the first time. As the student evaluation has shown, ACTA II was considered a successful tool by the students. We have also presented a tutorial demonstrating the solution of a rather complex problem of our automatic control course, related to the steering control system of a modern supersonic aircraft.

ACTA I and II are appropriate tools for Engineering Education problems, where there is no unique solution but many good solutions [13], [14]. Moreover, they give learners the possibility to experiment with different sets of parameters and stability criteria.

Matlab capabilities of GUI development and release allow us to make stand-alone applications [13]. The ACTA tools are distributed as stand-alone executables, which means that they work even if the students do not have the Matlab platform installed. This is possible with the use of the Matlab compiler [13]. This method solves the cost problem, which nowadays is becoming more and more critical.

The reader can freely download the ACTA tools from the unofficial wiki of the Division of Computer Engineering and Information Science of HAFA (t-h.wikispaces.com/acta_tools) and test them. The authors will be happy to receive feedback from the readers concerning possible errors or improvements; but please bear in mind that they currently are in beta version.

Our future plans include: a) preparation of a User's guide; b) re-evaluation of both tools and c) development of a series of assignments which will help the students gain a better understanding of the Aircraft control systems module, via the ACTA tools.

Acknowledgement

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