BMAS 2004

Modeling of a Piezoelectric Device with Shocks Management Using VHDL-AMS

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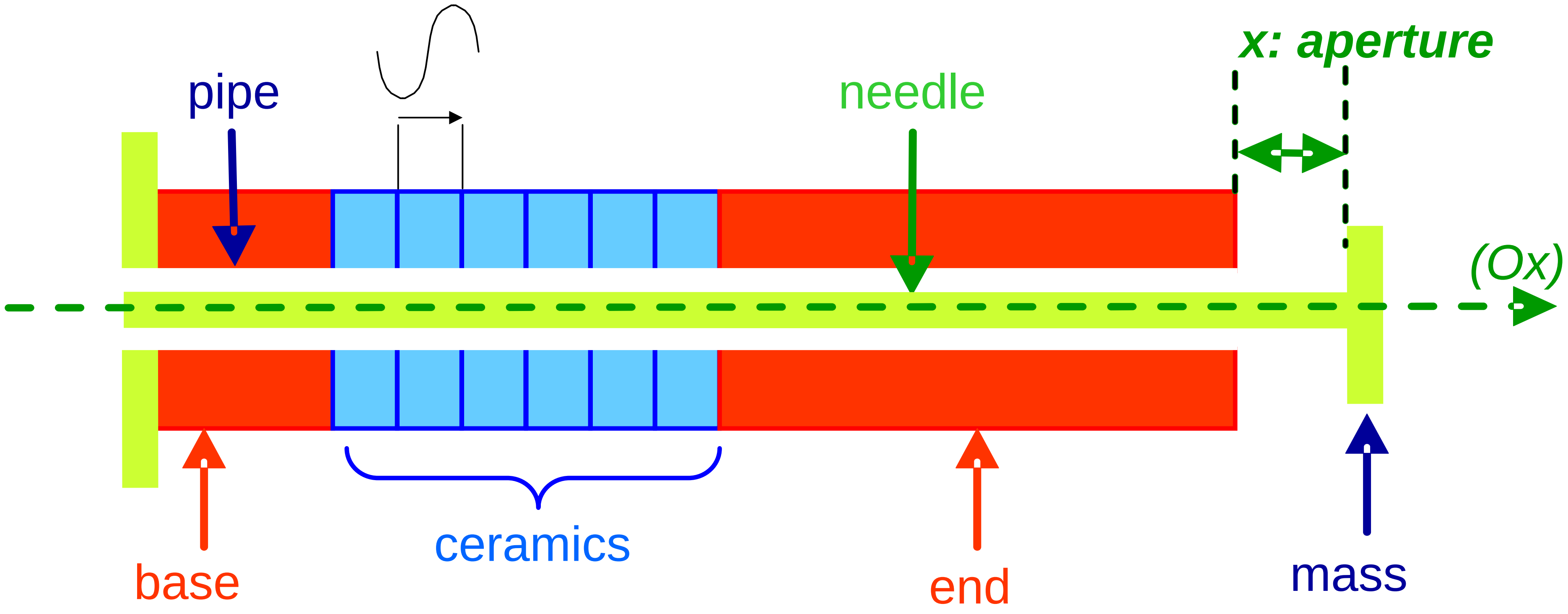
Purpose

- Modeling of mechanical systems:
  - composed of an assembly of metallic and piezoelectric parts
  - with some non-permanent contacts (shocks)

- What are the advantages of VHDL-AMS compared with MATLAB/Simulink or SPICE ?

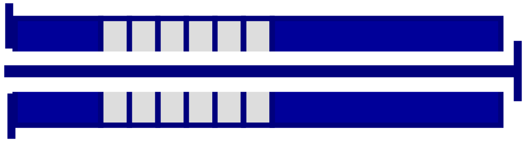
Piezoelectric device

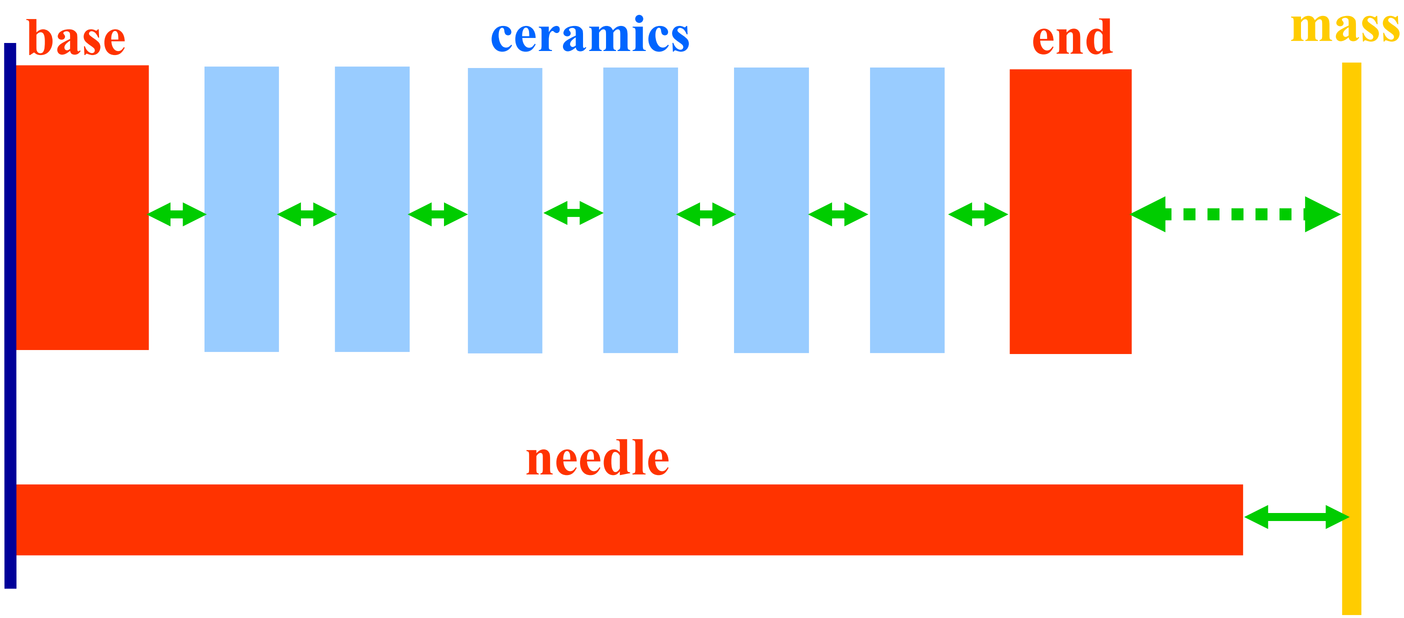


- Purpose: to spray liquid

Methodology

Modular approach

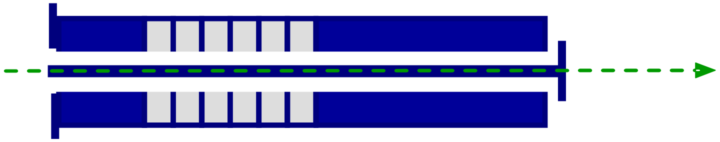




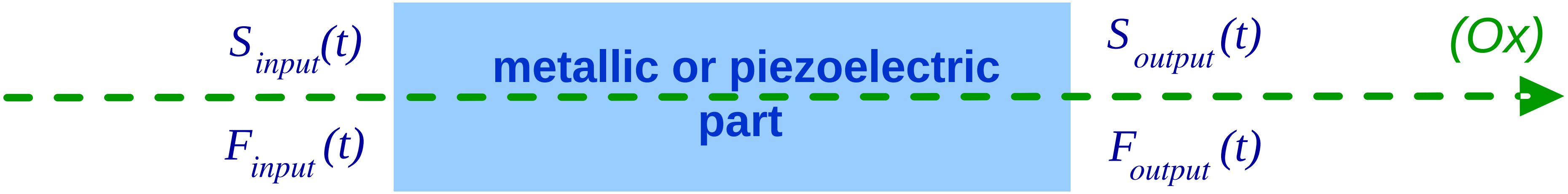
- **Single part behavior** (generic models for metallic and piezoelectric parts)
- **Assembly** (energy exchange at the interfaces)
- **Limit conditions** (permanent or discontinuous)

Methodology

Modular approach



- Single part behavior



$S_{input}(t)$

$F_{input}(t)$

metallic or piezoelectric part

$S_{output}(t)$

$F_{output}(t)$

(Ox)

- Unidirectional model
- Four quantities are considered:
  - Forces are considered as applying from left to right.
  - Speeds are considered as positive if the movement is from left to right
- Elastic deformations (except the mass)

Methodology

Tools

MATLAB/Simulink

- based on signal flow approach and block diagrams
- uses only one-directional signals

« Decoupling » approach

VHDL-AMS (ADVanceMS)

- multi-level : signal flow as well as Kirchhoff networks
- Kirchhoff networks use bi-directional quantities

Direct approach

Methodology

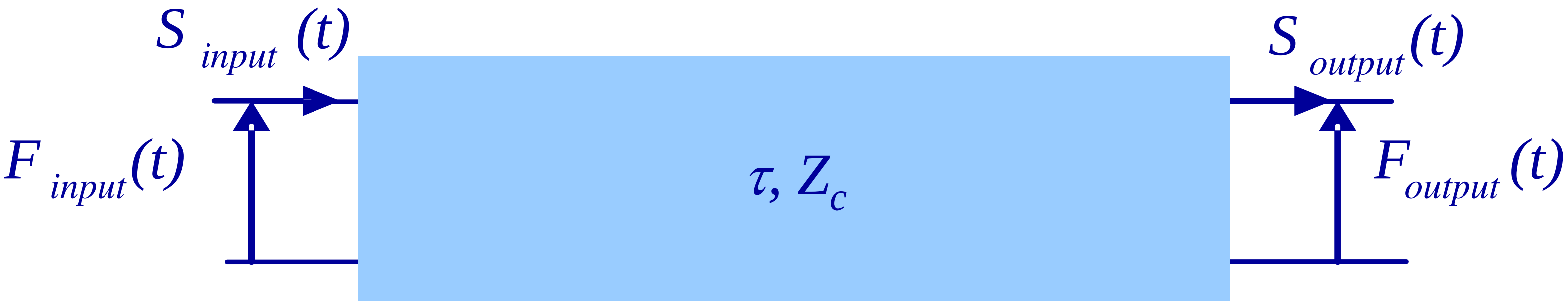
Electro-mechanical analogy

	Mechanical	**Electrical**
Effort	Force	Voltage
Flow	Speed	Current

- Mass ↔ Inductor
- Spring ↔ Capacitor
- Fluid friction ↔ Resistor

Methodology

Electro-mechanical analogy



- metallic part ↔ coaxial cable
- telegraphists’ equations ⇔ continuity equations in a homogeneous medium.

