


BMAS 2004



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

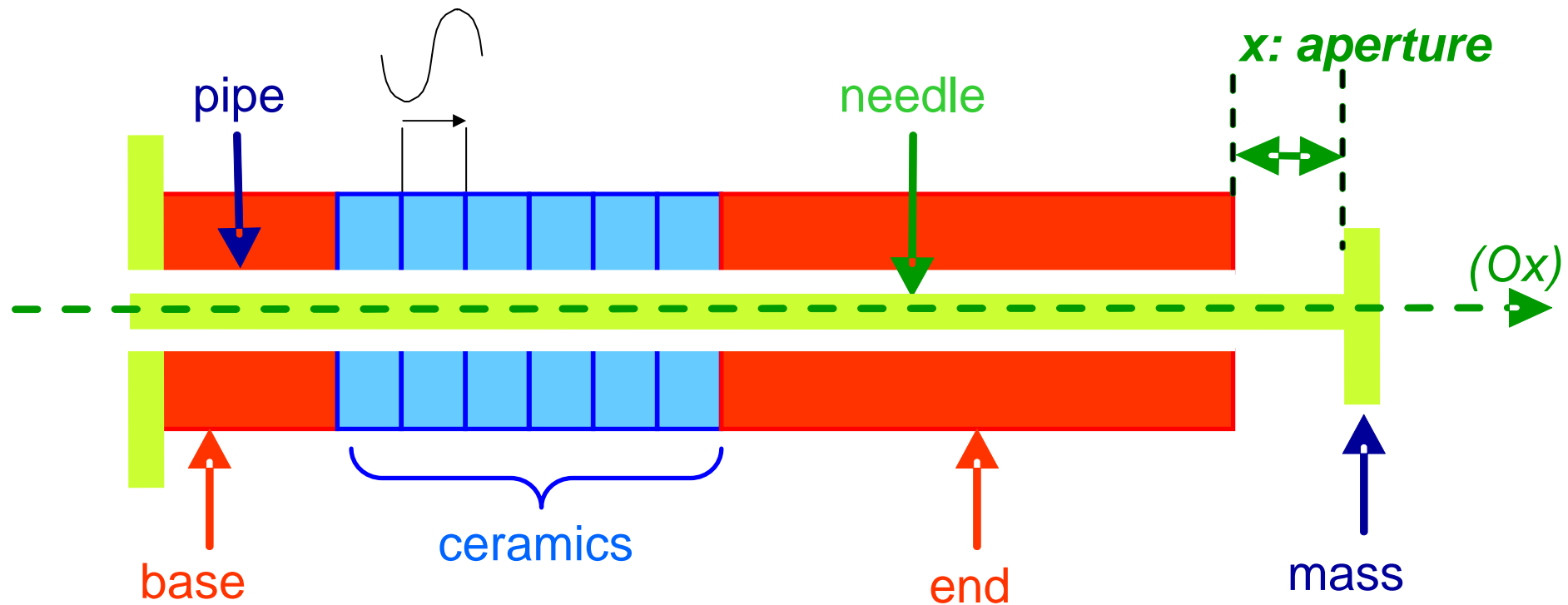
Sylvie Guessab – Supélec, Paris

Jean Oudinot – Mentor Graphics, Paris

# 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 ?

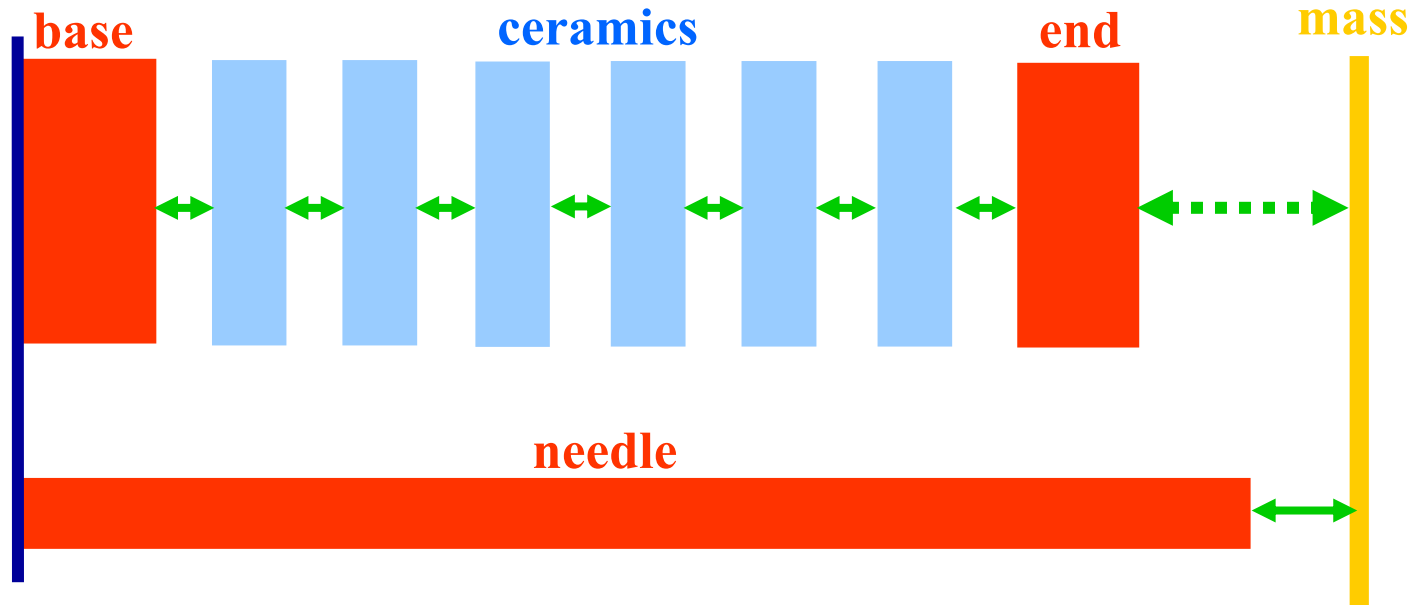
# Piezoelectric device



- Purpose: to spray liquid

# Methodology

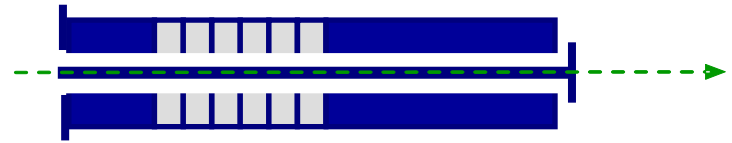
## *Modular approach*



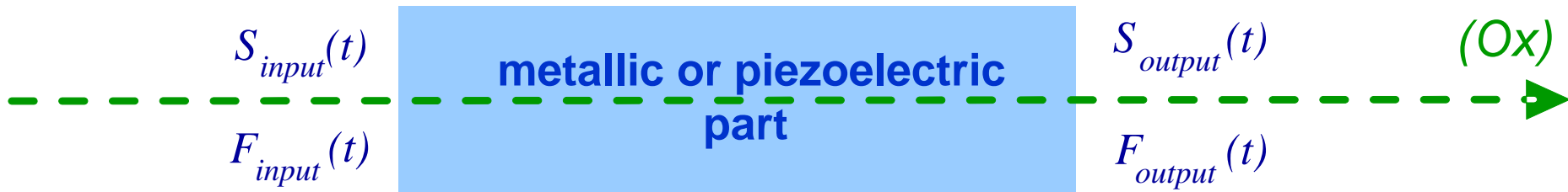
- Single part behavior (generic models for metallic and piezoelectric parts)
- Assembly (energy exchange at the interfaces)
- Limit conditions (permanent or discontinuous)

# Methodology

## *Modular approach*



### ■ Single part behavior



- 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**

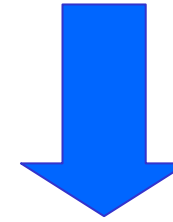
- based on signal flow approach and block diagrams
- uses only one-directional signals



