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**1-D Hydraulic slider simulation**

BK60A1001 Control of mechatronic machines

Lappeenranta–Lahti University of Technology LUT

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NOTE! Lists of figures and tables are optional.

1. Introduction

This report consists of simulation work done for hydraulic 1-D slider with PID control. Goal of the project has been to build a mathematical model of the system by using Matlab/Simulink. Simulation should provide results that can be replicated with a real physical system. Another goal for the project is to learn and apply knowledge of control systems to simulation of physical systems.

The modelled system consists of a hydraulic cylinder that is actuated by a servo valve. Servo valve has a nominal flow rate of 40,2 L/min and is equipped with linear variable differential transducer. Valve electronics are all embedded into valve. Valve’s input signal range is from -10V to +10V. Hydraulic cylinder is asymmetric double acting cylinder with a max stroke of 1 meter. The hydraulic cylinder actuates a mass of 210kg that’s situated on a slider. Hydraulic pump has a nominal pressure of 25 MPa and the working pressure is 14 MPa. Tank pressure is 0,3 MPa. System has 4 pressure sensors that are used to measure tank pressure, supply pressure and pressure in hydraulic cylinder extension and retraction lines. Displacement sensor is used to provide information about cylinder position.

Data acquisition is done with dSPACE digital signal processor. Input voltage for the valve is fed through DS1103 I/O card. Sampling frequency of the signal processor is 1000 Hz. Hardware of the system is connected to electrical convertor and amplifiers so that that they can be fed to data processing and analysis.

Physical constant values are given to use in formulas which are used to describe the inner workings of the system.

2. Mathematical model

Mathematical modelling is the basis for the simulation. The physical system should be described by mathematical equations that represent actual real-world phenomena. To get accurate result from the simulation small phenomena shouldn’t be ignored and needs to be accommodated into mathematical model. In this project hydraulic valve is assumed to have leakage which needs to be calculated and its effect into system must be modelled. Additionally, friction force of the hydraulic cylinder is modelled using LuGre model. Reason being that static friction models can’t explain real world phenomenon such as stick slip motion, pre-sliding displacement and friction lag. If such phenomena aren’t considered accurate PID control can’t be implemented in a way that can be replicated in real system.

2.1 Motion equations

Kuva, joka sisältää kohteen diagrammi, viiva, kuvakaappaus, Suunnitelma

Kuvaus luotu automaattisesti

Figure 1. Overview of system to be modelled.

Equation of the motion can be expressed with equation:

*(1)*

Where m is the actuated mass, p1 and p2 pressures acting on each side of hydraulic cylinder and A1, A2 respectively the area upon which pressure is acting on each side. Ff is the friction force calculated by the LuGre friction model. Friction force is calculated by following 3 equations.

*(2)*

*(3)*

*(4)*

Values for constants in equations can be found in system constants list.

2.2 Valve equations

Valve is the most complex part of the system that affects everything in the system. As such it is critical that valve is modelled mathematically correctly. Spool movement inside the valve is the most important part of the simulation and hence it needs to be accurate and correct. Spool dynamics can be represented by following formula:

*(5)*

Where u is the input voltage to spool and us is the actual voltage given by linear variable differential transducer. Constants for the equation are available in system constants list.

2.2.1 Valve flow equations

Valve flows can be calculated with following equations:

*(6)*

*(7)*

Valve has two output ports to hydraulic cylinder. Depending on the spool position the equation for calculating the flow is different. Hence there is two equations for both flows. Sign function is used to smooth the flow when changing the flow direction from port A to port B or vice versa.

2.2.2 Valve leakage equations

Leakage in valves is divided in to two separate leakages. The first being internal leakage of the valve and the second external leakage of the valve. Internal leakage of the valve can be calculated with following equation.

*(8)*

External leakage is calculated with following two equations.

*(9)*

*(10)*

Difference between these two leakage types is that internal leakage is the leakage that happens inside the hydraulic system when flow passes through unintended flow passage. Such as small circular gap between valve spool and spool housing. External leakage refers to leakage to outside the system. It is usually caused by loose fitting and damaged seals, but leakage is also an inherent feature of hydraulic systems. Leakage coefficients are available in system constant list.

2.2.3 Valve pressure equations

Pressure equations use calculated flows, piston movement and leakages to calculate the pressure in system.

*(11)*

*(12)*

Bulk modulus for pressure equations needs to be calculated with equation:

*(13)*

Coefficients a1-a3 are available in system constant list. Subscript i indicates values in either port. Pressure equation needs also volume that has a relation to hydraulic cylinder.

2.3 Hydraulic cylinder chamber volumes

Chamber volumes for pressure equations can be solved from following equations.