	Electrical line	Mechanical line
characteristic impedance (Z_c)	$\sqrt{\frac{L}{C}}$	$\sigma \cdot \sqrt{\rho E}$
propagation time (τ)	$l\sqrt{LC}$	$l\sqrt{\frac{\rho}{E}}$

l : length
L : lineic inductance
C : lineic capacitance

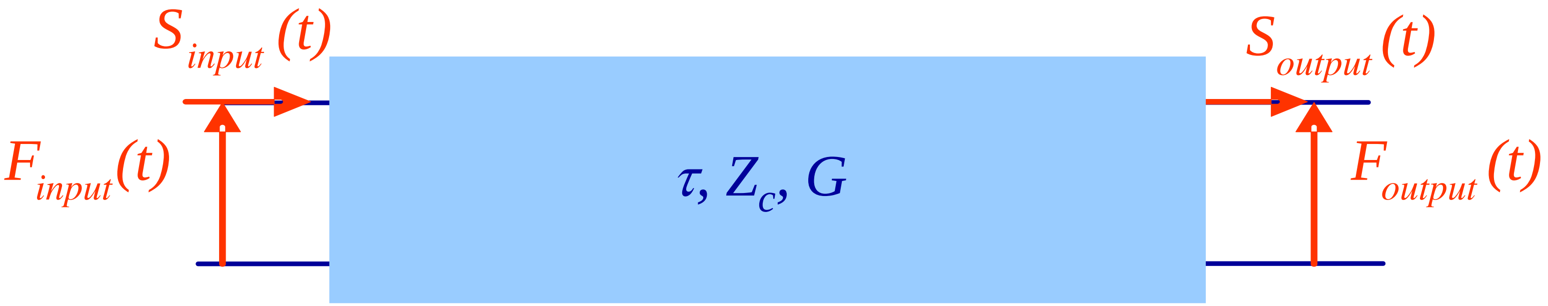
E : Young’s modulus
σ : section
ρ : volumic mass

Outline

- Introduction
    - ☐ Objectives
    - ☐ Device description
    - ☐ Methodology
        - Modular approach
        - Electro-mechanical analogy
- Actuator modeling
    - ☐ Generic models of single parts
    - ☐ Assembly
    - ☐ Limit conditions
- Shocks management
- Simulation results
- Conclusion

Generic models of single parts

Metallic part

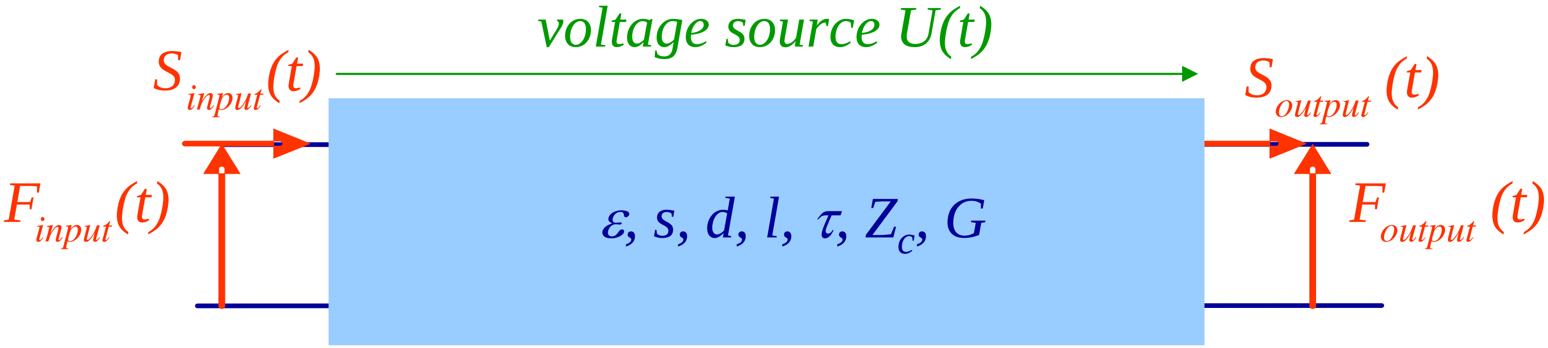


Propagation equations

$$\begin{cases} F_{input}(t) - G\cdot F_{output}(t-\tau) = Z_c\cdot\left(S_{input}(t) - G\cdot S_{output}(t-\tau)\right) \\ G\cdot F_{input}(t-\tau) - F_{output}(t) = Z_c\cdot\left(-G\cdot S_{input}(t-\tau) + S_{output}(t)\right) \end{cases}$$

Generic models of single parts

Piezoelectric part



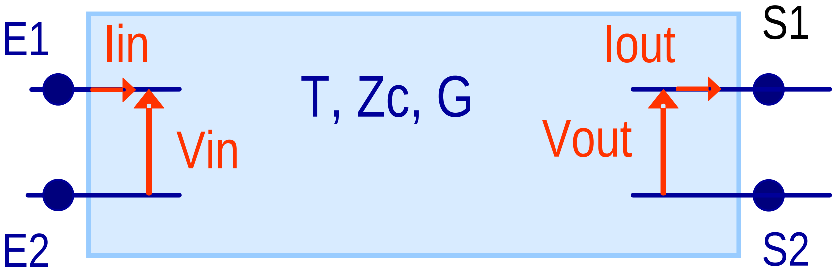
Propagation equations + piezoelectric effect

$$\begin{cases} F_{input}(t) - G \cdot F_{output}(t-\tau) = Z_C \cdot \left(S_{input}(t) - G \cdot S_{output}(t-\tau)\right) + \dfrac{\mathbf{d\sigma}}{\mathbf{\varepsilon s - d^2}}\left(\mathbf{D}(\mathbf{t}) - \mathbf{D}(\mathbf{t}-\boldsymbol{\tau})\right) \\ G \cdot F_{input}(t-\tau) - F_{output}(t) = Z_C \cdot \left(-G \cdot S_{input}(t-\tau) + S_{output}(t)\right) + \dfrac{\mathbf{d\sigma}}{\mathbf{\varepsilon s - d^2}}\left(\mathbf{D}(\mathbf{t}-\boldsymbol{\tau}) - \mathbf{D}(\mathbf{t})\right) \end{cases}$$

$$\mathbf{D}(\mathbf{t}) = \frac{\mathbf{\varepsilon s - d^2}}{\mathbf{l s}} \cdot \mathbf{U}(\mathbf{t}) + \frac{\mathbf{d}}{\mathbf{l s}} \cdot \int \left(\mathbf{S}_{\mathbf{output}}(\mathbf{t}) - \mathbf{S}_{\mathbf{input}}(\mathbf{t})\right)\mathbf{dt}$$

VHDL-AMS code

Metallic part

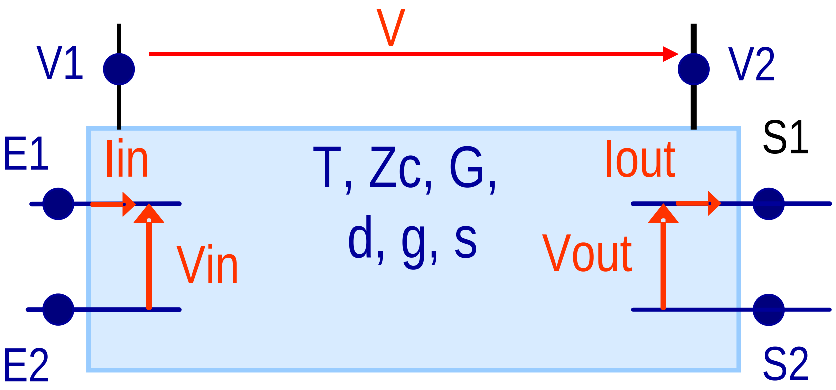


```
-- EXTERNAL VIEW: ENTITY
    entity metallic is
        generic (Zc, T, G : real :=0.0);
        port (terminal E1, E2, S1, S2 : electrical);
    end entity metallic ;

-- INTERNAL VIEW: ARCHITECTURE
    architecture propagation of metallic is
                    quantity Vin across E1 to E2; -- input force
                    quantity Iin through E1 to E2; -- input speed
                    quantity Vout across S1 to S2; -- output force
                    quantity Iout through S2 to S1; -- output speed
        begin
            -- propagation equations
                    Vin==-G*Zc*Iout'delayed(T)+Zc*Iin+G*Vout'delayed(T);
                    Vout==G*Zc*Iin'delayed(T)-Zc*Iout+ G*Vin'delayed(T);
       end architecture propagation;
```