« Decoupling » approach

### **VHDL-AMS (ADVanceMS)**

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



Direct approach

# Methodology

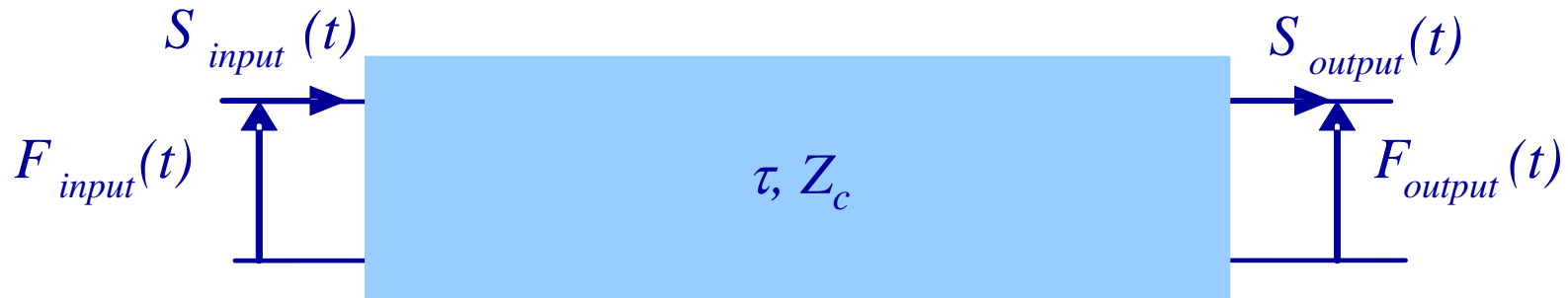
## *Electro-mechanical analogy*

	<b>Mechanical</b>	<b>Electrical</b>
<b>Effort</b>	Force	Voltage
<b>Flow</b>	Speed	Current

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

# Methodology

## *Electro-mechanical analogy*



- metallic part  $\leftrightarrow$  coaxial cable
- telegraphists' equations  $\Leftrightarrow$  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 ( $\tau$ )	$l\sqrt{LC}$	$l\sqrt{\frac{\rho}{E}}$

$l$ : length  
 $L$ : lineic inductance  
 $C$ : lineic capacitance

$E$ : Young's modulus  
 $\sigma$ : section  
 $\rho$ : volumic mass

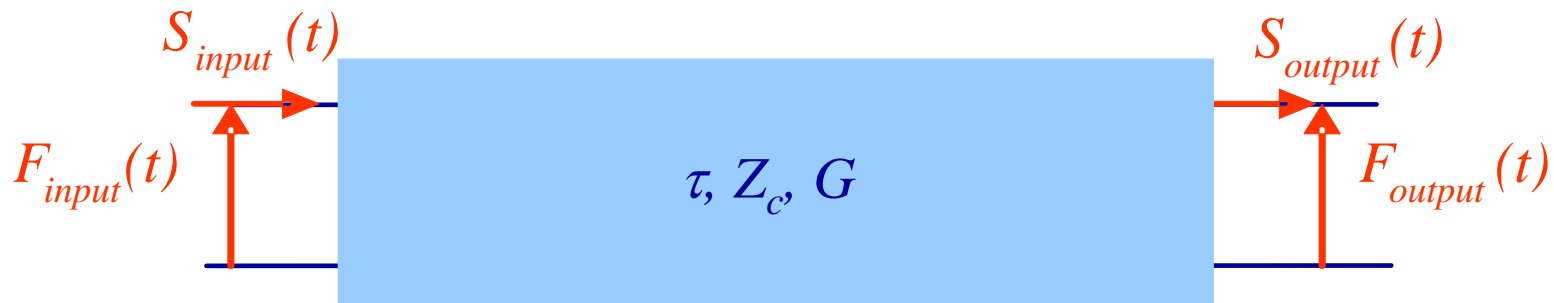


# Outline

- 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*

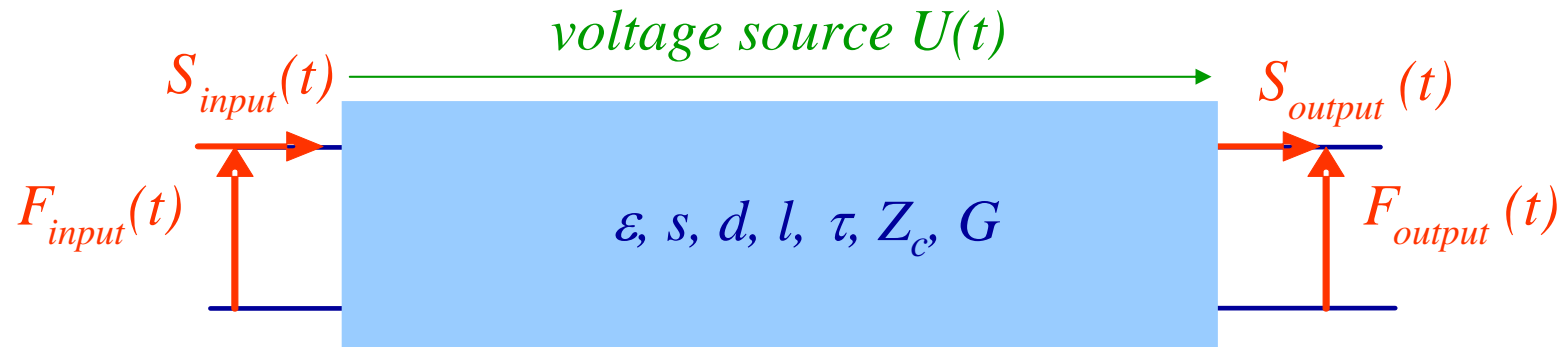


### Propagation equations

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

# Generic models of single parts

## *Piezoelectric part*



Propagation equations + piezoelectric effect

$$\begin{cases} F_{input}(t) - G \cdot F_{output}(t - \tau) = Z_c \cdot (S_{input}(t) - G \cdot S_{output}(t - \tau)) + \frac{d\sigma}{\epsilon s - d^2} (\mathbf{D}(t) - \mathbf{D}(t - \tau)) \\ G \cdot F_{input}(t - \tau) - F_{output}(t) = Z_c \cdot (-G \cdot S_{input}(t - \tau) + S_{output}(t)) + \frac{d\sigma}{\epsilon s - d^2} (\mathbf{D}(t - \tau) - \mathbf{D}(t)) \end{cases}$$

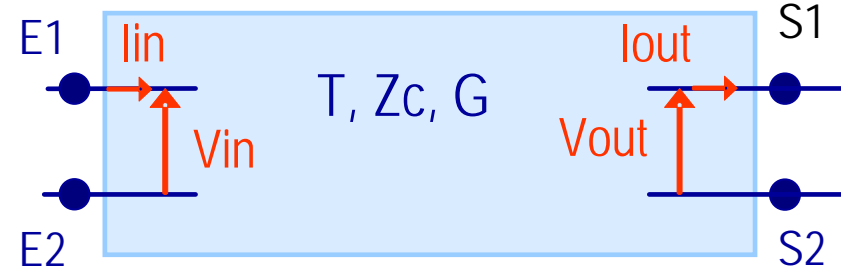
$$\mathbf{D}(t) = \frac{\epsilon s - d^2}{l s} \cdot \mathbf{U}(t) + \frac{d}{l s} \cdot \int (S_{output}(t) - S_{input}(t)) dt$$

