LECTURE # 01: SYLLABUS AND POLICIES & INTRODUCTIONS TO SIMILITUDE OF EXPERIMENTS

Dr. Hui Hu
Martin C. Jischke Professor in Aerospace Engineering
Dept. of Aerospace Engineering, Iowa State University
537 Bissell Road, Ames, Iowa 50011-1096, USA.
Tel: 515-294-0094 (O) / Fax: 515-294-3262 (O)
Email: huhui@iastate.edu

❑ Course Introduction

- ***Course policy***
  - ***Required attendance for lab exercises:*** *In this course, you will conduct lab experiments for various applications. These experiments involve computer data acquisition systems, pressure and velocity measurement techniques, uncertainty analysis, and report writing.* ***Unexcused absences from lab exercises will result in an "F" for the entire course!***
  - ***COVID-19 Related Medical Absence:*** *If any students in the class have confirmed or suspected COVID19 infections, they should follow ISU policy to fill "COVID-19 Reporting Form for Campus" as soon as possible. Please send a notice email to the course instructor about the reported COVID-19 case, which can be used as evidence to justify excused absence of the labs or final exam during the required quarantine period.*
  - ***Other Excusable Absence:*** *It is required for you to attend lab exercises and the final exam. Providing doctor's note to state the sickness is an example to justify the excusable lab or exam absence. You can also provide other reasonable evidence to justify your lab or exam absence.*
  - ***Make up the Excusable Absence:*** *Pease contact* ***the course instructor*** *as soon as possible to discuss about the plan to make up the excusable absence when you have an excusable absence from lab exercise and final exam.*

❑ MEASURABLE PROPERTIES

•*Material Properties:* $\rho, m, \textbf{specific volume}, \mu, \gamma, \mathbf{D}$

(Most of them can be found in handbooks)

•*Kinematic Properties:* *Describes the fluid motion w/o considering force. (Position, V, displacement, acceleration, momentum, volume flow rate, mass flow rate…*

•*Dynamic properties:* *Related to applied forces. (Pressure, shear stress , Torque)*

•*Thermodynamic properties:* *Heat and Work. (T, e, h, S)*

❑ Descriptions of Flow Motion

- ***Lagrangian Method*** — ***Focused on fluid particles***

$$V = \lim_{\Delta t \to 0} \frac{\Delta L}{\Delta t}$$

- ***Eulerian Method:*** — ***Focused on space location.***

$$U(x_i, t) = V(x_{0i}, t)$$

Acceleration:

$$\begin{cases} \vec{a} = \dfrac{D\vec{V}}{Dt} \quad \Rightarrow \quad Langragian\ domain \\ \vec{a} = \dfrac{\partial \vec{U}}{\partial t} + (\vec{U} \bullet \nabla)\vec{U} \\ \quad = \dfrac{\partial \vec{U}}{\partial t} + U_1 \dfrac{\partial \vec{U}}{\partial x_1} + U_2 \dfrac{\partial \vec{U}}{\partial x_2} + U_3 \dfrac{\partial \vec{U}}{\partial x_3} \quad \Rightarrow \quad Eulerian\ domain \end{cases}$$

- ***Rate of Strain:***

$$e_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_i}{\partial x_j} \right)$$

- ***Shear stress:***

$$\tau_{ij} = \mu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_i}{\partial x_j} \right)$$

❑ PRIMARY PROPERTIES AND SECONDARY PROPERTIES

- ***Primary Properties:*** ***Properties which are independent to each other***

Name	*Abbreviations*	*Unit*
Length	*L*	*M*
Mass	*m*	*kg*
Time	*t*	*s*
Temperature	*T*	*K*
Electric current	*I*	*A*
Amount of substance	*mole*	*mol*
Luminous intensity	*Candela*	*Cd*
Plane Angle	*Radius*	*rad*
Solid Angle	*Storadian*	*Sr*