*(14)*

*(15)*

Where L is the maximum stroke of the cylinder, xp the current position of the cylinder. A1 and A2 respective piston side and rod side areas. Volumes v01 and v02 are the volumes of hydraulic piping/hoses between the valve and hydraulic cylinder.

3. System modelling

System was modelled with Matlab/Simulink. To begin with system constants were defined in .m file script. The advantage of using .m file with system constants rather than using constants in Simulink is the ease of updating simulation model. Constant value can be easily updated in .m file script and updating of the new values to simulation requires only running the script to update values. If done by constants in Simulink each instance of changed constant would need to be manually changed to a new value.

Kuva, joka sisältää kohteen teksti, kuvakaappaus, numero

Kuvaus luotu automaattisesti

Figure 2. System constants in .m file

4. Closed loop systems and PID tuning

The conclusions explain how well your research achieved its objectives, what its findings were and what they mean in a wider perspective and for the future. The conclusions should examine how your findings differ from or coincide with those of previous studies. Analyse the impact of your research: its theoretical or practical contribution and wider societal importance. In addition, mention possible limitations of your study and research topics that should be dealt with in the future.

Remember that if or when someone other than your supervisor reads your thesis, they will most likely read the introduction and conclusions first.

5. Results

Saaasas

6. Conclusion and discussion

asasasaas

References

Hirsjärvi, S., Remes, P. & Sajavaara, P. 2009. Tutki ja kirjoita. 15th ed. Helsinki, Tammi.

Stratton, C. R. 1976. Needs assessment for communication system design. Journal of Technical Writing and Communication. Vol. 6, no. 2, pp. 135–144.

Virtanen, V. 2011. Esimerkkilähteen otsikko. Lappeenranta–Lahti University of Technology LUT. Accessed 1 January 2018. Available at the [LUT Academic Library](http://esimerkki.fi)

Note: More information on referencing is available in Appendix 2.

Appendix 1: Text processing and layout in a thesis

Good text processing skills make writing your final thesis and using this template easier. Therefore, you should make sure you have the sufficient basic skills to edit long documents with text processing software before you start. This involves applying the styles, understanding automatic referencing and knowing how to divide your text into sections.

The essential thing is to understand the following basics of Word:

* Do not modify your layout by adding consecutive spaces or line breaks. If you need to press Enter or the space bar more than once, you are probably doing something wrong. When you want to start a new paragraph, press Enter once at the end of the sentence and use styles to create a space between the paragraphs.
* Do not do any numbering manually (section numbers, page numbering, numbering of figures/tables/charts/appendices). Word has efficient automatised tools for all of this. They keep the numbers in the right order even if you modify, add or remove information.
* Do not add hyphenation at the end of a line manually. Word’s automatic hyphenation tool can be used in this template. If you need to add more hyphens, select manual hyphenation in Word. The automatic hyphenation is usually turned off, but you can activate it yourself.

Line spacing, font, margins, alignment, page numbering and headings

Official layout guidelines state that the line spacing should be 1.5 except for the abstract and possible direct citations, where the spacing is 1. You can choose from two fonts: Times New Roman (12 pt) or Arial (11 pt). This template has been written in Times New Roman 12 pt. Leave an empty line between paragraphs. Also leave an empty line after tables and figures.

Leave the following margins:

• top and left 35 mm

• bottom and right 20 mm.

The page number of the title page is 1, but the page numbering should not be visible before the first page of the table of contents. Place the page numbers at the top of the page, either centred or in the right-hand corner. Page numbering ends on the final page of the reference list: appendices do not have page numbers unless the appendix is multiple pages.

Always use heading styles in your headings (Heading 1, Heading 2, Heading 3). Always place chapter headings (Heading 1) on a fresh page. If you add large figures or tables, remember to check that the empty space after the figure or image covers no more than 20% of the page.

The heading numbering starts from the introduction and continues consecutively. Do not place a period after the heading number. Do not number the heading of the reference list at the end of the thesis.

The thesis should include no more than three heading levels, and the headings should progress in a logical order (first Heading 2, then Heading 3, etc.). If you need even more detailed subheadings, do not number them, and leave them out of the table of contents. Concise headings that describe the text sufficiently are the best. You can use question marks or exclamation marks, but do not add a period if the heading is a regular sentence.

A heading cannot be followed by a heading. Always write something between them. For instance, there must be text between headings 1 and 1.1.

Lists are a good way to express things clearly. Use the same type of bullet or symbol in lists throughout your thesis. A section should never end in a list. There should always be two or three sentences after a list.

