Imperial College London

Signals and Systems

Lecture 5

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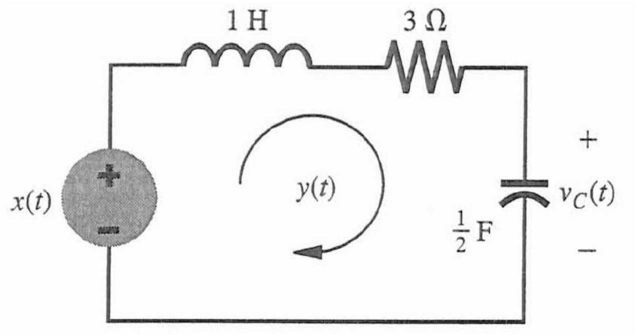
Properties of convolution

No	$x_1(t)$	$x_2(t)$	$x_1(t) * x_2(t)$
1	$\boldsymbol{x(t)}$	$\boldsymbol{\delta(t-T)}$	$\boldsymbol{x(t-T)}$
2	$e^{\lambda t}u(t)$	$u(t)$	$\frac{1-e^{\lambda t}}{-\lambda}u(t)$
3	$u(t)$	$u(t)$	$tu(t)$
4	$e^{\lambda_1 t}u(t)$	$e^{\lambda_2 t}u(t)$	$\frac{e^{\lambda_1 t}-e^{\lambda_2 t}}{\lambda_1-\lambda_2}u(t),\ \lambda_1 \neq \lambda_2$
5	$e^{\lambda t}u(t)$	$e^{\lambda t}u(t)$	$te^{\lambda t}u(t)$
6	$te^{\lambda t}u(t)$	$e^{\lambda t}u(t)$	$\frac{1}{2}t^2e^{\lambda t}u(t)$

Find the output of a system using convolution

- Find the loop current $y(t)$ of the RLC circuit shown below for input $x(t) = 10e^{-3t}u(t)$ when all the initial conditions are zero.
- We have seen that the system's equation is

$$\frac{d^2y(t)}{dt^2} + 3\frac{dy(t)}{dt} + 2y(t) = \frac{dx(t)}{dt}$$



- The above can be written as $(D^2 + 3D + 2)y(t) = Dx(t)$.

- We solved the equation of the above system in the previous lecture and we found that the impulse response of the system is

$$h(t) = (-e^{-t}+2e^{-2t})u(t)$$

- Therefore, $y(t) = x(t) * h(t)$. We can solve this convolution using Property 4 of Slide 2 shown below.

4	$e^{\lambda_1 t}u(t)$	$e^{\lambda_2 t}u(t)$	$\frac{e^{\lambda_1 t}-e^{\lambda_2 t}}{\lambda_1-\lambda_2}u(t),\ \lambda_1 \neq \lambda_2$

Find the output of a system using convolution cont.

- $y(t) = \ x(t) * h(t)$
- $x(t) = 10e^{-3t}u(t)$ and $h(t) = (-e^{-t}+2e^{-2t})u(t)$.
- $y(t) = 10e^{-3t}u(t) * (-e^{-t}+2e^{-2t})u(t) =$
  $$10e^{-3t}u(t) * (-e^{-t})u(t) + 10e^{-3t}u(t) * 2e^{-2t}u(t)$$
- For the first term we have:
  $$10e^{-3t}u(t) * (-e^{-t})u(t) = -10e^{-3t}u(t) * e^{-t}u(t)$$
  $$= -10\frac{e^{-3t} - e^{-t}}{(-3) - (-1)}u(t) = 5(e^{-3t} - e^{-t})u(t)$$
- For the second term we have:

$$10e^{-3t}u(t) * 2e^{-2t}u(t) = 20\frac{e^{-3t} - e^{-2t}}{(-3) - (-2)}u(t) = -20(e^{-3t} - e^{-2t})u(t)$$

- $y(t) = \ x(t) * h(t) = (-15e^{-3t} + 20e^{-2t} - 5e^{-t})u(t)$

The output of a LTI system when the input is complex

- What happens if the input $x(t)$ of a system is complex instead of real?
  $x(t) = x_r(t) + jx_i(t)$ with $x_r(t)$, $x_i(t)$ the real and imaginary parts of the input, respectively.

