title

- Good morning, Ladies and gentlemen.
- The lecture topic is Passivity and Thermodynamics Applied to Chemical Process Control. Before I give my presentation, I'd like to say sth about.
- The topic is rather difficult as it involves knowledge from four different area: mathematics, mechanics, thermodynamics and control theory. Actually, I never heard passivity this word before I got the topic. Therefore it is big challenge and very demanding work for me to do. I have to say I was a little bit upset at beginning However after 10 days intense reading work, now I agree with Prof. Skogestad that the topic is very interesting and worth to do.
- next I'm giving the lecture on this topic.

outline

- When I got the topic, the first question come in my mind is ‘what is passivity’, I think this is also the question I should answer at first to most audience.

- After having the concept of passivity, the next Q coming immediately, i.e., what is its role in control, or what it can be used fro control purpose?

- The 3rd subtopic is a brief survey on the application of passivity-based approach in control area.

- The second issue in this topic is thermodynamics. The Q involved in this lecture is how thermodynamics can be linked with passivity theory.

- because chemical process control is concerned in this lecture, so I will say briefly about the incentives for chemical process control and associated problems

- Finally, I’ll give a discussion about the applicability of passivity-based approach linked with thermodynamics to chemical process control

physical meaning

- Roughly speaking, systems are said to be passive in the sense they don't generate energy of their own.

- Let us look at an example as shown by figure. This is a RLC circuit connected with a voltage source. The RLC system is obviously passive system because it can't produce energy at all.

- we will take the voltage u as input to the RLC system and the current y as its output. the product uy is the power flow into this RLC system. Taking the current through the inductor, x_1 and voltage across the capacitor x_2 as state variables. The energy stored in the system is given by V.

- since the network is passive, the energy absorbed by the network over a period of time from 0 to t must be greater that or equal to the increase in the energy stored in the network over the same period.

- so we have this equation. when it holds with equality, that means no energy dissipation, we called the system lossless. when it is strict inequality, then the difference between the absorbed energy and the increase in the energy stored must be the energy dissipated in these resistive components. the system is said strictly passive.

physical meaning

- Let us look at this example again, we will see various special cases.

- this is the state model. by substituting state model into the equation for stored energy V and calculating its derivative, we get the Instantaneous power inequality:

- now if resistances R1 and R3 are very large, and no resistance R2, then $uy = \dot{V}$, in this case there is no energy dissipated, that is the system is lossless.

- look at the 2nd case, take $R_2 = 0,\ R_3 = \infty$ then $uy = ..$ the dissipation rate is proportional to input u^2. so there is no energy dissipation iff input u is identically zero. so we called this case as input strictly passive.

- if take $r_1 =$ ... in this case the current $y = x_1$ then $uy =$ ... so the dissipation rate is proportional to output y^2. so there is no energy dissipation iff output y is identically zero. so we called this case as output strictly passive.

- take $r_1 =$ ..., then $uy =$ .... the dissipation rate is a positive definite function of state x. there is no energy dissipation iff state x is identically zero. we called this case as state strictly passive.

definition

- Now we have got to know the physical meaning of passivity. After this, we need a precise or mathematical definition of what we mean by passivity. (followed by showing the slides)

- Since the notion of “passivity” of an input-output system is motivated by the energy dissipation across resistors in an electrical circuit, I need to give a brief introduction to dissipative system theory before I give the definition of passivity.

- The theory of dissipative system was laid down by Willems, 1972 in his fundamental papers.

- Consider state space systems as described these formula, we also define a variable called supply rate.

- Definition 1 dissipative... this is called dissipation inequality. it will be used frequently later.

- Definition 2 passive, note a special defined supply rate is used , that is product of input and output uy this imply that u and nd y have same dimmention

- it is also necessary to define a dissipation rate d by the equality.

- For the definition of Dissipation rate, there is an error in Willems' paper (1972) on page 333... In fact the physical meaning is “supply rate - increase in the stored energy = dissipation rate”.

its role in control

- After having the concept of passivity, the next question coming immediately, i.e. what is its role in control or what it can be used for control purpose? (show next slides)

- generally, passivity approach is an alternative approach to the stability analysis of feedback systems.

- at first we consider input-output stability. I need to introduce basic notions of input-output stability, such as L_q space and L_q stable.

- the signal spaces under consideration are L_q spaces, or their extensions. the set Lq consists of all functions f which are mappings from positive real line R+ to whole real line R, these functions are measurable and satisfy this equation.

- set L_q^n is introduce as the set of all n-tuples $f = ...$ with fi belongs to Lq set for each i. The Lq spaces are banach space (i.e. complete normed linear spaces) with respect to the norms f_q... we called Lq norm.

- now we define a function ft called truncation of f to the interval between 0 to T, given by this eq. Then the set Lqe consists of all measurable functions f map R+ to R such that ft belongs to Lq, that means its qth power integral is finite. Lqe is called the extension of Lq. Note that the extended Lq space is linear but not normed space.