Appendix 2: References

The text must include references to the sources you use. LUT University applies the Harvard referencing style, also called the author-date style with in-text referencing and a detailed reference list at the end.

The purpose of a reference is to provide sufficient information on a source used in the study, allowing the reader to consult the original source for further information. The reference enables the reader to find detailed information on the source easily in the list of references. You should refer to the original and most recent sources. If no new studies have been published on the topic in question, also older ones may be used.

Referring to a source means that you explain the contents of the source material in your own words. Direct citations, on the other hand, are placed in parentheses (“ ”). Plagiarism or using another person’s original material without appropriate referencing is not allowed.

Referencing technique

In the Harvard system, the citation is placed in parentheses directly in the text to indicate the passage that has been cited from another source. Place the citation before the period that ends the sentence when it refers only to the sentence in question (Kaasinen et al. 2020, pp. 173–174). If you are referring to more than that one sentence, place the citation after the paragraph like a sentence of its own. In such cases, add a period at the end of the citation. (Kaasinen et al. 2020, p. 174.)

Typically, the citation mentions the author (the last name is sufficient, unless authors of several sources have the same last name), the publication year and the page number. Please note that the author does not always have to be a person, but it may also be an organisation, for instance. If the source does not mention who the author is, the reference should include the name of the publication instead of the author. (Nykänen 2002, 77.) The author (or the title of the work) is very commonly mentioned as a part of a sentence: “According to a study conducted by Möttönen (2007, 68), a pike is a fish”.

If the source has more than one author, they are all mentioned in the reference by their last name and separated with the word ‘and’ or the symbol ‘&’. Make later references to the same work with the first author’s last name and “et al.” If you reference several works published by the same author in the same year, add lower-case letters (a, b, c…) after the publication year to distinguish the sources. Use the same alphabetical organisation also in the list of references.

Examples and detailed instructions on referencing:

[LUT Academic Library’s instructions](https://libguides.lut.fi/citingelectronicdocuments) on how to cite electronic documents

[Aalto University citation guide](https://libguides.aalto.fi/citation_guide)

[Harvard referencing](https://www.librarydevelopment.group.shef.ac.uk/referencing/harvard.html), University of Sheffield

Appendix 3: Tables, figures, equations, numbers, symbols and abbreviations

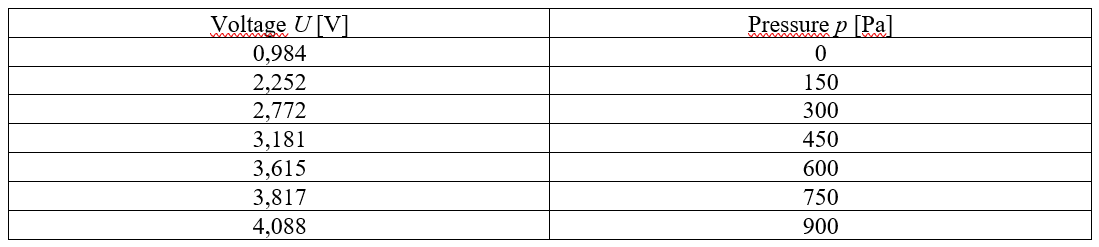
It is a good idea to illustrate your text with figures and tables. Figures and tables must have captions and consecutive numbering. The captions of tables are placed above the table and those of figures below the figure. Refer to the figures and tables in the text body, preferably before you introduce them, and align them with the text body.

Remember to add alt text (alternative text) to your figures and tables to ensure accessibility. Alt text is read with a designated reader and can be viewed even when the image cannot be displayed on the page. The MS Word text processing software creates alt text automatically, but you should make sure it describes the object sufficiently and understandably. You can modify the alt text by right-clicking on the figure or table.

Tables

Give your tables numbers and captions. Place the caption above the table, name its columns and mention the units applied, as in Table 1 below. Avoid empty columns or rows. The recommended font size is 10.

Table 1: Sensor measurements



Figures, charts, graphic elements

Images help illustrate your text. Number your figures and place a caption underneath. You should use a software programme such as Excel or Matlab to draw charts. Charts should be clear and easy to understand. Use a white background. A background grid is allowed if it does not make the figure difficult to interpret. Variables and measurement points should be clearly visible, as in Figure 1. Name the axes and their units.

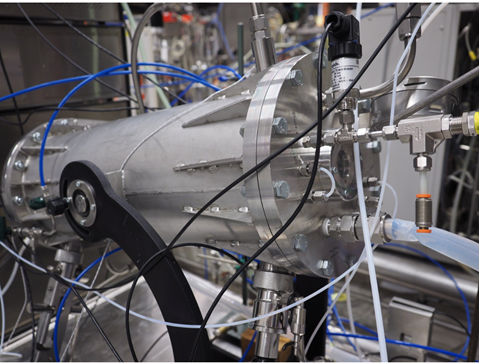


Figure 1. Gas fermentor (VTT, LUT image bank).