- The output of the system is:
  $y(t) = h(t) * [x_r(t) + jx_i(t)] = h(t) * x_r(t) + j\, h(t) * x_i(t)$

- That is, we can consider the convolution on the real and imaginary components separately.

Intuitive/graphical explanation of convolution

- Assume that the impulse response decays linearly from the value of 1 at $t=0$ to the value of 0 at $t=1$. See figure below left.
- The system's response at t is the convolution between $x(t)$ and $h(t)$

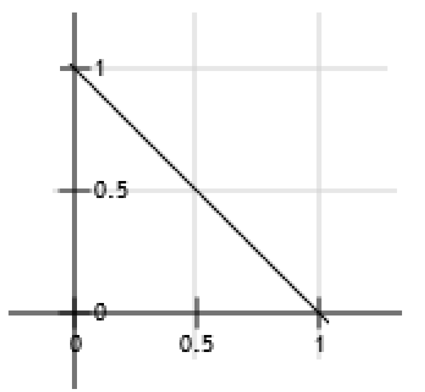
$$y(t)=\int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau$$

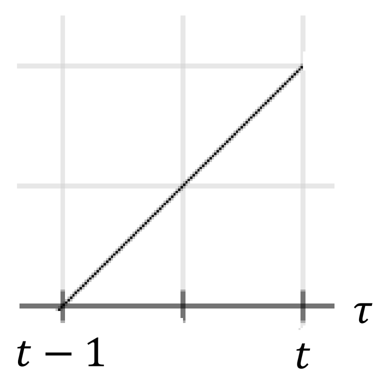
- Since $h(t)\neq 0$ if $0\leq t\leq 1$ we see that

$h(t-\tau)\neq 0$ if $0\leq t-\tau\leq 1 \Rightarrow -1\leq \tau - t\leq 0 \Rightarrow t-1\leq \tau\leq t$.

For $h(t-\tau)$ see figure below right. Therefore,

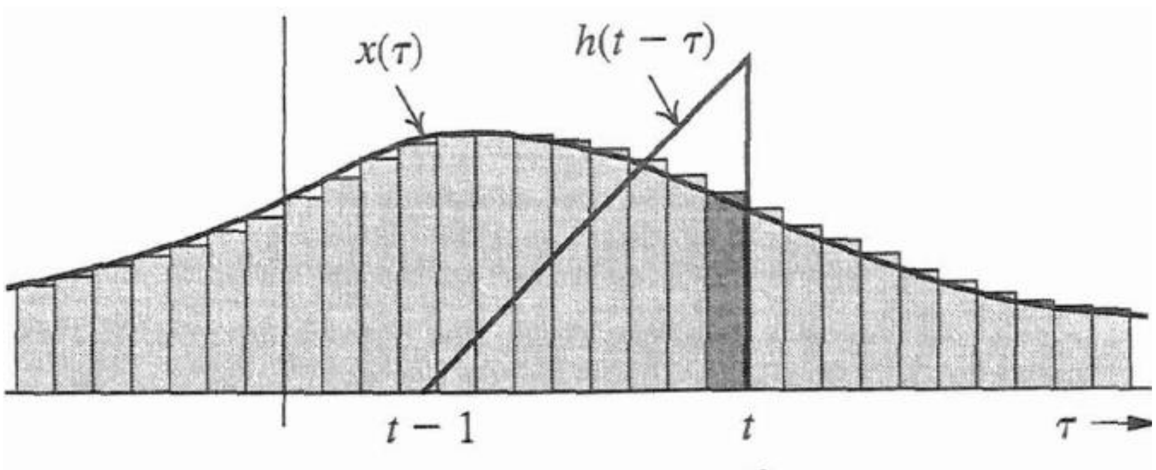
$$y(t)=\int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau=\int_{t-1}^{t} x(\tau)h(t-\tau)d\tau$$





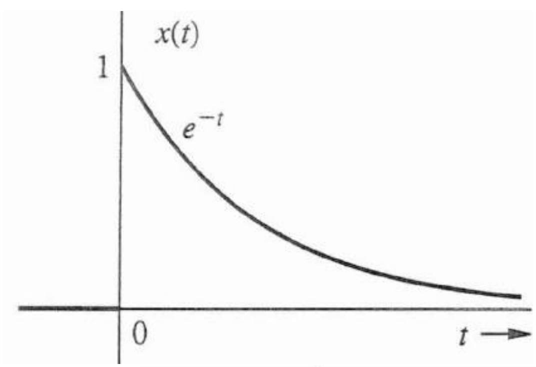
Intuitive/graphical explanation of convolution cont.