VHDL-AMS code

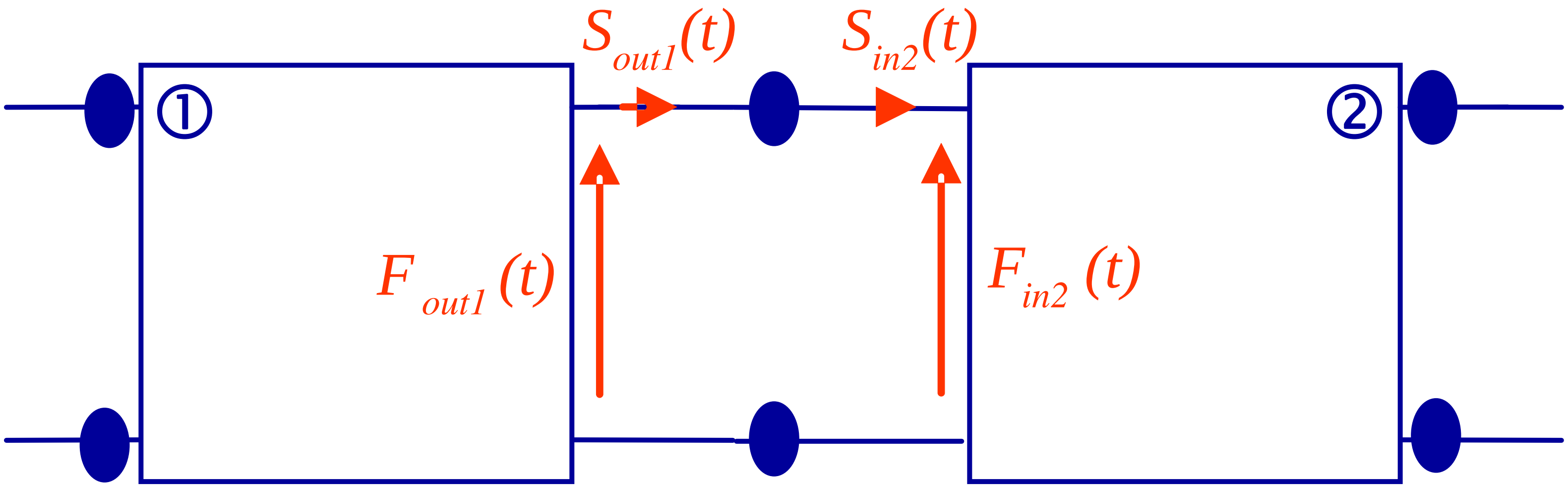
Piezoelectric part

```
-- EXTERNAL VIEW: ENTITY
    entity piezo is
        generic (Zc, T, l, d, g, s, G : real) ;
        port( terminal E1, E2, S1, S2, V1, V2 : electrical);
    end entity piezo;

-- INTERNAL VIEW: ARCHITECTURE
    architecture propagation of piezo is
        constant eps : real := d/g;
        quantity Vin across Iin through E1 to E2; -- input force and speed
        quantity Vout across S1 to S2;            -- voltage source
        quantity Iout through S2 to S1;           -- output speed
        quantity V across V1 to V2: real;         -- output force
        quantity D0 : real;                       -- piezoelectric term
      begin
        --Propagation equations + piezoelectrical term
Vin==-G*Zc*Iout'delayed(T)+Zc*Iin+G*Vout'delayed(T)-d*Sig/(eps*s-d*d)*(D0'delayed(T)-D0);
Vout==G*Zc*Iin'delayed(T)-Zc*Iout+G*Vin'delayed(T)-d*Sig/(eps*s-d*d)*(D0'delayed(T)-D0);
V==l*s/(eps*s-d*d)*D0-d/(eps*s-d*d)*(Iout'integ - Iin'integ);
      end architecture propagation;
```



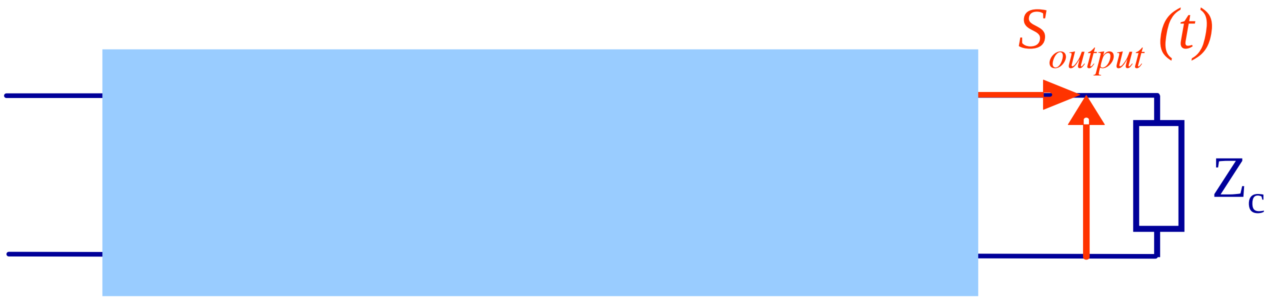
Assembly

Structural modeling



$$\begin{cases} F_{out1}(t) = F_{in2}(t) \\ S_{out1}(t) = S_{in2}(t) \end{cases}$$