- after introduce notions lq and lqe, we can talk the lq stability. let G is a map from the extended lqm space to extended lqp space. if for every input u belongs to lqm imply the output Gu belongs to lqp space, then we call G is lq stable.

- further, if there exist finite constants γ_q and b_q such that for all $T \geq 0$ this inequality holds, we say that G is finite gain Lq stable. this is tighter than only saying Lq stable

closed loop stability

- so far we have discussed open-loop stability. for closed-loop stability, we look at the feedback configuration as shown in the figure, denoted by sigma with subscripts g1 and g2, superscript f. where G1 map u1 in the extended Lqe m1 space to y1 in extended Lqe m2 space, G2..., are input-output maps. here e1 and e2 represents external signals injected in the closed-loop configuration.

- the overall closed-loop system sigma is thus described by the equations:...

- we are ready to give the basic versions of the classical small-gain theorem. for the system shown in this figure. suppose that both G1 and g2 have finite L_q-gain given as $\gamma(G_1)$ and $\gamma(G_2)$. Then the *closed-loop system* $\Sigma^f_{G_1,G_2}$ is L_q-stable if $\gamma(G_1) \cdot \gamma(G_2) < 1$.

- this inequality is known as small gain condition. In other words, two stable systems G1 and g2 which are interconnected as shown in this fig will result in a stable closed-loop system provided the loop gain is small, or more precisely less than 1.

passivity theorem

- While the small gain theorem can be naturally formulated for all Lq spaces, $q = 1, 2, ...$, the passivity theorem is primarily concerned with L2, having the inner product.

- the inner product of f and g is defined as the integral of fg product between 0 and infinity, with f and g g in L2 space. then the square of L2 norm is equal to inner product of itself.

- Now we give the definition of the passivity in regarding to input-output map.

- let G be a map from extended L2e to L2e. then g is passive if exist some constant β such that... the inner product of u and Gu greater that β for all u in L2e and all T large than 0.

- more specially, if we say input strictly passive..., out strictly passive

passivity theorem

- now consider the closed-loop system sigma as shown in the figure. A fundamental property is the passivity invariance via feedback. that is the feedback intersection of passive systems is again passive, ...

- in relation to the L2 stability, if ..., then the well-defined... Here we say the system is well defined in the sense that for every pair of inputs $e_1, e_2 \in L_{2e}^m$ there are exist unique outputs $u_1, u_2, y_1, y_2 \in L_{2e}^m$.

- in the book by van der schaft, it is only claimed that if both G_1 and G_2 are strictly output passive then closed-loop system is L_2-stable. In fact this condition is more tighter. as indicated in these two books, only one of these conditions mentioned above is satisfied, then the closed loop system can be stable.

- therefore from the passivity theorem, a passive process, which is not necessarily stable, can be closed-loop stable via strictly feedback controller.

Lyapunov Stability

- Now we discuss Lyapunov Stability, which is about the stability of equilibrium points. consider state space system as described by this equation.

- we say an equilibrium point, for instance x=0, is stable if all solutions starting at nearby points will stay nearby, mathematically given by this equation... if it is not stable we call as unstable.

- the equilibrium point is asymptotically stable means that all solutions starting at nearby points will not only stay nearby, but also tend to the equilibrium point as time approaches infinity.

- the second definition gives what is *Lyapunov function* if a continuously ...

- the 3rd definition deals with observability. The system ... more weakly condition proposed by Byrnes is zero -state detectable...

Lyapunov Stability linked with passivity

- In regarding to this state space system, we have the following relationship between passivity and Lyapunov Stability
- if passive..., then stable
- if strictly passive, ... observable, then asymptotically stable. that is, under additional observability conditions the properties of strict output passivity or finite L_2-gain imply asymptotic stability

passivity, Lyapunov, small gain

- Now we come to a state space interpretation of small-gain theorem and passivity theorem:
- let us start with the closed-loop system shown in this figure, with G1 and G2 replaced by the state space systems, sigma1...
- suppose ... this is small gain theorem; we also suppose ...passive, and storage functions V1...
- This proposition has immediate applications to robustness analysis. For details, see paper by Krstic and the book by schaft.

render passive via feedback

- After discussing the links between passivity and Lyapunov stability, the interesting Q is when a nonlinear system can be rendered passive by feedback?

- Byrnes indicated that a nonlinear...

- In the work by Ortega, he concluded that

I'm sorry to say, Because of limited time I only give the conclusions for these people's work. Then for more interests, please look at these relevant papers I have given the references.

summary

- From the previous discussion, we see that the concept of passivity ...
- Also there is a fundamental property, i.e. the passivity invariance via feedback
- As it is (motivated by the dissipation of energy, there is close connection with physical ...
- generally speaking, Passivity, as a physical notion, is a useful analysis tool in the sense that the results can easily be interpreted in terms of energy in the system.
- Besides, many important processes exhibit passivity properties as mechanical systems. for these passive systems, control system analysis and design is more simple, more intuitive, and better understood, by means of the concept of passivity.
- e.g. previous global stabilization results can be *alternatively* obtained and extended using passivity arguments, see these papers.
- before I close this section, I like to make a comparison with feedback linearization method, which is based on concepts from differential geometry. the feedback linearization method is one of the popular methods for nonlinear control design.