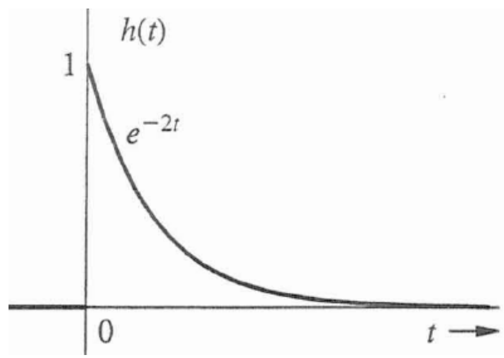
- The system's output is $y(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau = \int_{t-1}^{t} x(\tau)h(t-\tau)d\tau$.
- We approximate, as previously, the input $x(\tau)$ as a collection of rectangular pulses.
- The system's response $y(t)$ at t is determined by $x(\tau)$ weighted by $h(t-\tau)$ (i.e., $x(\tau)h(t-\tau)$) shown in the shaded pulse, PLUS the contribution from all the previous pulses of $x(\tau)$ within the range $[t-1, t]$ where $h(t)$ is non-zero. The system's response is shown **graphically** below.
- The summation of all these weighted inputs is also shown **functionally** in the convolution integral $y(t) = x(t) * h(t)$ above.

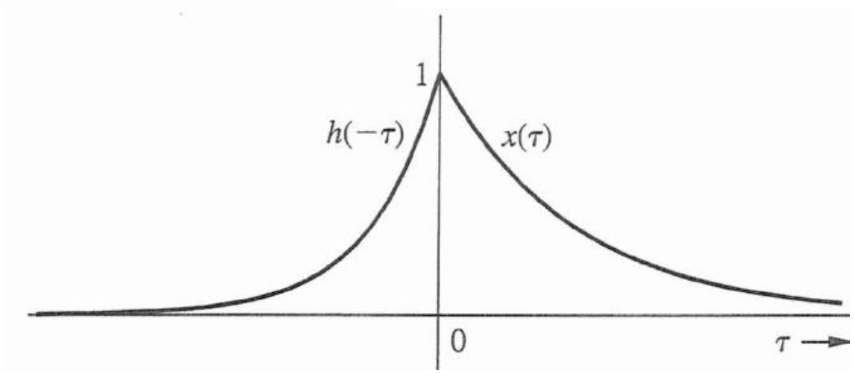


Example for graphical demonstration of convolution

- Demonstrate graphically the convolution
  $y(t) = \ x(t) * h(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau$ with
  $x(t) = e^{-t}u(t)$ and $h(t) = e^{-2t}u(t)$.
- Remember: the variable of integration is τ and not t.