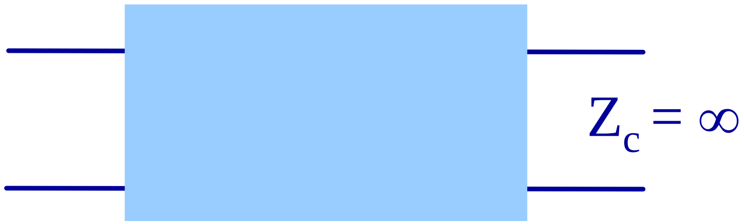
Limit conditions



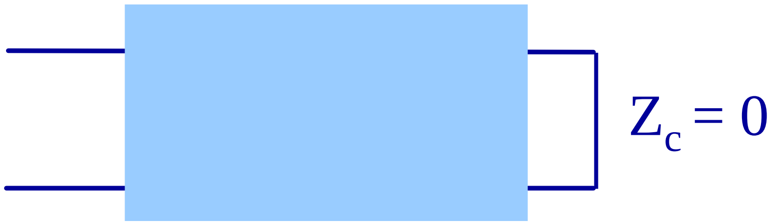
$$F_{output}(t) = Z_c S_{output}(t)$$

Exemples

Fixed part



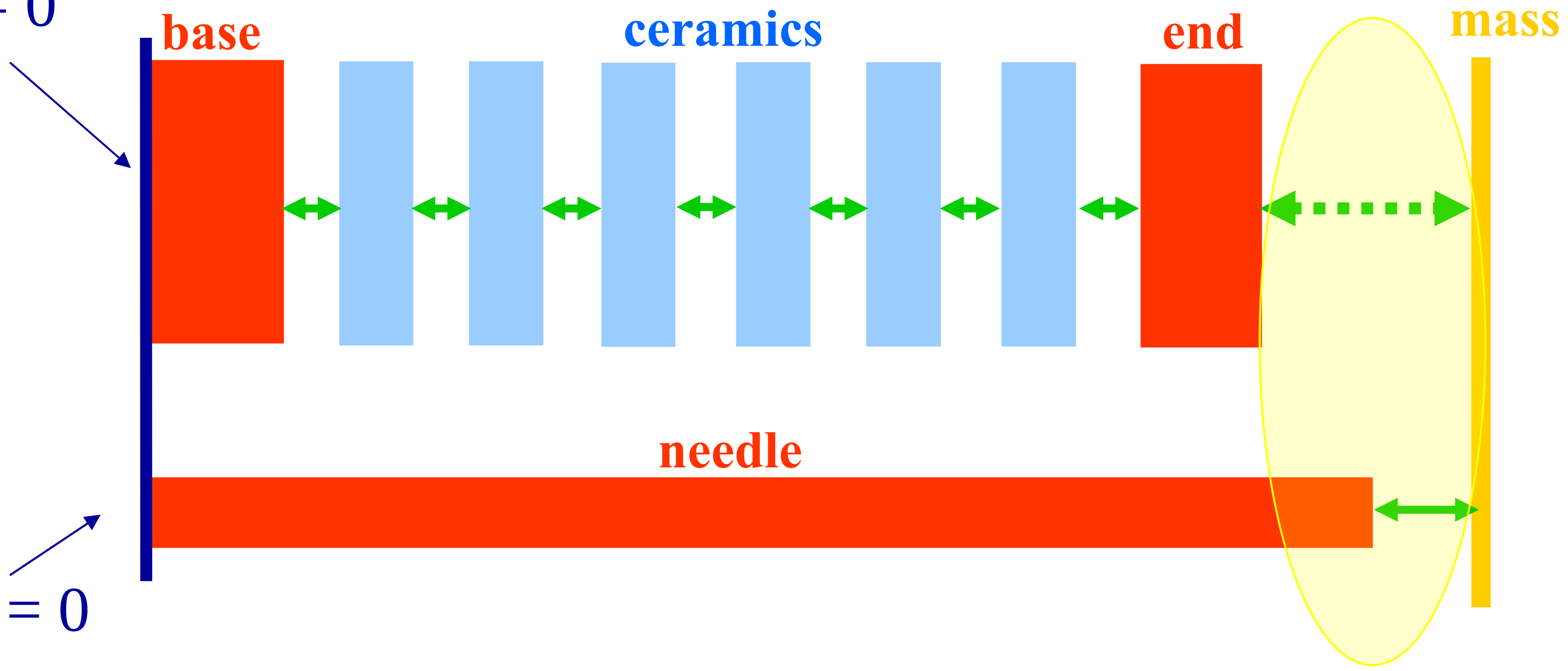
Part moving in an empty space



Part fixed to a free rigid mass *m*

Limit conditions

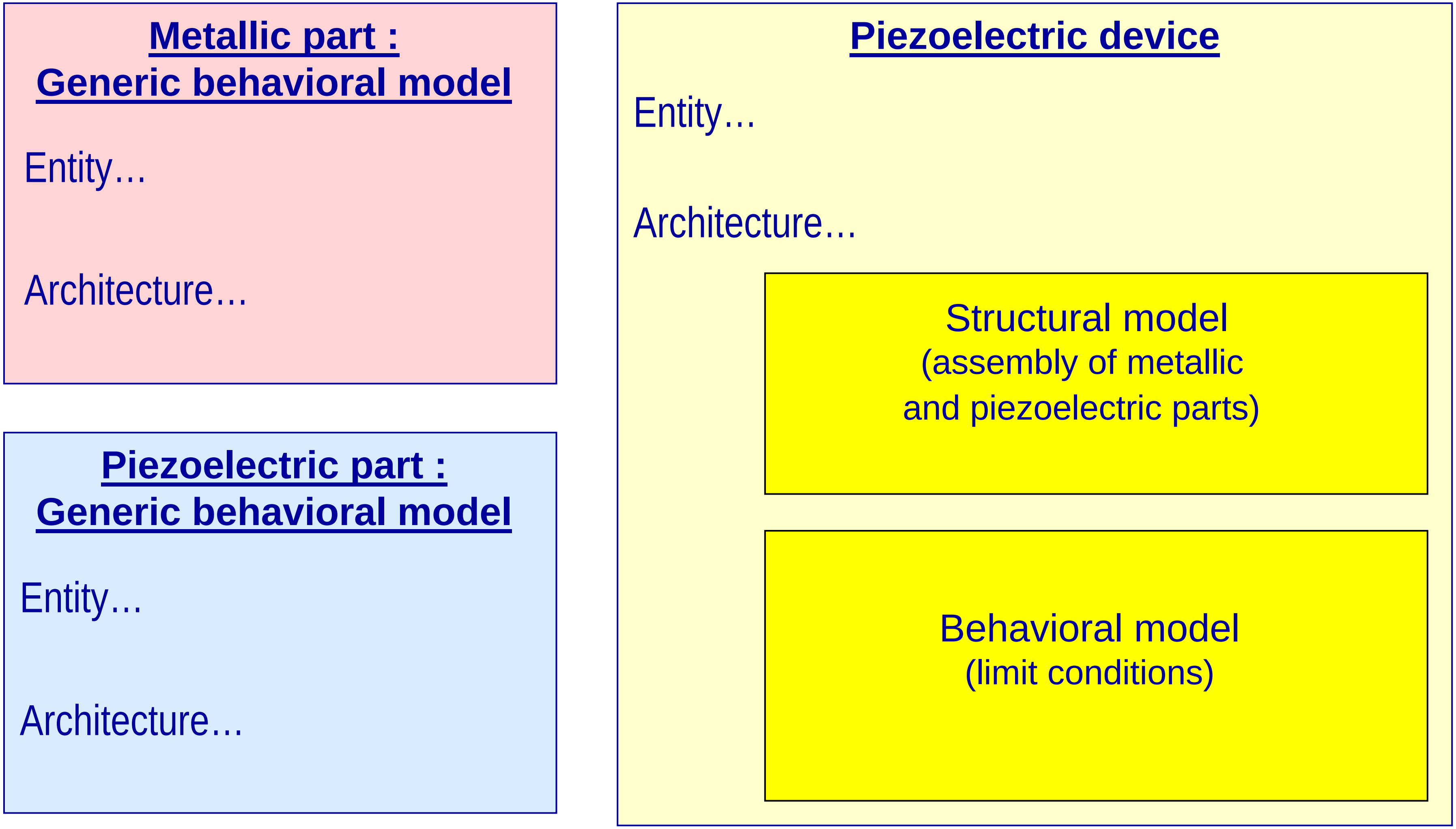
$S_{input\_base} = 0$



$S_{input\_needle} = 0$

Methodology

VHDL-AMS Model



Metallic part :
Generic behavioral model

Entity…

Architecture…

Piezoelectric part :
Generic behavioral model

Entity…

Architecture…

Piezoelectric device

Entity…

Architecture…

Structural model
(assembly of metallic
and piezoelectric parts)

Behavioral model
(limit conditions)

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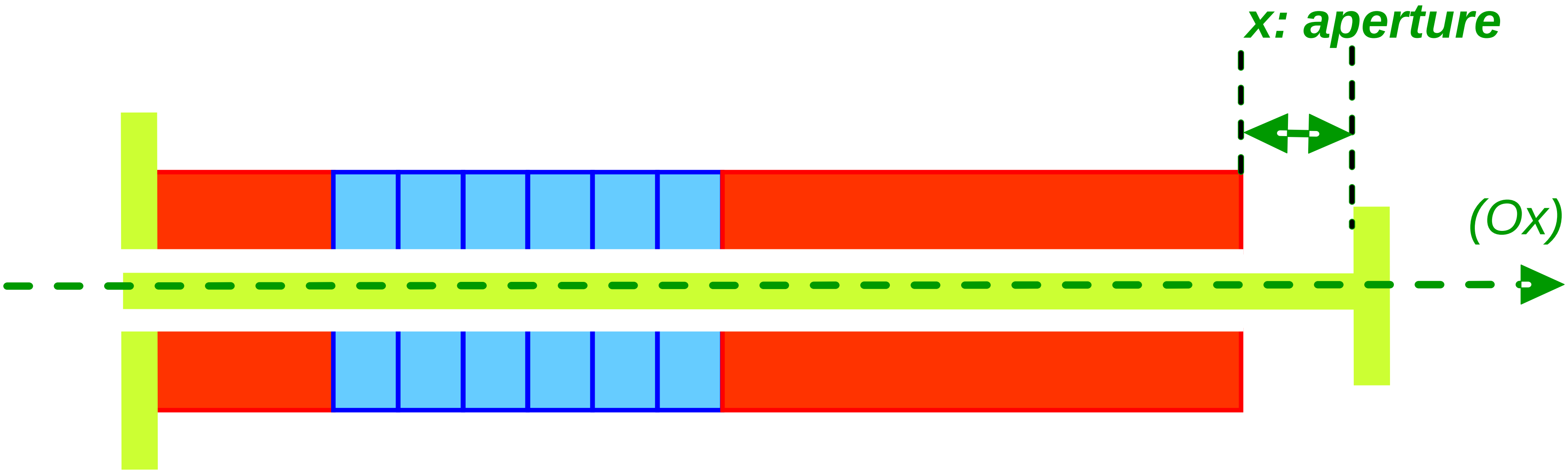
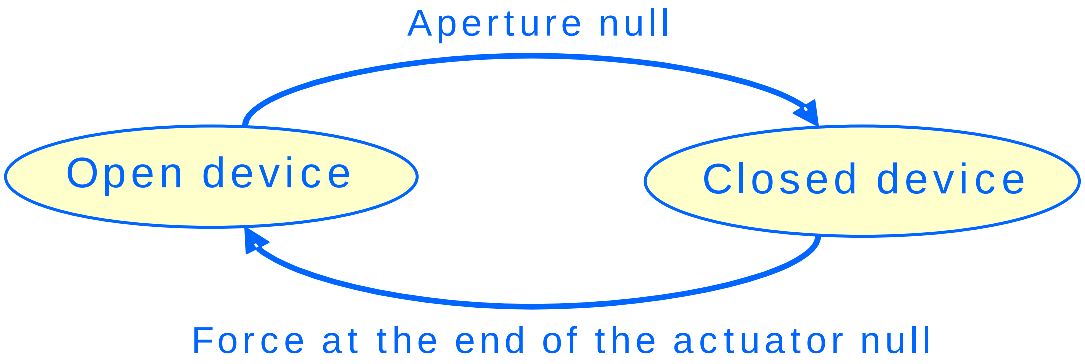
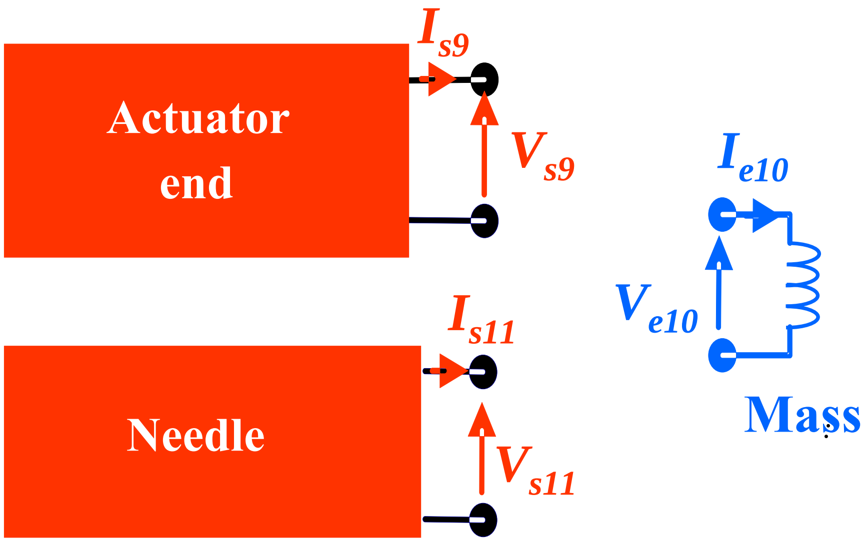
Principle


x: aperture
(Ox)