# 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 lin 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*lin + G*Vout'delayed(T);
    Vout == G*Zc*lin'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 lin through E1 to E2; -- input force and speed
  quantity Vout across S1 to S2;           -- voltage source
  quantity lout through S2 to S1;         -- output speed
  quantity V across V1 to V2: real;       -- output force
  quantity D0 : real;                     -- piezoelectric term
begin
```

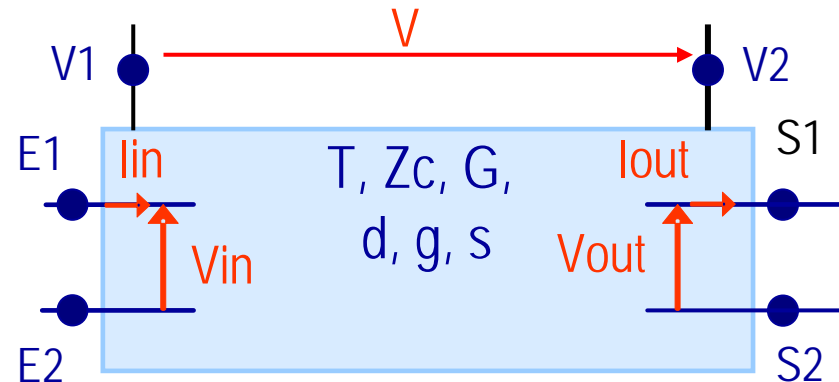
*--Propagation equations + piezoelectrical term*

$$V_{in} = -G \cdot Z_c \cdot l_{out}' \text{delayed}(T) + Z_c \cdot l_{in} + G \cdot V_{out}' \text{delayed}(T) - d \cdot \text{Sig} / (\epsilon \cdot s - d \cdot d) \cdot (D_0' \text{delayed}(T) - D_0);$$

$$V_{out} = G \cdot Z_c \cdot l_{in}' \text{delayed}(T) - Z_c \cdot l_{out} + G \cdot V_{in}' \text{delayed}(T) - d \cdot \text{Sig} / (\epsilon \cdot s - d \cdot d) \cdot (D_0' \text{delayed}(T) - D_0);$$

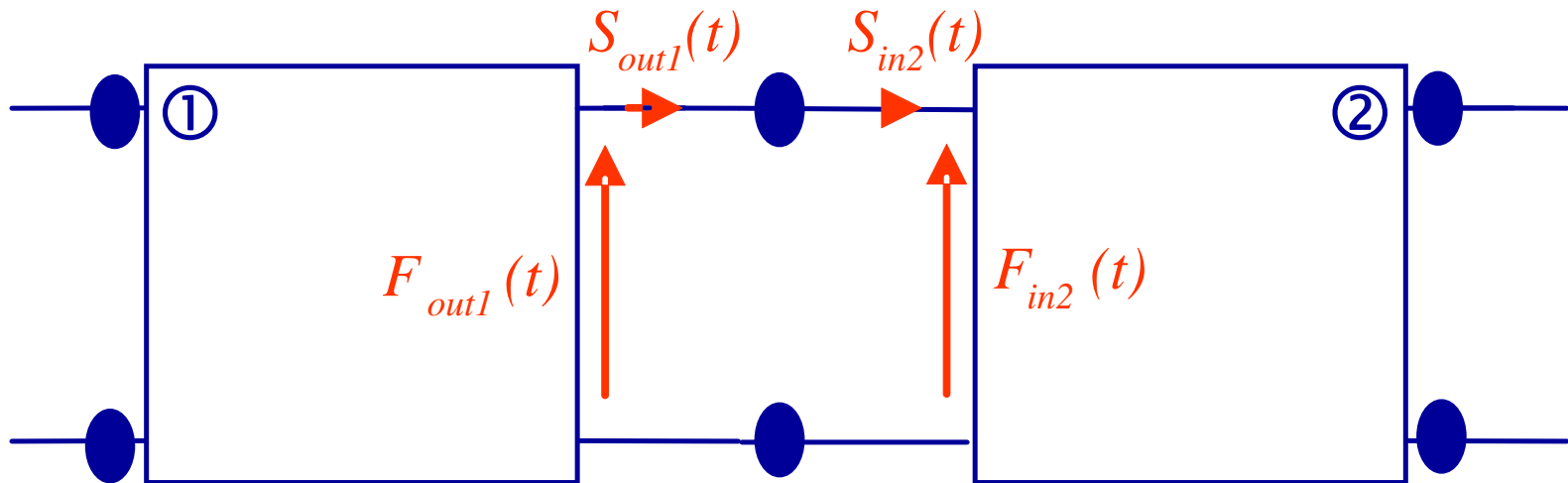
$$V = l \cdot s / (\epsilon \cdot s - d \cdot d) \cdot D_0 - d / (\epsilon \cdot s - d \cdot d) \cdot (l_{out}' \text{integ} - l_{in}' \text{integ});$$