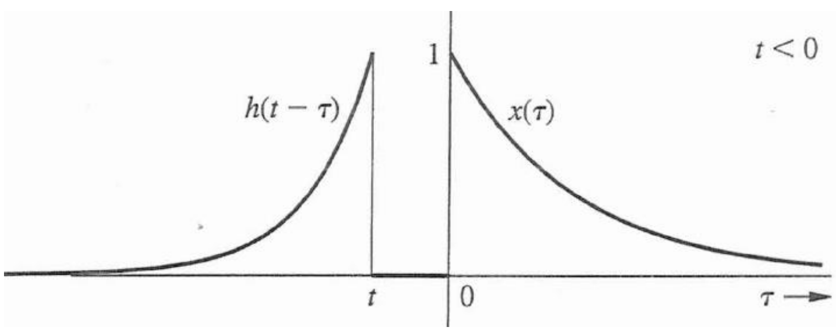


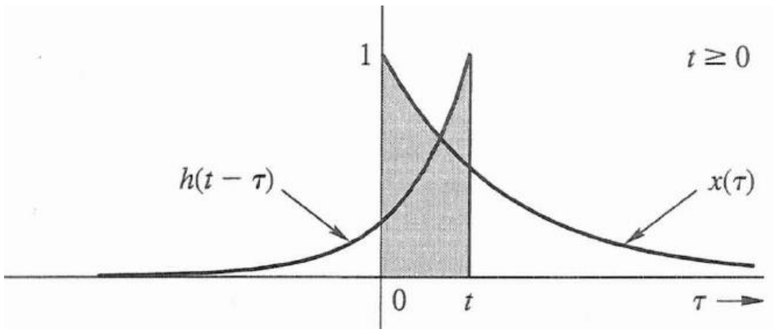
Graphical demonstration of convolution cont.

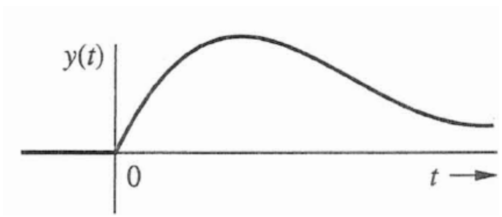
- By definition we have:

$$y(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau = \int_{-\infty}^{\infty} e^{-\tau}u(\tau)e^{-2(t-\tau)}u(t-\tau)d\tau.$$

- We found previously that $y(t) = (e^{-t} - e^{-2t})u(t)$.

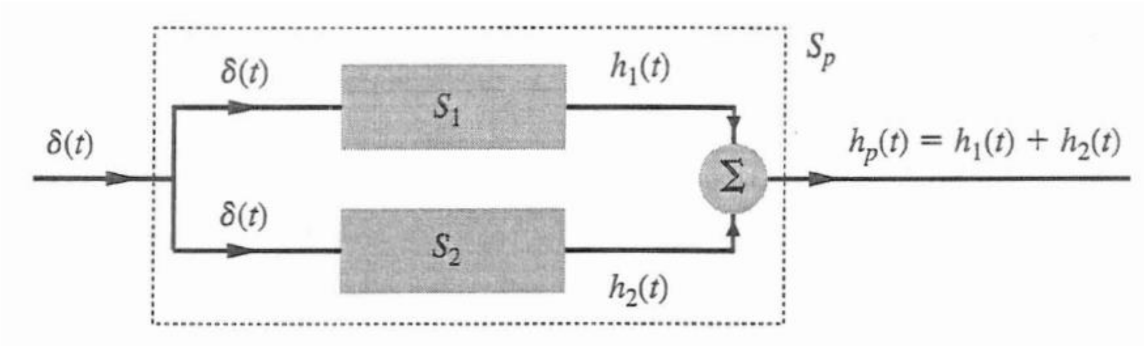




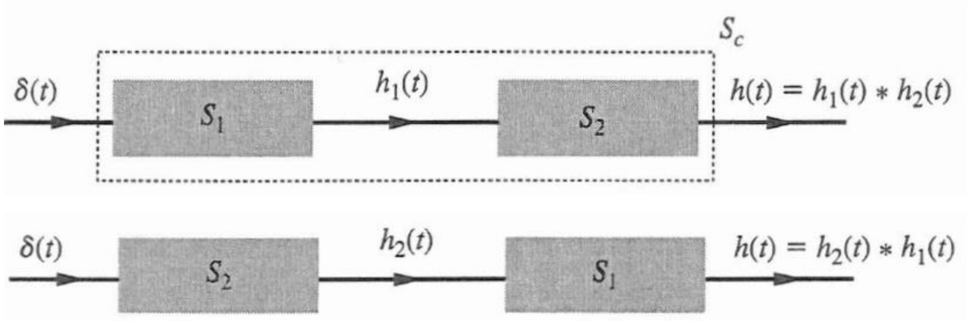


Interconnected systems

- For the parallel connection of two systems with impulse responses $h_1(t)$ and $h_2(t)$ the output is $y(t) = h_1(t) * x(t) + h_2(t) * x(t)$.