Aperture null
Open device
Closed device
Force at the end of the actuator null

VHDL-AMS code

Shocks management

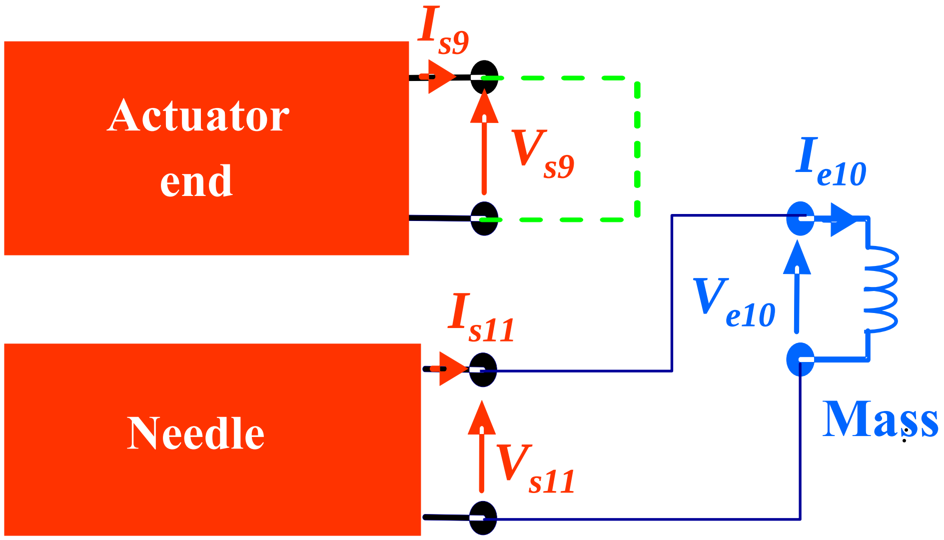


```
-- signal triggering state changings
aperture == Ie10'integ - Is9'integ ;
force_contact == Ve10-Vs11 ;
aperture_s <= '1' when aperture'above(0.0) else '0';
force_contact_s <= '1' when  force_contact'above(0.0) else '0';
-- Conditional branching
Ie10 == Is11 ;
if  etat = '1' use Vs9 == libre*Is9 ; force_contact == 0.0;
else Is9 == Ie10 ; Vs9 == force_contact ;
end use;
-- process to change the state
process
begin
        if etat = '0' then if (force_contact_s'event) then etat <= '1' ;else etat <=etat  ;end if ;
         else
          if (aperture_s'event) and (not aperture'above(0.0)) then etat <= '0' ; else etat <=  etat  ;
          end if ;
        end if ;
        wait for 0.01us ; wait on force_contact_s, aperture_s ;
end process ;
```

VHDL-AMS modeling

Conditional branching

state = 1, open device

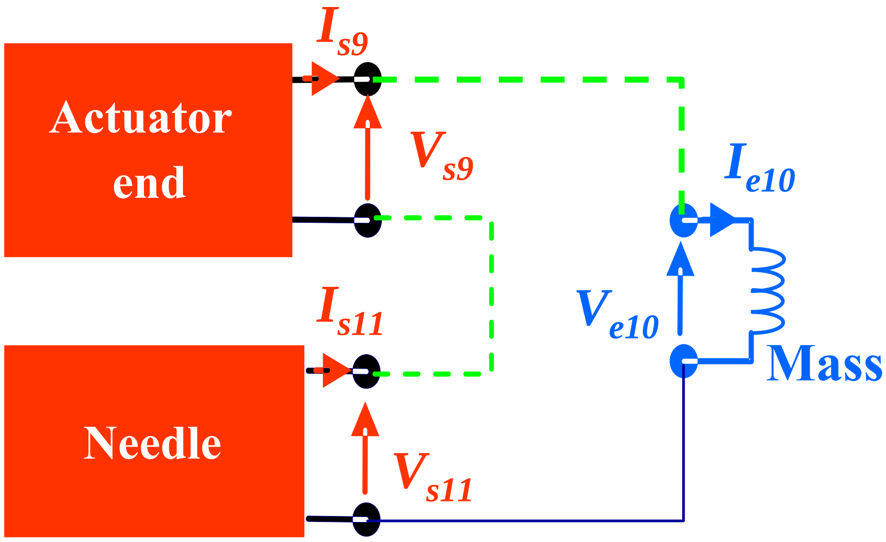


$I_{e10} = Is_{11}$ (permanent contact mass/needle)

$V_{s9} = 0$

$V_{e10} = V_{s11}$

state = 0, closed device



$I_{e10} = Is_{11}$ (permanent contact mass/needle)

$I_{e10} = Is_{9}$

$V_{e10} = V_{s11} + V_{s9}$

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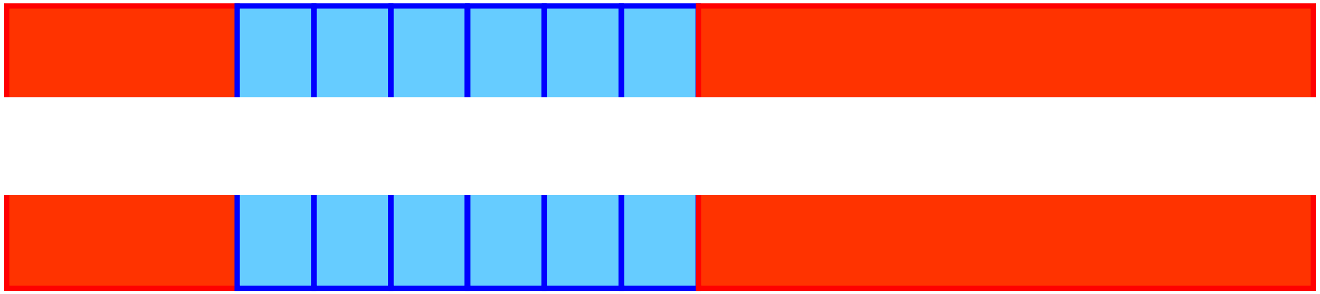
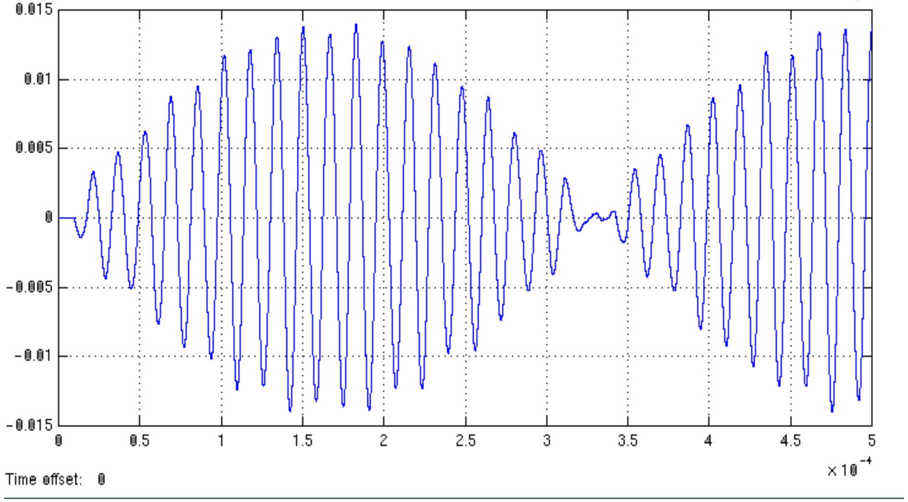
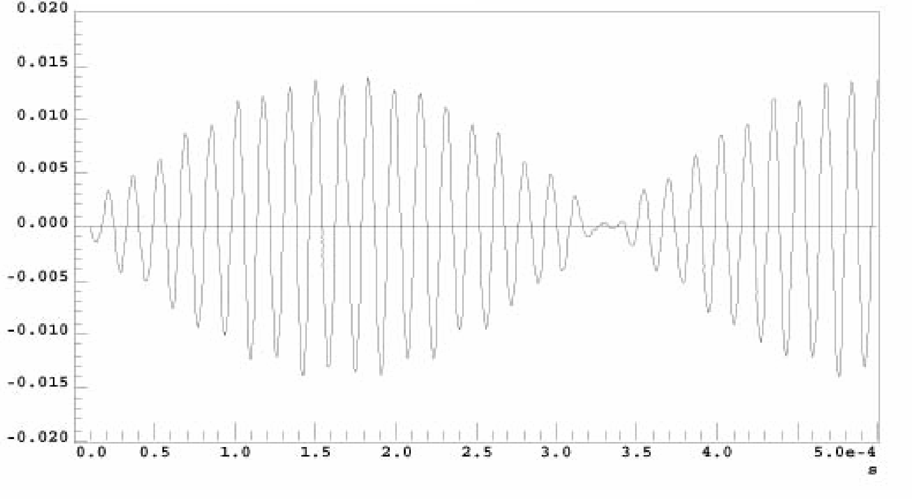
Free actuator