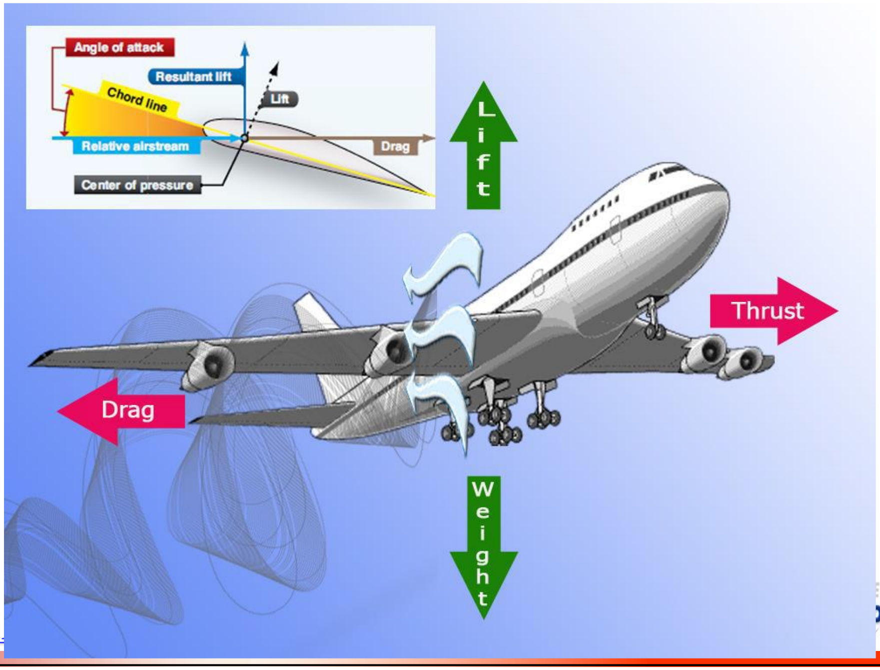
- ***Secondary Properties:*** ***Related to other properties through their definition or basic principles***

Base properties:

- Length: L, SI unit m
- Mass: m, SI unit kg
- Time: t, SI unit s
- Temperature: T, SI unit K
- Electric current: I, SI unit A
- Amount of substance: mole, SI unit mol
- Luminous intensity: I, SI unit Cd

Interesting properties:

- Lift
- Drag
- Moments



❑ Similitude and Dimensional Analysis

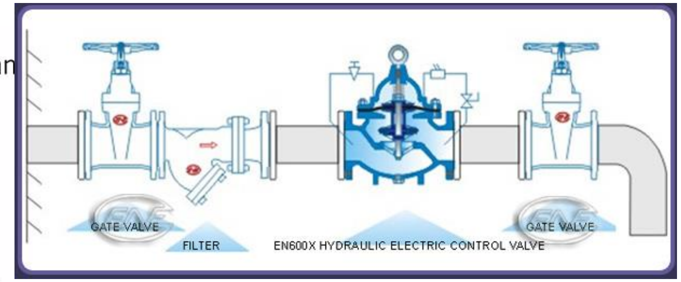
- ***Similitude:***
  - *The study of predicting prototype conditions from model observations.*