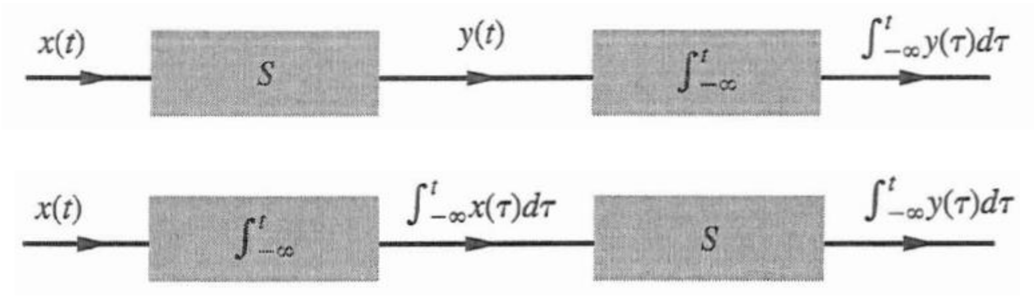


- For the connection in series of two systems with impulse responses $h_1(t)$ and $h_2(t)$ the output is $y(t) = h_1(t) * h_2(t) * x(t)$. The order of the connection is not important.



Interconnected systems cont. Step response

- Integration: if $x(t) \Rightarrow y(t)$ then $\int_{-\infty}^{t} x(\tau)d\tau \Rightarrow \int_{-\infty}^{t} y(\tau)d\tau$.



- Differentiation: if $x(t) \Rightarrow y(t)$ then $\frac{dx(t)}{dt} \Rightarrow \frac{dy(t)}{dt}$.

- Knowing that $\int_{-\infty}^{t} \delta(\tau)d\tau = u(t)$ and that $\delta(t) \Rightarrow h(t)$ we can say that if the input of the system is the step function, i.e., $x(t) = u(t) = \int_{-\infty}^{t} \delta(\tau)d\tau$ then the output of the system, which is called the step response must be:

$$g(t) = \int_{-\infty}^{t} h(\tau)d\tau$$

Total response

- We learnt that:

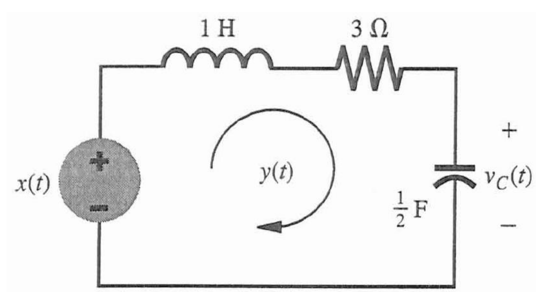
Total response = zero-input response + zero-state response

$$\sum_{k=1}^{N} c_k e^{\lambda_k t} + x(t) * h(t)$$

- We will combine everything using the same RLC circuit as an example.
- Let us assume $x(t) = 10e^{-3t}u(t),\ y(0) = 0,\ \dot{y}(0) = -5$.
- The total current (which is considered to be the output of the system) is:

Total current = zero-input current + zero-state current

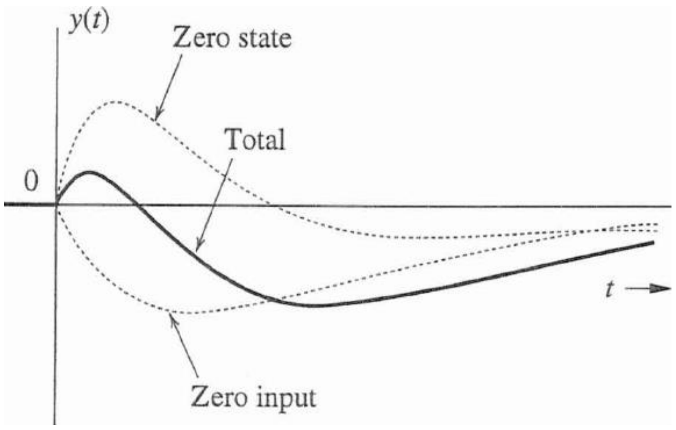
$$y(t) = (5e^{-2t} - 5e^{-t})u(t) + (-15e^{-3t} + 20e^{-2t} - 5e^{-t})u(t)$$
$$= (5e^{-2t} - 5e^{-t}) + (-15e^{-3t} + 20e^{-2t} - 5e^{-t}), \qquad t \geq 0$$