```
end architecture propagation;
```



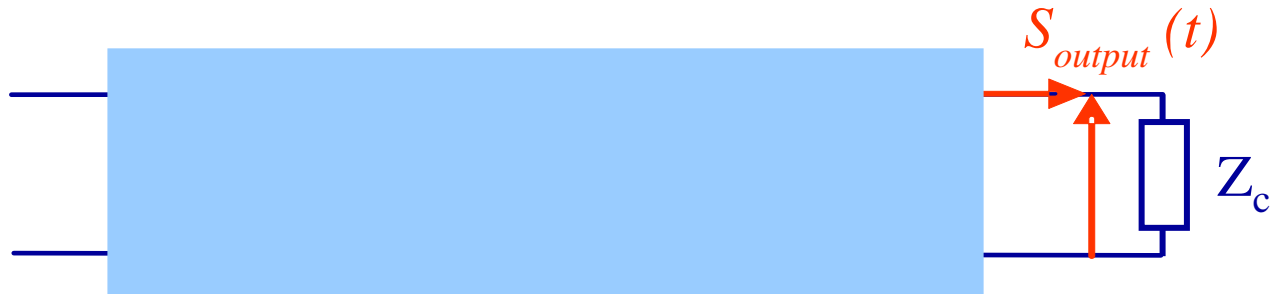
# Assembly

## *Structural modeling*



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

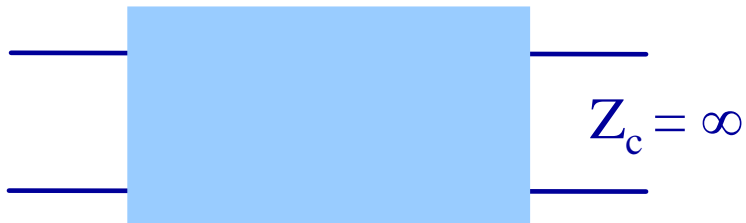
# Limit conditions



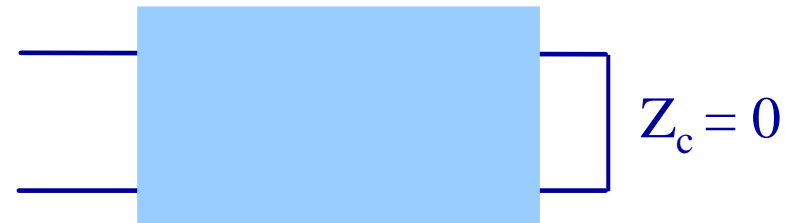
$$F_{output}(t) = Z_c S_{output}(t)$$

## Exemples

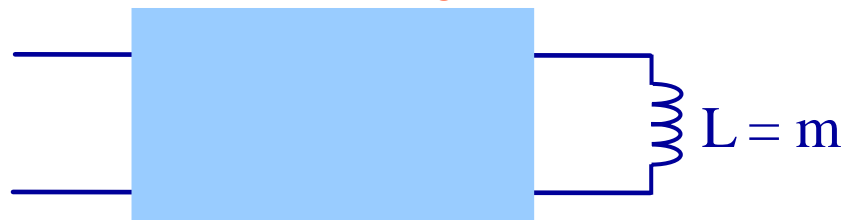
Fixed part



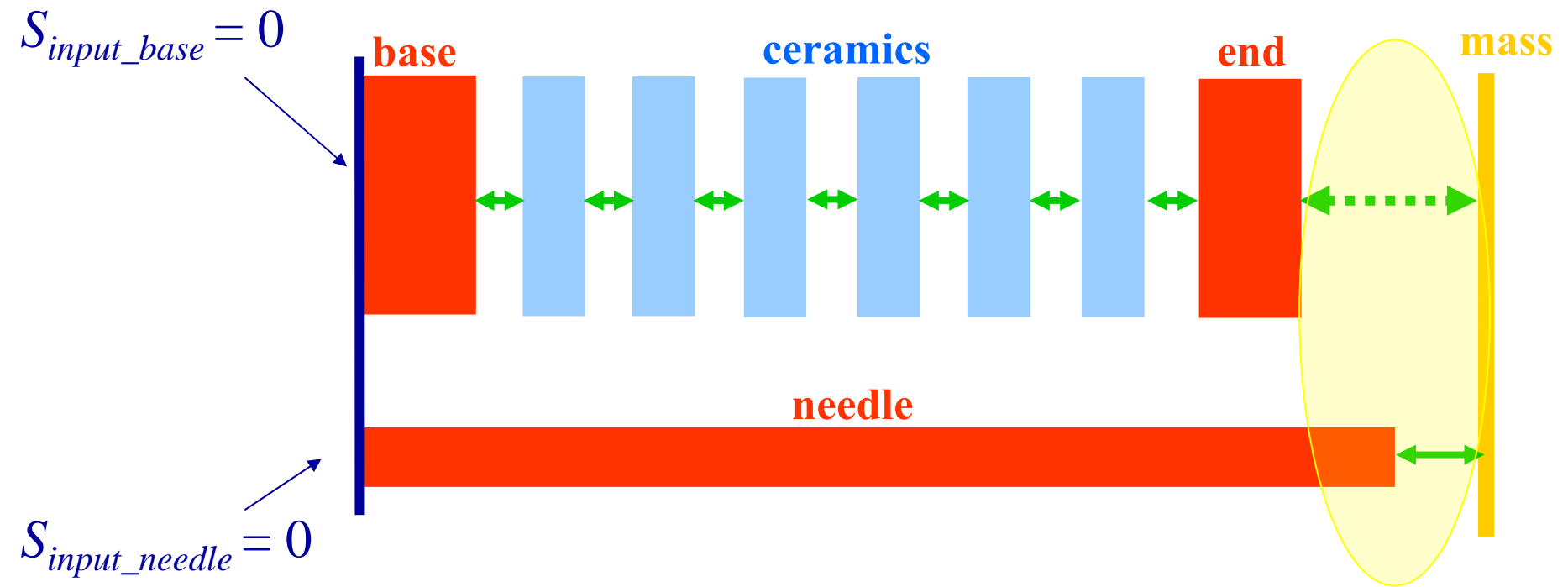
Part moving in an empty space



Part fixed to a free rigid mass  $m$



# Limit conditions





# Methodology

## *VHDL-AMS Model*

**Metallic part :**  
**Generic behavioral model**

Entity...

Architecture...

**Piezoelectric part :**  
**Generic behavioral model**

Entity...

Architecture...

**Piezoelectric device**

Entity...

Architecture...

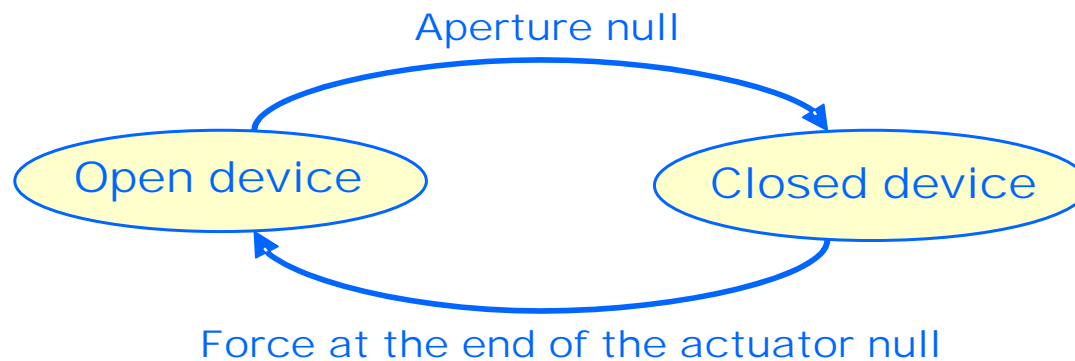
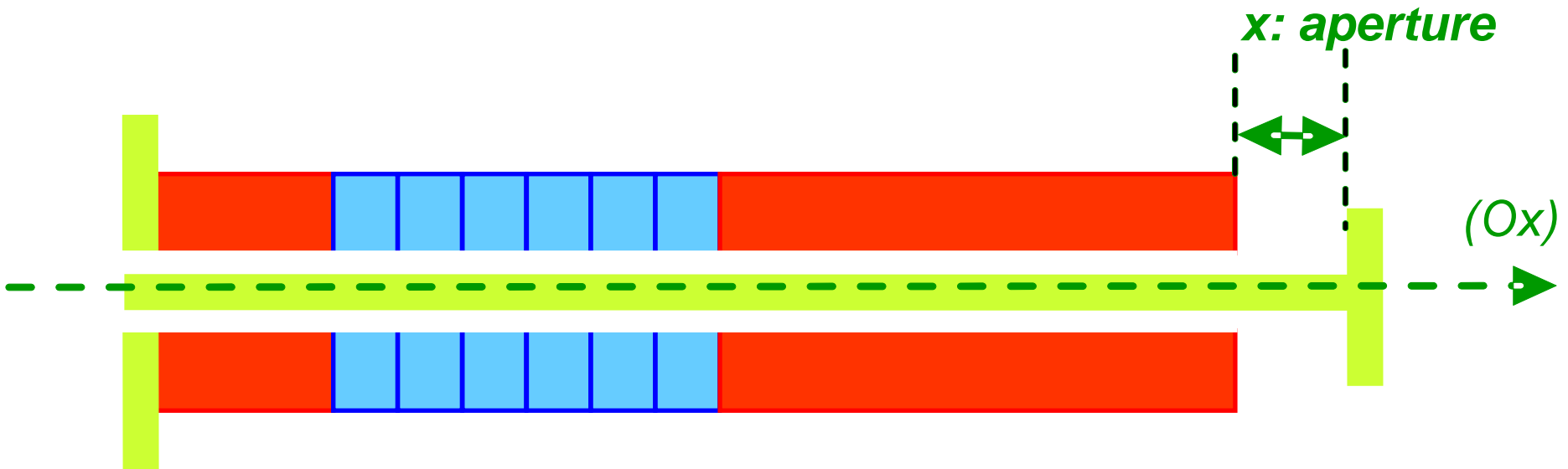
**Structural model**  
(assembly of metallic  
and piezoelectric parts)

**Behavioral model**  
(limit conditions)

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# Principle



# VHDL-AMS code

## *Shocks management*

```
-- signal triggering state changings
aperture == le10'integ - ls9'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

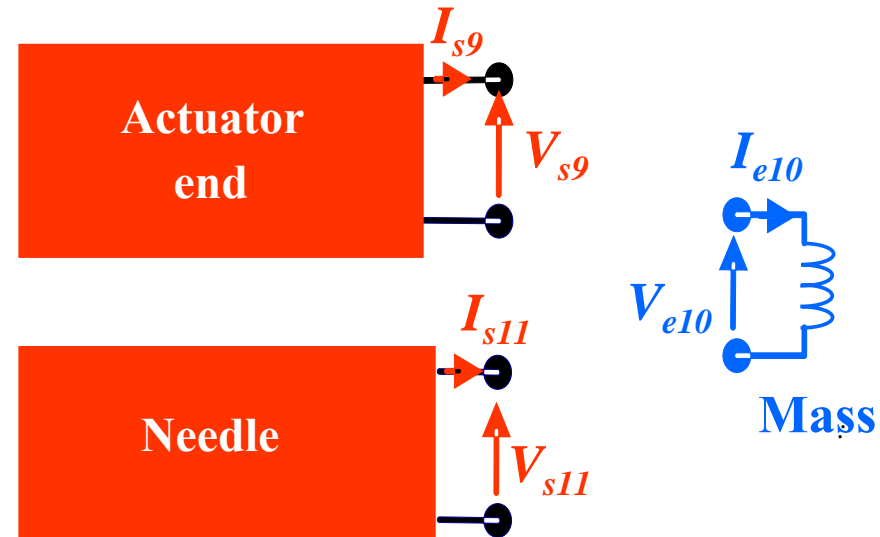
```
le10 == ls11 ;
if etat = '1' use Vs9 == libre*ls9 ; force_contact == 0.0;
else ls9 == le10 ; Vs9 == force_contact ;
end use;
```