A great deal of research has been devoted to this subject over the last twenty years.

- However in contrast to the passivity-based approach, because this method stems from a general system theoretic methodology, thereby neglecting the natural structure imposed by the physical character of system.

- also it rely on ... and require perfect model.

application

- the motivation is primarily from the control of mechanical systems...
- here I give a brief summary on the application of passivity-based approach.
- The idea of stabilizing mechanical systems by reshaping the potential energy via feedback and by adding damping can be traced back to the work by Takegaki in 1981 this can be thought as starting point of “passivity-based control”
- ...
- I’ll say more about their work in the later section.

Thermodynamics

- The second issue in this topic is thermodynamics. Thermodynamics is concerned with *energy* and its transformations
- the first law deals with the conservation of energy, ...
- the second law restrict the behavior of a process in such a way that Entropy is produced. In other words, that all natural processes results in an increase in total entropy.
- this is also called Clausius inequality. S denotes entropy.

- Now the Q is how thermodynamics can be linked with passivity theory?

- In 1972 Willems tried to make a connection between thermodynamics and dissipation theory.

- He explained the first law in such a way that a thermodynamic system is lossless w.r.t the supply rate ...

- the second law could be formulated by stating that a thermodynamic system is dissipative w.r.t. this supply rate. please recall the dissipation inequality.

- however, Ydstie indicated that the entropy S can't be ...simply by a sign change since S is ...

- The novel idea they explored is that combing.., so V is defined by this eq. so that can be used as a candidate storage function

introduction to ydstie's work

- here I give a very brief introduction to ydstie's work
- When no mass and energy exchanged with the external environment, we say the system as isolated. In isolation, a system relaxes to a state of equilibrium after sufficiently long time. Nevertheless, certain classes of processes and actions exist that cause the system to reach non-equilibrium steady states, which are called passive states. Here They introduced a term called action. Exchanges with environment are called actions on the system. for example, supplied energy and supplied entropy are actions
- regarding to 1st law, we say ... conservation, in relation to 2nd law..
- now we define a function V and corresponding action ϕ_V...
- They first claimed that for ..., so V is storage function
- The 2nd proposition is ...
- finally they proposed that the ..., that is a local minimum of entropy production, or minimum dissipation. In this way, they establish a link between thermodynamics and passivity theory. Their work can be thought as starting point of application of passivity approach to chemical process.

chemical process control

- because chemical process control is concerned in this lecture, so I will say briefly about the incentives for chemical process control and associated problems

- There are three general classes of needs for controlling a chemical process, i.e

  1. Suppressing the influence of external disturbances, and
  2. Ensuring the stability of a chemical process, and
  3. Optimizing the performance of a chemical process

- The associated problems are mainly in several aspects

  1. Modeling difficulties, which are arising from Poorly understood chemical or physical phenomena, and caused from inaccurate values of various parameters, and caused from the size and complexity of the resulting model. To cope with model uncertainty, Robustness is an important issue need to be considered.
  2. Higher-order dynamic behavior: Systems with higher-order dynamics are not uncommon in chemical processes. For example, processes with dead time; as it is well known, dead time is a main source of closed-loop instability (p384); and also processes with inverse response. All these higher-order systems are particularly difficult to control and require special attention.

3. As a matter of fact, most chemical process can be highly nonlinear, the improved performance can be expected by nonlinear control of chemical process

Applicability

- Now the final q: is it possible to apply passivity approach linked with thermodynamics to chemical process control.

- at first I would like to say this is a opening issue, because no any...

- nevertheless, based on the discussion presented above, there is big potential in this research subject. On one hand, thermodynamics has proven to be a useful tool for process design and modeling, it can be also a useful foundation for process control.

- on the other hand, passivity-based approach offers the advantages in ... it obviously cope with the nonlinearity ...

- At last, let us see the applicability of passivity approach to distillation...

- As it is well known, distillation is the most important unit operation in chemical engineering in which a given feed is separated into two or more products of different compositions. the separation requires input of large amounts of energy. However it is shown that distillation columns may have multiple steady-state solutions and unstable operating points. so there exist stability problems.

- Now in terms of passivity, distillation columns are passive system. According to the passivity theorem I presented before, by designing a strictly passive feedback controller, the closed-loop stability is attained.

- I would like to thank these people at dept...for their help in recommend interesting papers and inspiring discussion, especially at the beginning when I stared this work. thanks also to prof. Ydstie for providing me their recent publications related with this topic.

- Thank you for your attention