Output speed



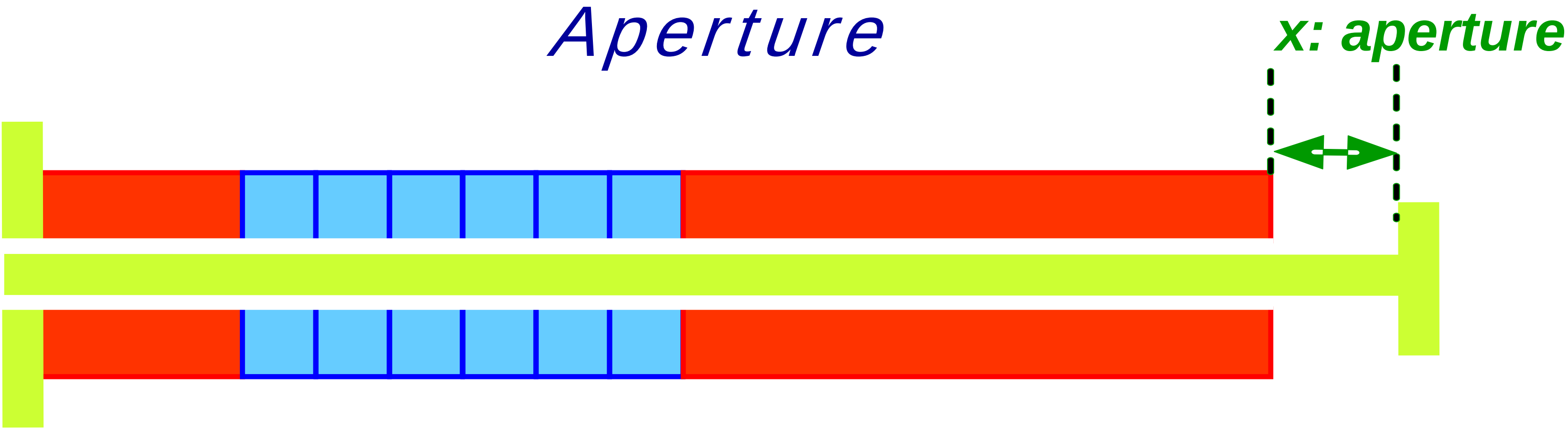
Simulink model

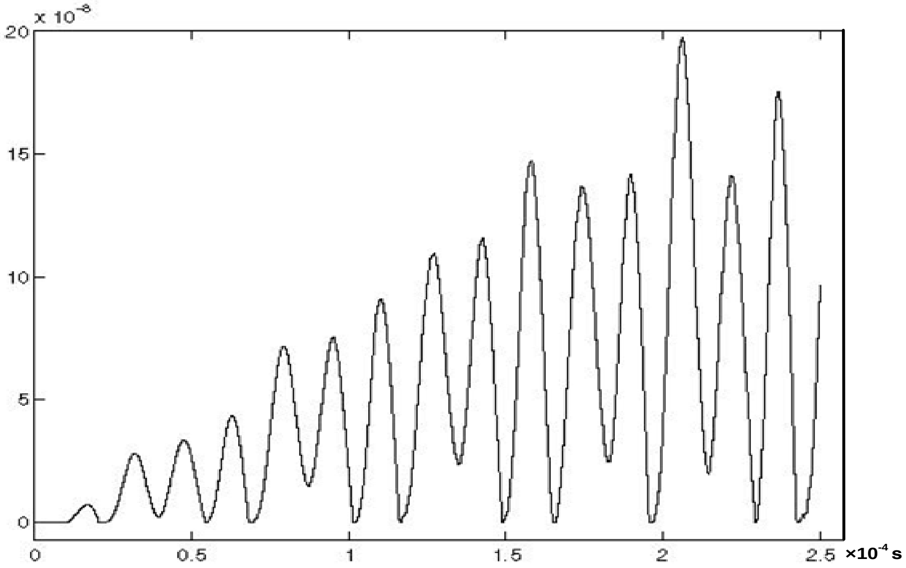


VHDL-AMS model

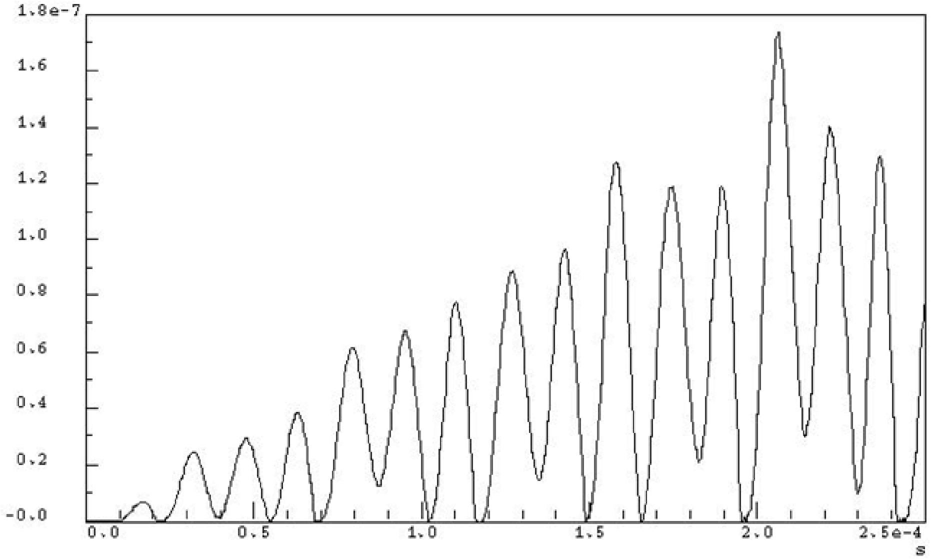
Complete device

Aperture





Simulink model



VHDL-AMS model

Outline

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Conclusion

☐ VHDL-AMS model for a piezoelectric device:

- ✓ Kirchhoff network level
- ✓ behavioral/structural approach
- ✓ shocks management

☐ VHDL-AMS facilities demonstrated for:

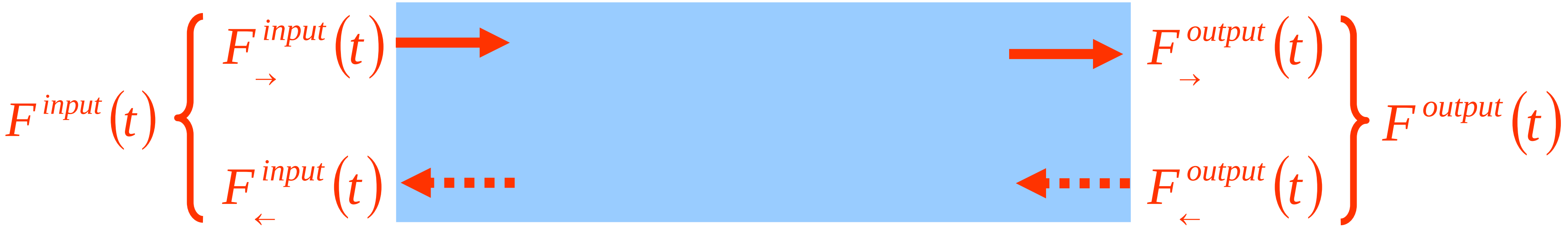
- ✓ physical systems composed with transmission lines
- ✓ with state changings

Supplementary slides

Single parts modeling

Decoupling approach

- Principle



$$F^{input}(t)\begin{cases}\underset{\rightarrow}{F}^{input}(t)\\ \underset{\leftarrow}{F}^{input}(t)\end{cases}\qquad\qquad\left.\begin{matrix}\underset{\rightarrow}{F}^{output}(t)\\ \underset{\leftarrow}{F}^{output}(t)\end{matrix}\right\}F^{output}(t)$$

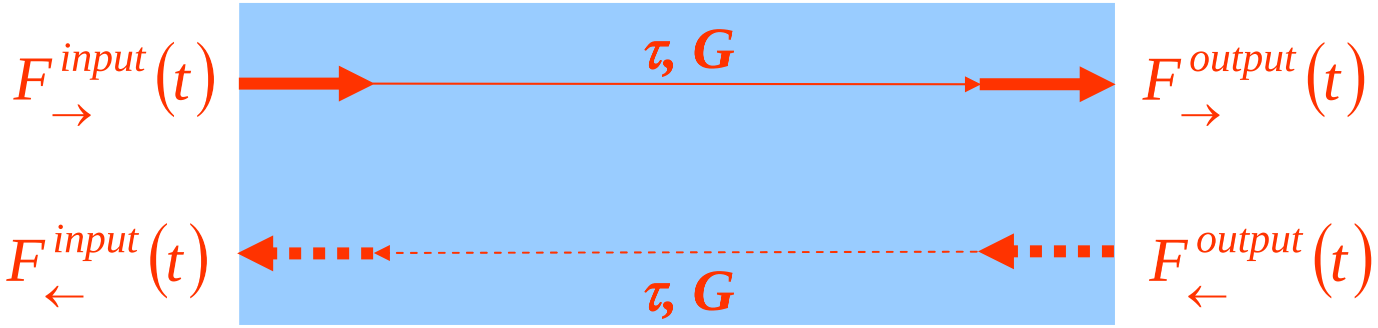
$$F_{input}(t)=\underset{\rightarrow}{F}^{input}(t)+\underset{\leftarrow}{F}^{input}(t)$$

$$F_{output}(t)=\underset{\rightarrow}{F}^{output}(t)+\underset{\leftarrow}{F}^{output}(t)$$