### -- 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 ;
```

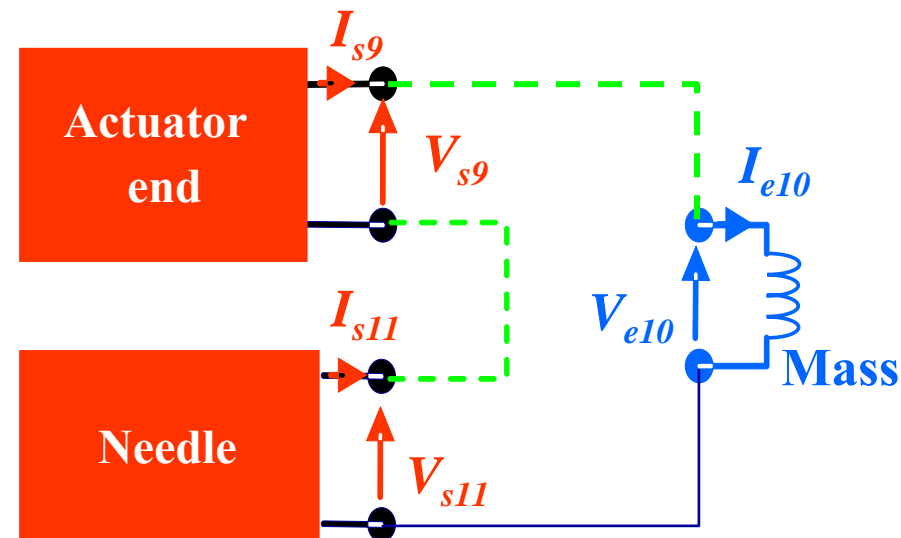
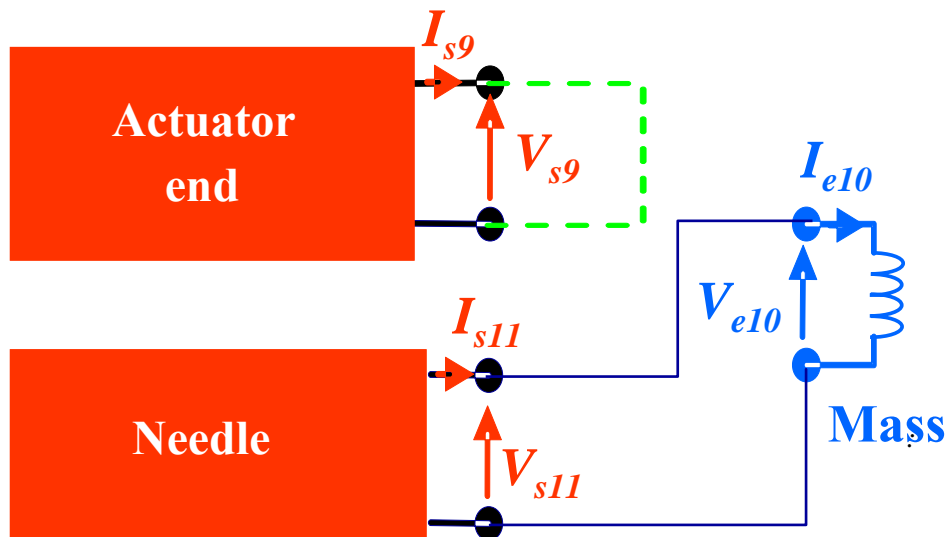


# VHDL-AMS modeling

## *Conditional branching*

state = 1, open device

state = 0, closed device



$$I_{e10} = I_{s11} \quad (\text{permanent contact mass/needle})$$

$$V_{s9} = 0$$

$$V_{e10} = V_{s11}$$

$$I_{e10} = I_{s11} \quad (\text{permanent contact mass/needle})$$

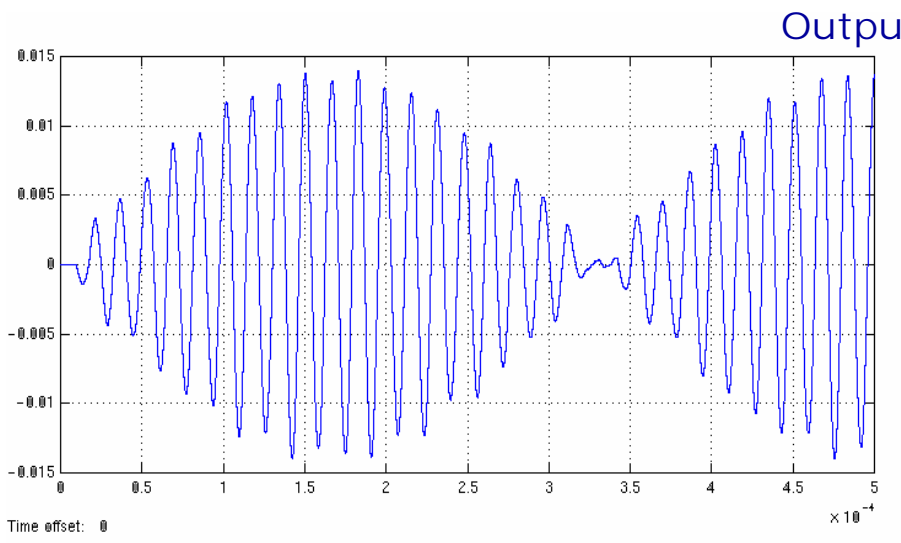
$$I_{e10} = I_{s9}$$

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

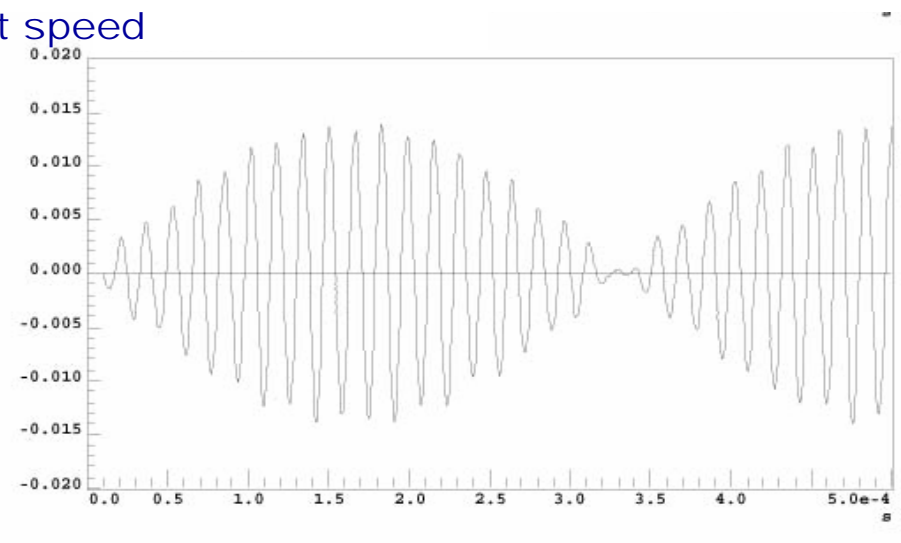
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- Conclusion

# Free actuator



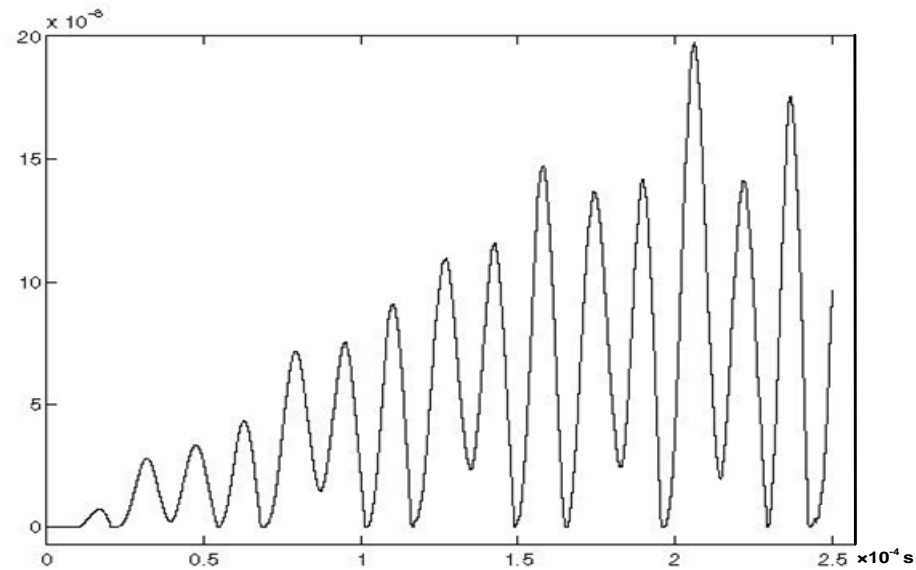
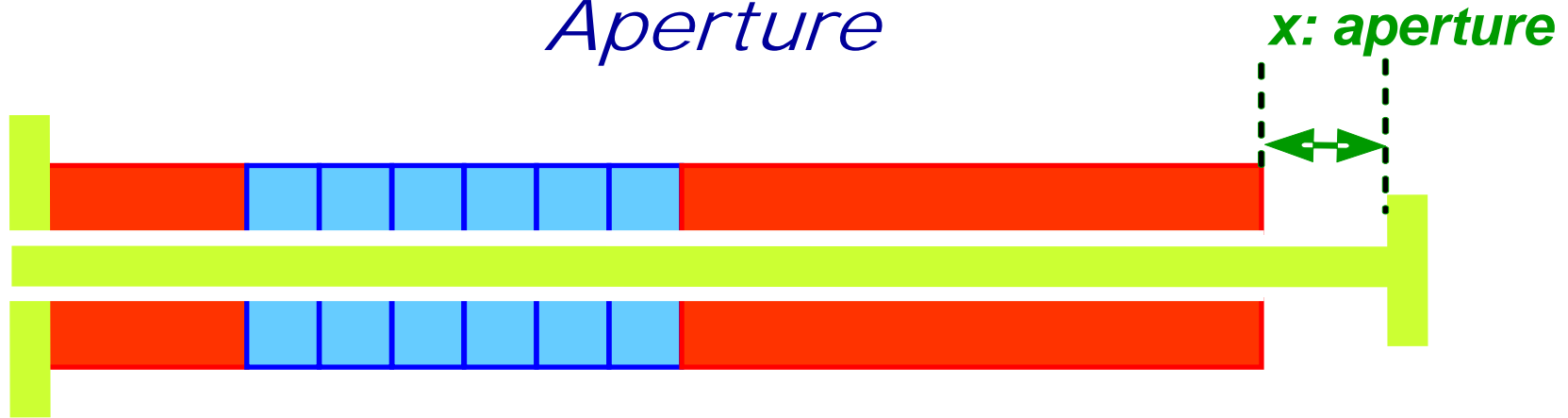
Simulink model