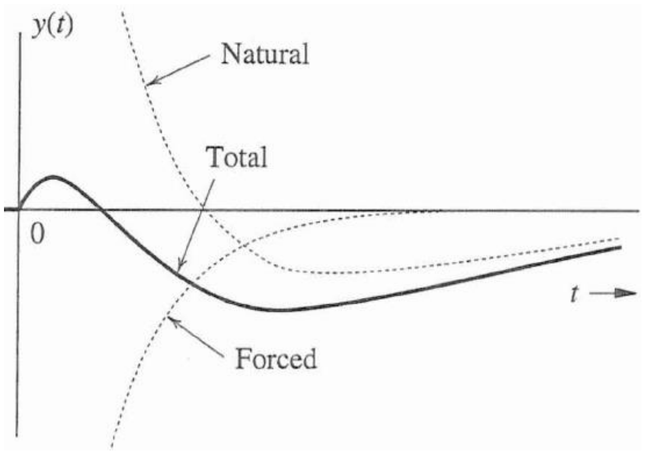


Natural versus forced responses

- Note that characteristic modes also appears in zero-state response (because it has an impact on $h(t)$).
- We can collect the e^{-t} and e^{-2t} terms together, and call these the **natural response**.
- The remaining e^{-3t} which is not a characteristic mode is called the **forced response**.

$$y(t) = (25e^{-2t} - 10e^{-t})u(t) + (-15e^{-3t})u(t)$$





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Appendix: More properties of convolution

7	$t^N u(t)$	$e^{\lambda t} u(t)$	$\dfrac{N!\,e^{\lambda t}}{\lambda^{N+1}} u(t) - \displaystyle\sum_{k=0}^{N} \dfrac{N!\,t^{N-k}}{\lambda^{k+1}(N-k)!} u(t)$
8	$t^M u(t)$	$t^N u(t)$	$\dfrac{M!N!}{(M+N+1)!} t^{M+N+1} u(t)$
9	$te^{\lambda_1 t} u(t)$	$e^{\lambda_2 t} u(t)$	$\dfrac{e^{\lambda_2 t} - e^{\lambda_1 t} + (\lambda_1 - \lambda_2) t e^{\lambda_1 t}}{(\lambda_1 - \lambda_2)^2} u(t)$
10	$t^M e^{\lambda t} u(t)$	$t^N e^{\lambda t} u(t)$	$\dfrac{M!\,N!}{(N+M+1)!} t^{M+N+1} e^{\lambda t} u(t)$
11	$t^M e^{\lambda_1 t} u(t)$	$t^N e^{\lambda_2 t} u(t)$	$\displaystyle\sum_{k=0}^{M} \dfrac{(-1)^k M!(N+k)!\,t^{M-k} e^{\lambda_1 t}}{k!(M-k)!(\lambda_1 - \lambda_2)^{N+k+1}} u(t)$
	$\lambda_1 \neq \lambda_2$		$+ \displaystyle\sum_{k=0}^{N} \dfrac{(-1)^k N!(M+k)!\,t^{N-k} e^{\lambda_2 t}}{k!(N-k)!(\lambda_2 - \lambda_1)^{M+k+1}} u(t)$

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Appendix: More properties of convolution

12	$e^{-\alpha t}\cos(\beta t+\theta)u(t)$	$e^{\lambda t}u(t)$	$\dfrac{\cos(\theta-\phi)e^{\lambda t}-e^{-\alpha t}\cos(\beta t+\theta-\phi)}{\sqrt{(\alpha+\lambda)^2+\beta^2}}u(t)$ $\phi=\tan^{-1}[-\beta/(\alpha+\lambda)]$
13	$e^{\lambda_1 t}u(t)$	$e^{\lambda_2 t}u(-t)$	$\dfrac{e^{\lambda_1 t}u(t)+e^{\lambda_2 t}u(-t)}{\lambda_2-\lambda_1}$ $\quad \operatorname{Re}\lambda_2>\operatorname{Re}\lambda_1$
14	$e^{\lambda_1 t}u(-t)$	$e^{\lambda_2 t}u(-t)$	$\dfrac{e^{\lambda_1 t}-e^{\lambda_2 t}}{\lambda_2-\lambda_1}u(-t)$