Single parts modeling

Decoupling approach

- Metallic part



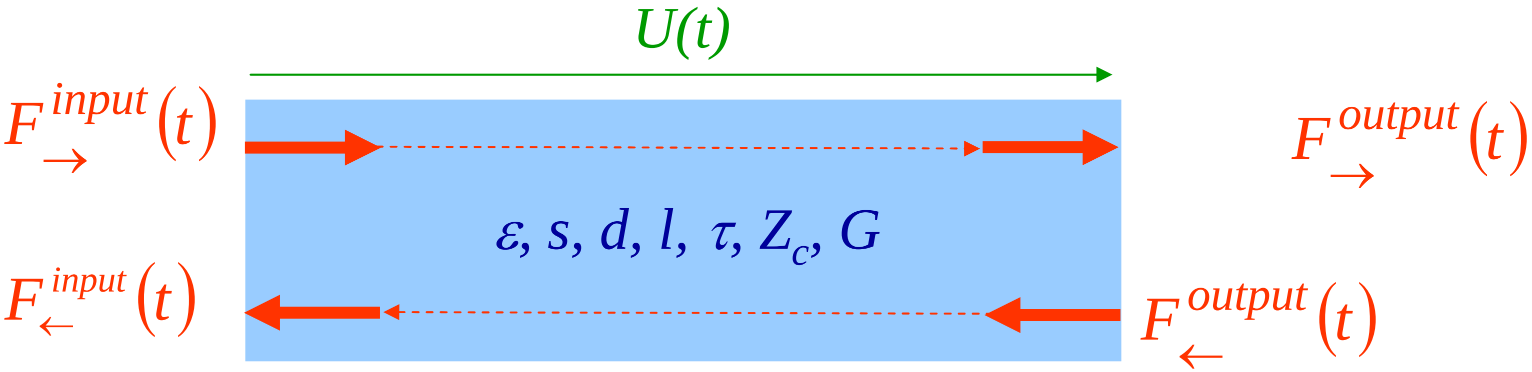
$$F_{\rightarrow}^{output}(t) = G \cdot F_{\rightarrow}^{input}(t-\tau)$$
$$F_{\leftarrow}^{input}(t) = G \cdot F_{\leftarrow}^{output}(t-\tau)$$

$$S(t) = \frac{1}{Z_c}\left(F_{\rightarrow}(t) - F_{\leftarrow}(t)\right)$$

Single parts modeling

Decoupling approach

- Piezoelectric part



$$\begin{cases} F_{\leftarrow}^{input}(t) = G\cdot F_{\leftarrow}^{output}(t-\tau) + \dfrac{\mathbf{d\sigma}}{\mathbf{2\cdot(\varepsilon s - d^2)}}\mathbf{(D(t)-D(t-\tau))} \\ F_{\rightarrow}^{output}(t) = G\cdot F_{\rightarrow}^{input}(t-\tau) + \dfrac{\mathbf{d\sigma}}{\mathbf{2\cdot(\varepsilon s - d^2)}}\mathbf{(D(t-\tau)-D(t))} \end{cases}$$

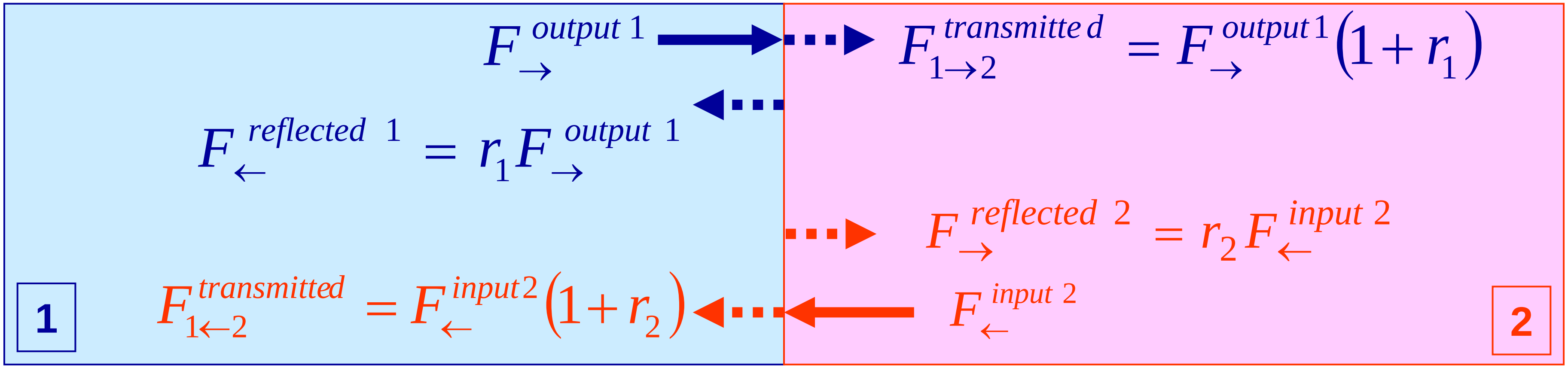
$$\int\left(\mathbf{S_{output}(t)-S_{input}(t)}\right)\mathbf{dt} = \frac{\mathbf{1}}{\mathbf{Z_c}}\int\left(\mathbf{F_{\rightarrow}^{output}(t)-F_{\leftarrow}^{output}(t)+F_{\rightarrow}^{input}(t)-F_{\leftarrow}^{input}(t)}\right)$$

Assembly

Decoupling approach

- Interface between two parts

Interface : Output 1= Input 2



$$F_{\rightarrow}^{output\ 1}$$

$$F_{1\rightarrow 2}^{transmitted} = F_{\rightarrow}^{output\ 1}\left(1+r_1\right)$$

$$F_{\leftarrow}^{reflected\ 1} = r_1 F_{\rightarrow}^{output\ 1}$$

$$F_{\rightarrow}^{reflected\ 2} = r_2 F_{\leftarrow}^{input\ 2}$$

$$F_{1\leftarrow 2}^{transmitted} = F_{\leftarrow}^{input\ 2}\left(1+r_2\right)$$

$$F_{\leftarrow}^{input\ 2}$$

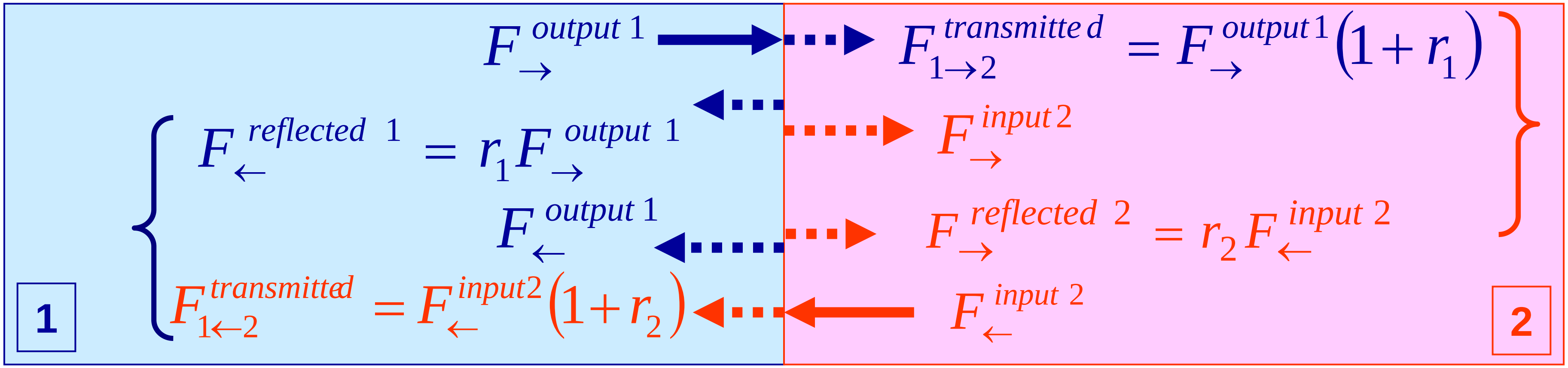
$$\begin{cases} r_1 = \dfrac{Z_c^{\ 2} - Z_c^{\ 1}}{Z_c^{\ 1} + Z_c^{\ 2}} \\ r_2 = -r_1 = \dfrac{Z_c^{\ 1} - Z_c^{\ 2}}{Z_c^{\ 1} + Z_c^{\ 2}} \end{cases}$$

Assembly

Decoupling approach

- Interface between two parts

Interface : Output 1= Input 2



$$F_{\rightarrow}^{output\ 1}$$

$$F_{1\rightarrow 2}^{transmitted} = F_{\rightarrow}^{output\ 1}\left(1+r_1\right)$$

$$F_{\rightarrow}^{input\ 2}$$

$$\left\{\begin{array}{l} F_{\leftarrow}^{reflected\ 1} = r_1 F_{\rightarrow}^{output\ 1} \\ F_{\leftarrow}^{output\ 1} \\ F_{1\leftarrow 2}^{transmitted} = F_{\leftarrow}^{input\ 2}\left(1+r_2\right) \end{array}\right.$$