Create as much of the figures yourself as you can. Use the same font as in the text body and equations. If you use images created by someone else, remember to cite them correctly. Captions need to be in the same language as the text body.

Do not end a paragraph in a figure or table. Add text underneath, such as comments on the figure. Large figures, tables, long equations and other supporting material can be appended, if needed.

Numbers, symbols and equations

Numbers in the text are usually approximations. Their accuracy depends on the observational error. Include only significant figures in the results. Interim results should include at least two figures more to avoid round-off errors. Present large and small figures in powers of ten 10ⁿ, where n should preferably be divisible by three.

Equations and other mathematical expressions must consist of standardised symbols if ones exist. You may use your own symbols only there are no applicable standardised or established ones.

Explain the symbols in an equation when you use them for the first time. Write each equation clearly on its own line and indent it. Number your equations consecutively or by paragraphs so that the number is in parentheses on the right side of the equation and aligned to the right. You can refer to an equation only after you have presented it, with certain exceptions, such as if the object you are referring to is far ahead. Example:

*pv* = *RT* (1)

where *p* is pressure [Pa], *v* is specific volume [m3/kg], *R* is the gas constant [J/kgK] and *T* is temperature [K].

When you write symbols in your thesis, do the following:

* Write all variables in italics.
* Write subscripts upright unless there is a need to italicise them. Write abbreviated subscripts and numerals e.g. as follows: Δ*σw, σ*1*, σ*min. For instance, in the summation the subscript needs to be italicised because it represents a running number *i*.
* If you wish to express change in e.g. pressure Δ*p*, write Δ in a regular font. In some cases, *Δ* may also be a variable and should then be italicised. π is the ratio of a circle’s circumference to its diameter. *π* may be the pressure ratio.
* Do not italicise mathematical operators such as sin *x* or lg *y.*
* Distinguish absolute values as follows: ”variable\_=\_number\_unit”, with the exception of a percentage sign after a numeral, e.g. *a* = 5.2 mm, γ = 97.7%.

Use a decimal point (“.”) in accordance with international standards. In contrast, a decimal comma is used in theses written in Finnish. This also applies to figures and tables.

List of symbols and abbreviations

List symbols and abbreviations and their definitions that are not common knowledge separately on their own page before the table of contents. Divide them into groups: Roman symbols, Greek symbols, and finally, abbreviations. Give the page the heading Symbols if there are no abbreviations or Abbreviations if there are no symbols.

When you use a symbol or abbreviation in the text body for the first time, introduce it to the reader for example as follows: “The concept design for manufacturing and assembly (DFMA) is...”. After this, you can use only the abbreviation, and the reader can verify its meaning from the abbreviation list. Do not add concepts to the list of symbols and abbreviations that you do not mention in your text body.

Appendix 4. Appendices to the thesis

Appendices may include e.g. interview questions, survey forms or other content relevant to the work but not necessary to include in the text body.

In your text body, refer to the appendices by adding their title in parenthesis (Appendix 1) where relevant. Give all appendices a title based on their content and list them in the table of contents in the order in which they are referred to in the thesis.

Single-page appendices do not require page numbering. Multiple-page appendices do.

Appendix 5. Publishing the thesis

LUT’s degree regulations state that Bachelor's and Master's theses are public documents. They are published in the LUTPub repository, and related instructions are available on the library web site: <https://libguides.lut.fi/lutpub/opinnaytetyot>.

Together with the first examiner, make sure that the commissioner of your thesis is aware of the publicity requirements from the very beginning of the discussions. If it is necessary to include information in your Master’s thesis that the commissioner wants to keep secret, the university may allow keeping the Master’s thesis confidential for up to two years. In such cases, the commissioner needs to provide the university with a notification on the confidentiality requirements. The student is responsible for submitting the confidentiality notification to Student Services no later than in connection with the assessment application. The notification must relate the scope of the confidentiality, grounds for it and the confidentiality period in full years. The confidentiality period starts from the date the thesis is assessed. Information that needs to remain confidential for over two years must be excluded from the thesis text. The thesis will be evaluated based on the version submitted to the university.

All theses in LUTPub must fulfil accessibility requirements. Your text must be as legible as possible to readers. Remember

* to use styles to create headings
* add/check the alt text of your figures and tables.
* embed hyperlinks into your text or a description of the linked content; do not include hyperlinks.