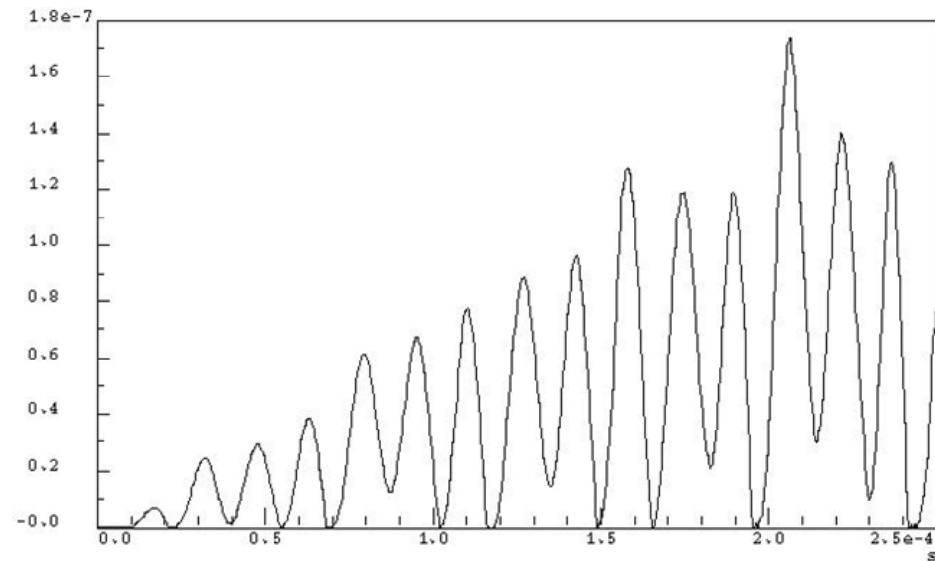
VHDL-AMS model

# Complete device

## *Aperture*



Simulink model



VHDL-AMS model



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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:

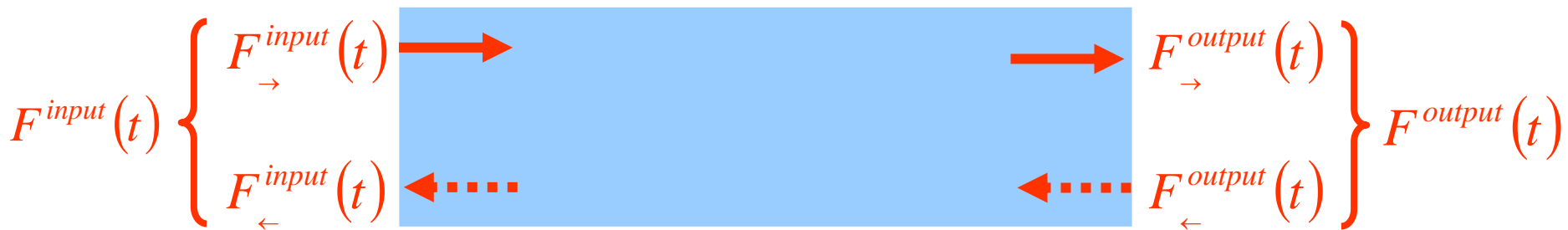
- ✓ physical systems composed with transmission lines
- ✓ with state changings

# Supplementary slides

# Single parts modeling

## *Decoupling approach*

### ■ Principle



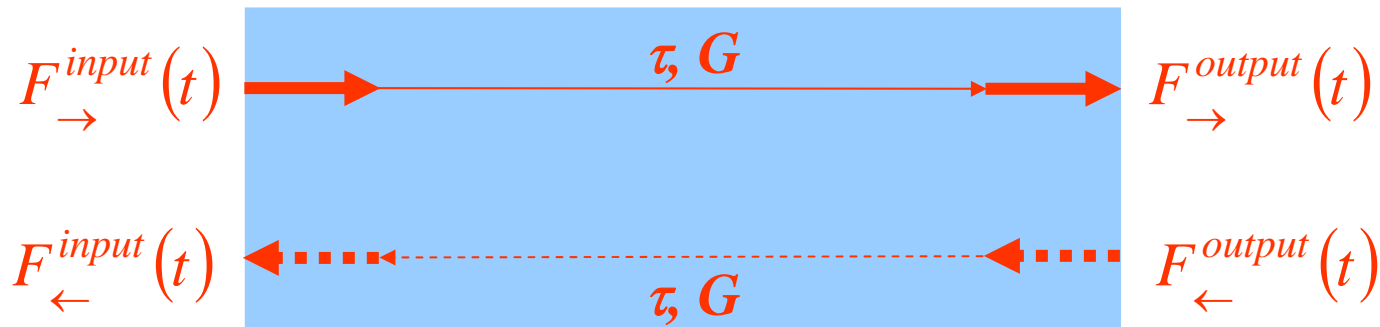
$$F_{input}^{\rightarrow}(t) = F_{\rightarrow}^{input}(t) + F_{\leftarrow}^{input}(t)$$

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

# Single parts modeling

## *Decoupling approach*

- Metallic part



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

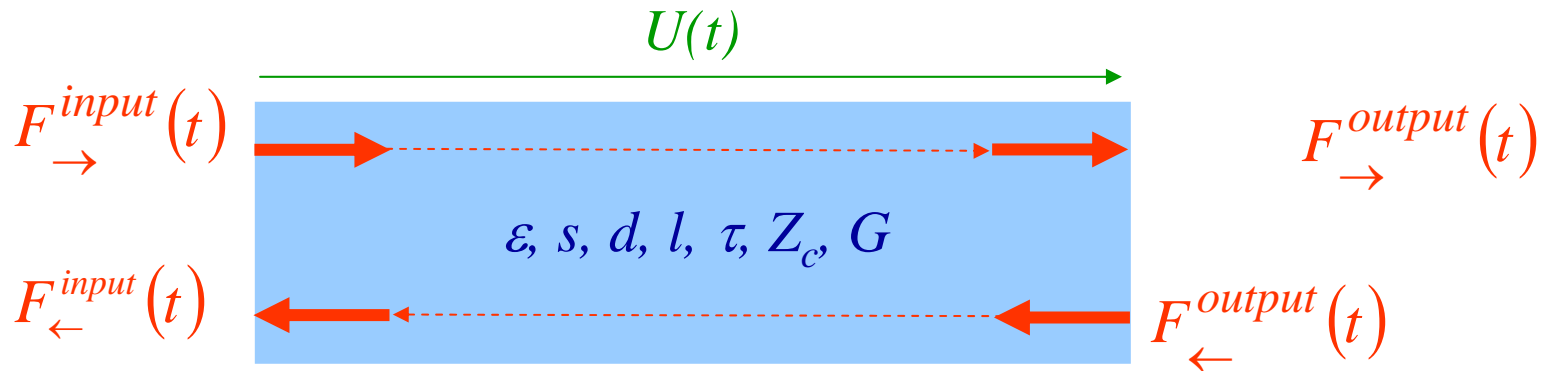