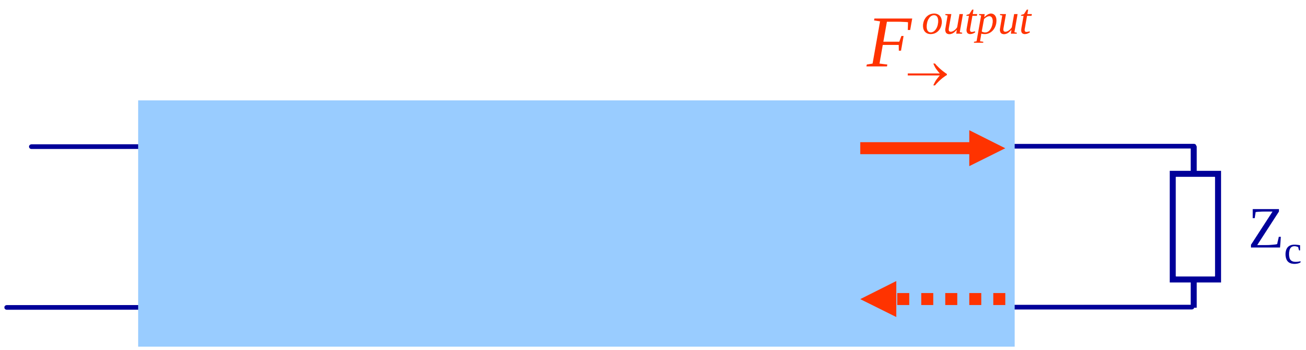
$$F_{\rightarrow}^{reflected\ 2} = r_2 F_{\leftarrow}^{input\ 2}$$

$$F_{\leftarrow}^{input\ 2}$$

Limit conditions

Coupling approach

- Limit conditions



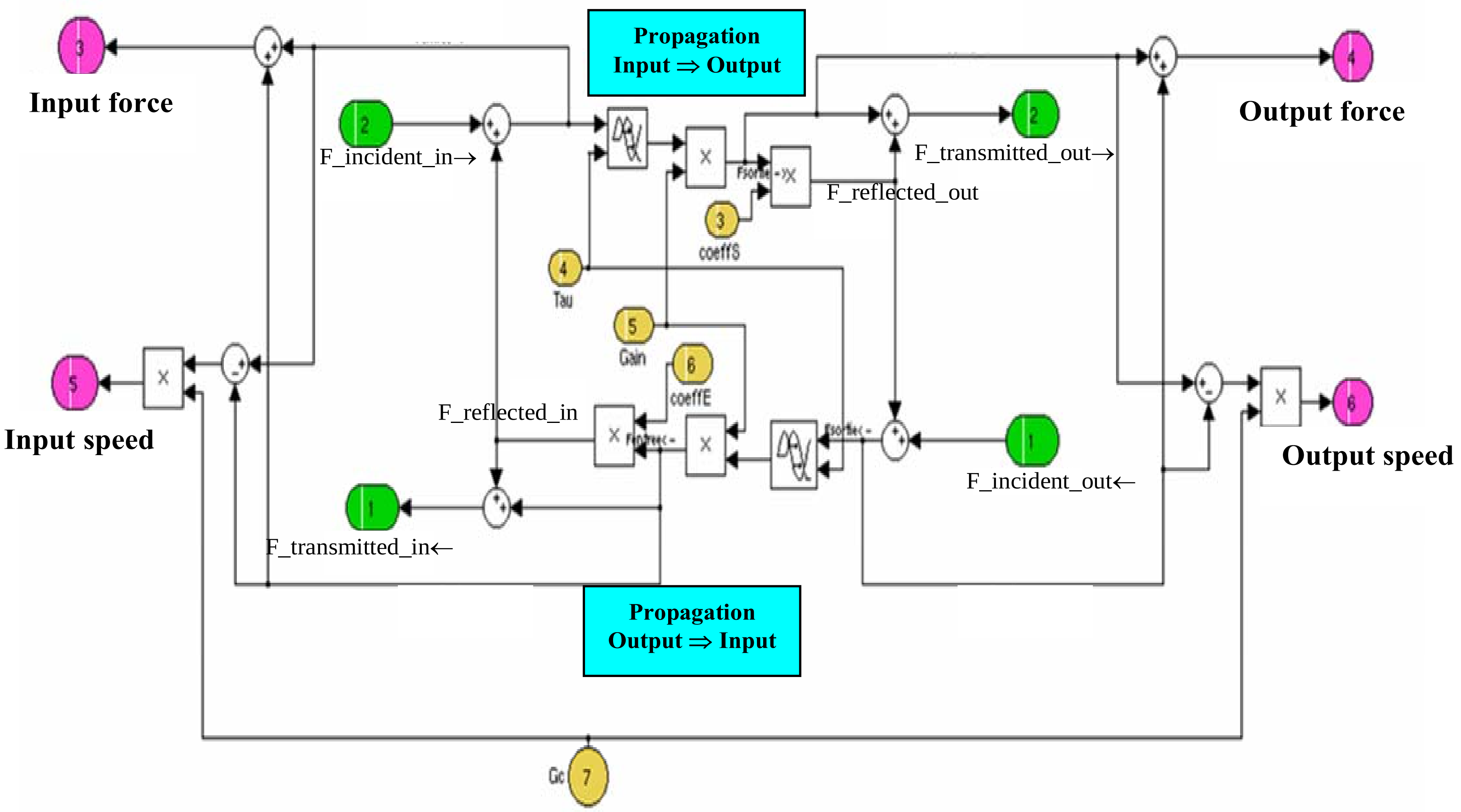
$$F_{\leftarrow}^{output} = F_{\leftarrow charge}^{transmitted} + F_{\leftarrow}^{reflected}$$

$$F_{\leftarrow charge}^{transmitted}(t) = 0$$

$$F_{\leftarrow}^{reflected}(t) = \frac{Z_{charge} - Z_c}{Z_{charge} + Z_c} F_{\rightarrow}^{output}(t)$$

MATLAB/Simulink model

Metallic part



Propagation
Input ⇒ Output

Input force

F_incident_in→

Output force

F_transmitted_out→

F_reflected_out

Input speed

F_reflected_in

Output speed

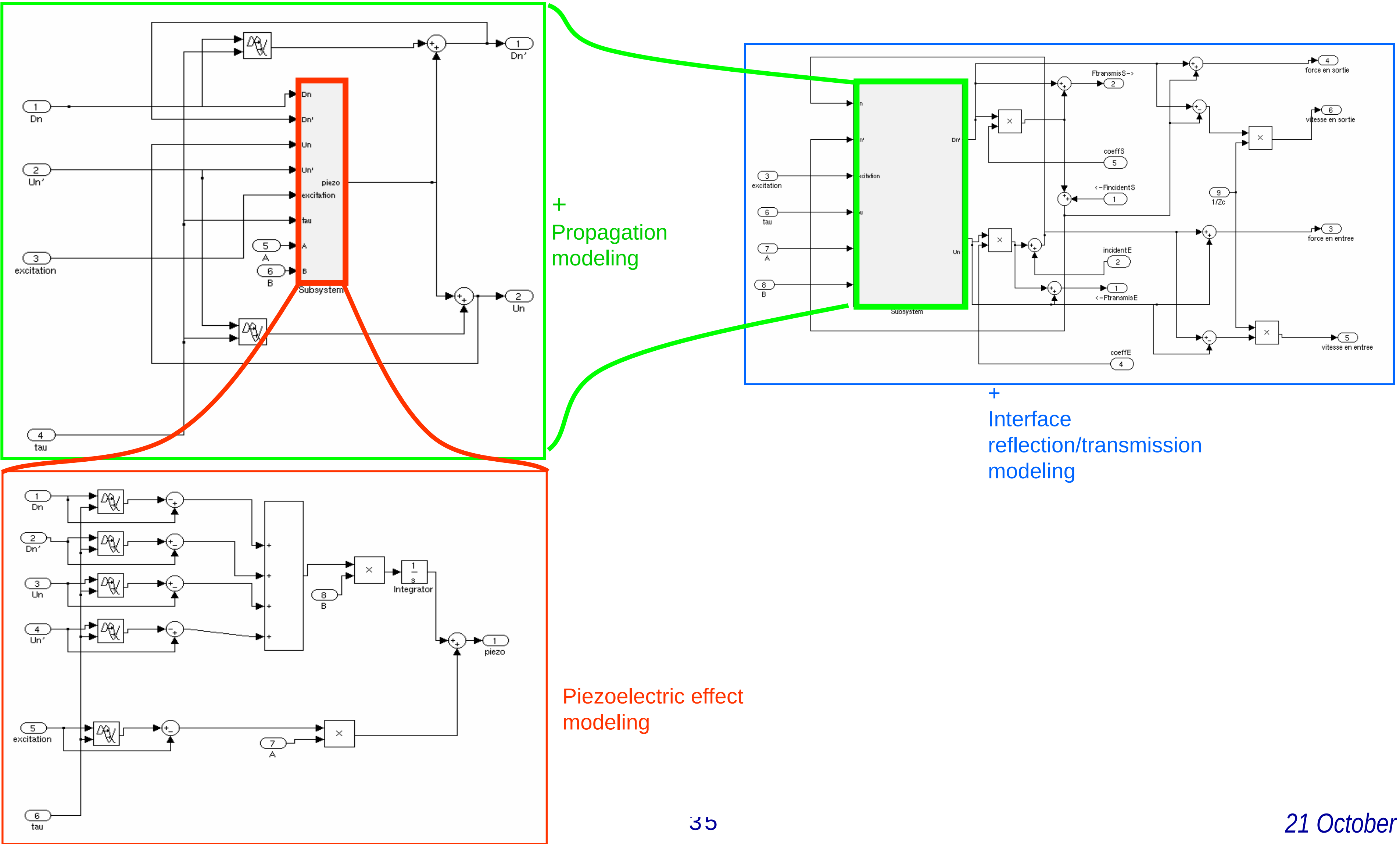
F_incident_out←

F_transmitted_in←

Propagation
Output ⇒ Input

MATLAB/Simulink model

Piezoelectric part



\+
Propagation
modeling

\+
Interface
reflection/transmission
modeling

Piezoelectric effect
modeling

MATLAB/Simulink model

Assembly