$$F_{\leftarrow}^{input}(t) = G \cdot F_{\leftarrow}^{output}(t - \tau)$$

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

# Single parts modeling

## *Decoupling approach*

### ■ Piezoelectric part



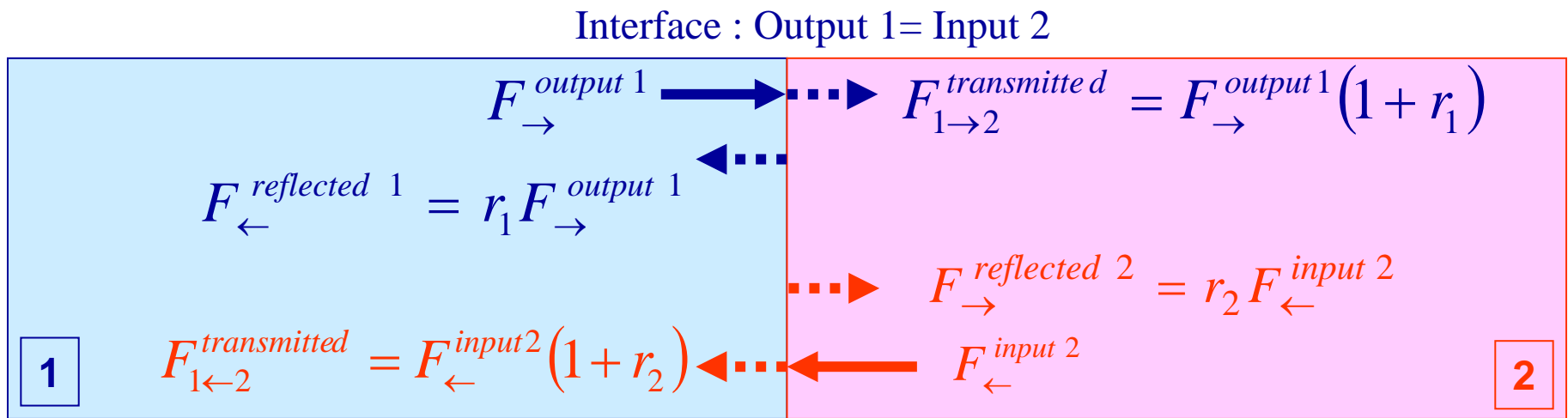
$$\begin{cases} F_{\leftarrow}^{input}(t) = G \cdot F_{\leftarrow}^{output}(t - \tau) + \frac{d\sigma}{2 \cdot (\epsilon s - d^2)} (D(t) - D(t - \tau)) \\ F_{\rightarrow}^{output}(t) = G \cdot F_{\rightarrow}^{input}(t - \tau) + \frac{d\sigma}{2 \cdot (\epsilon s - d^2)} (D(t - \tau) - D(t)) \end{cases}$$

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

# Assembly

## *Decoupling approach*

- Interface between two parts

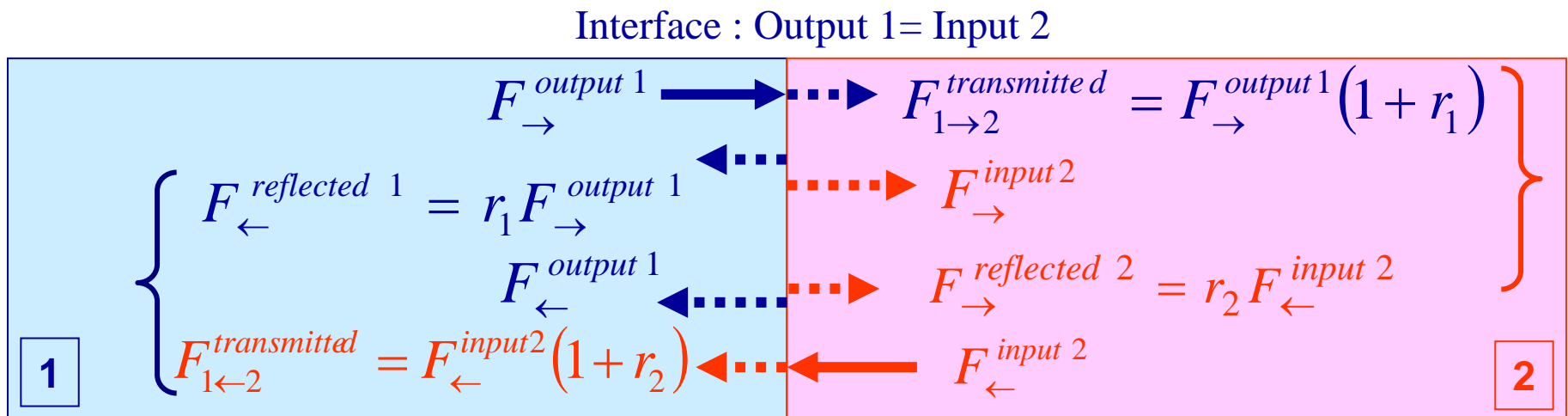


$$\begin{cases} r_1 = \frac{Z_c^2 - Z_c^1}{Z_c^1 + Z_c^2} \\ r_2 = -r_1 = \frac{Z_c^1 - Z_c^2}{Z_c^1 + Z_c^2} \end{cases}$$

# Assembly

## *Decoupling approach*

- Interface between two parts





# Limit conditions

## *Coupling approach*

- Limit conditions



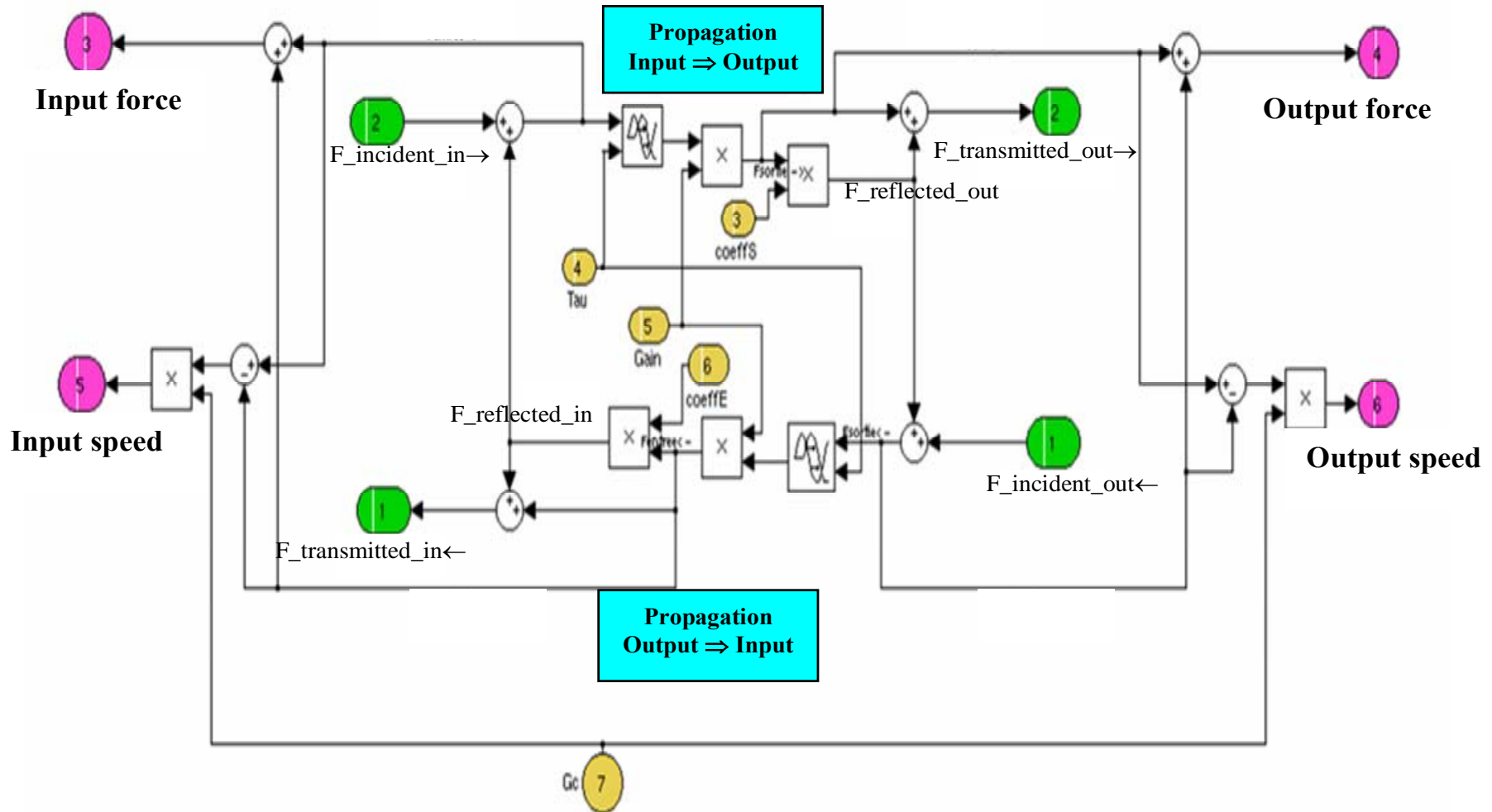
$$F_{\leftarrow}^{output} = F_{\leftarrow charge}^{transmitted} + F_{\leftarrow}^{reflected}$$

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

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

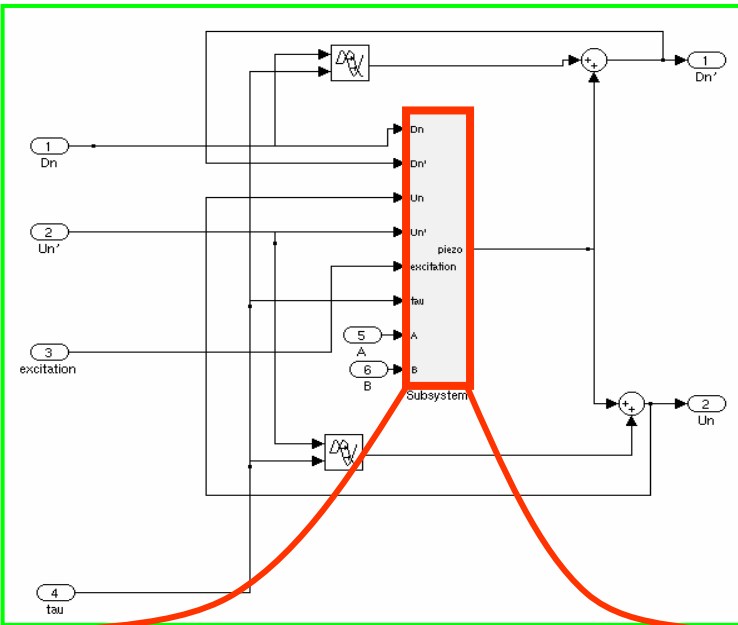
# MATLAB/Simulink model

## *Metallic part*

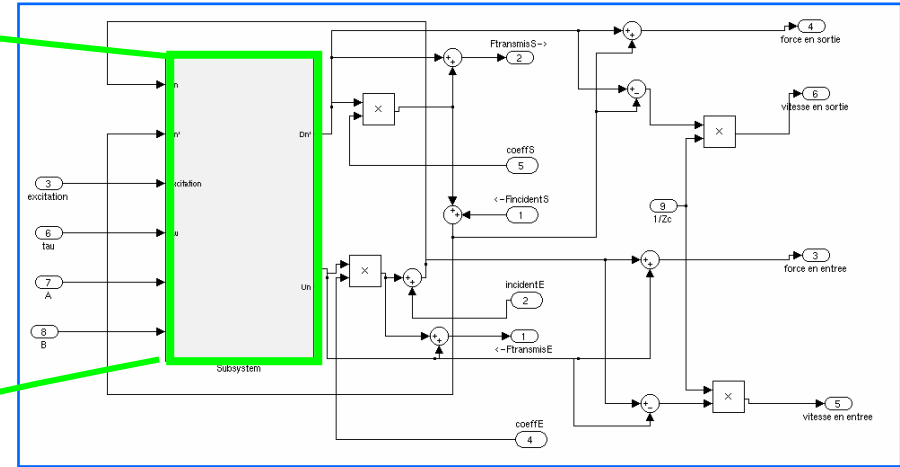


# MATLAB/Simulink model

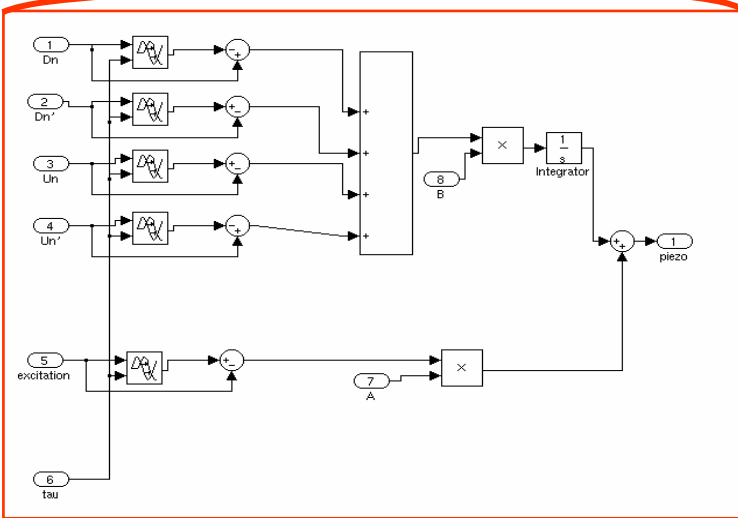
## Piezoelectric part



+ Propagation modeling



+ Interface reflection/transmission modeling



Piezoelectric effect modeling

# MATLAB/Simulink model *Assembly*