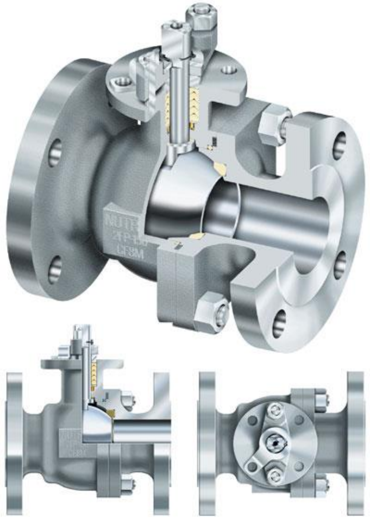


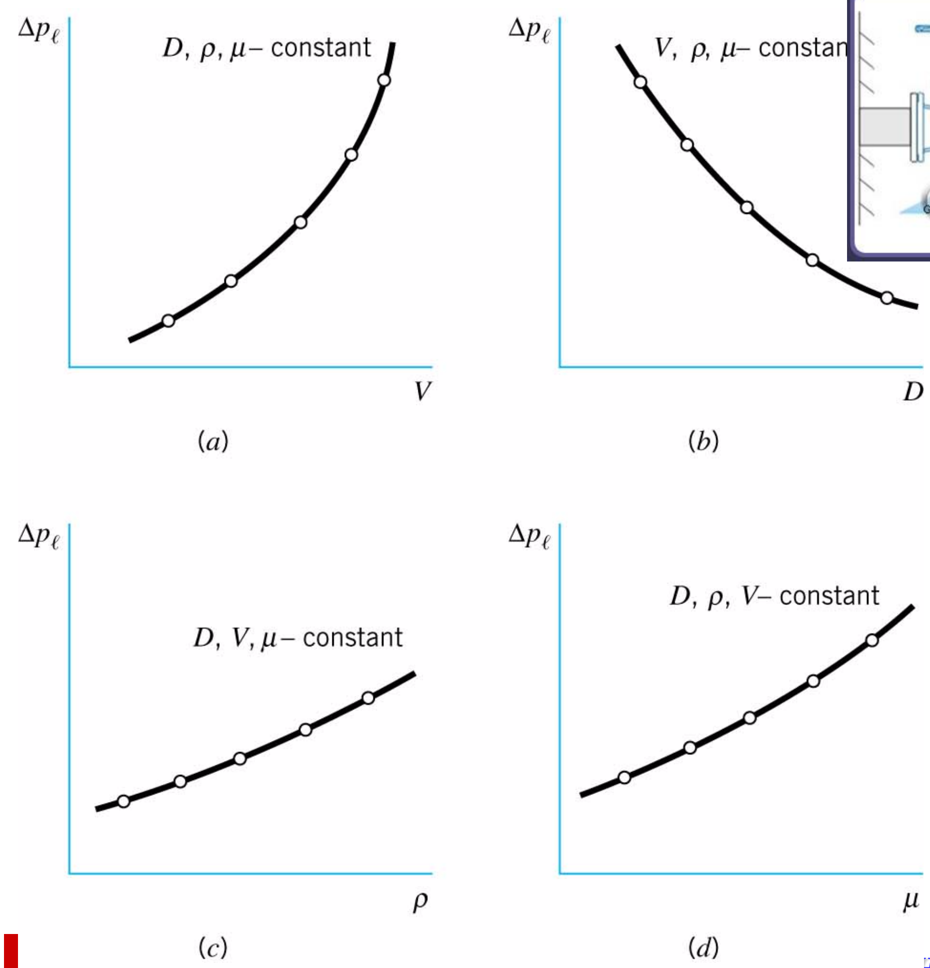
- *F-22 Raptor Air Superiority Fighter*

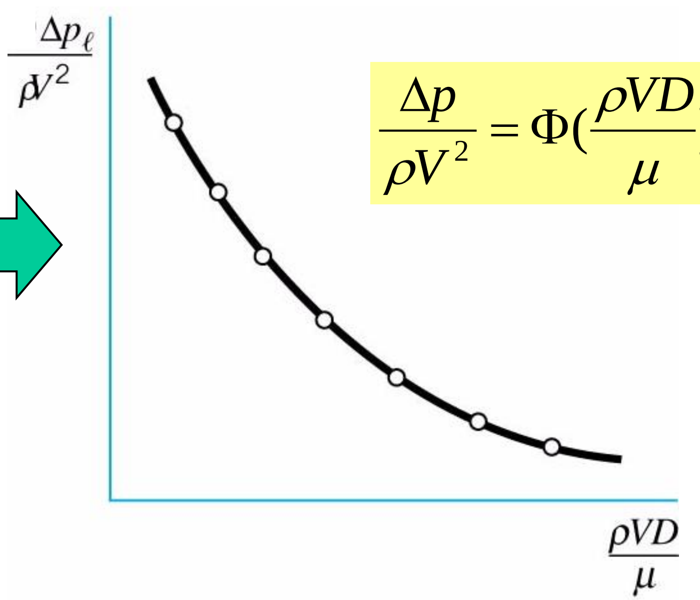
Dimensional Analysis and Similitude

$$\Delta p_l = f(D, \rho, \mu, V)$$









$$\frac{\Delta p}{\rho V^2} = \Phi\left(\frac{\rho V D}{\mu}\right)$$

❑ Buckingham π - Theorem

- *Step 1:* List all the variables that are involved in the problem.
- *Step 2:* Express each of the variables in terms of basic dimensions.
  - Basic dimension: M, L,T, F
  - Force - $F=MLT^{-2}$, density - $\rho=ML^{-3}$; or $\rho=FL^{-3}T^{2}$.
- *Step 3:* Determine the required number of pi-terms.
  - Number of pi-terms is equal to k-r, where k is the number of variables in the problem, r is the number if reference dimensions required to described the variables.
- *Step 4:* Select a number of repeating variables, where the number required is equal to the number of reference dimensions.
- *Step 5;* Form a pi-term by multiplying one of the non-repeating variables by the product of repeating variables, each raised to an exponent that will make the combination dimensionless.
- *Step 6:* Repeat Step 5 for each of the remaining non-repeating variables.
- *Step 7:* Check all the resulting pi terms to make sure they are dimensionless
- *Step 8:* Express the final form as a relationship among the pi-terms, and think about what it means.

$$\Pi_1 = \Phi(\Pi_2, \Pi_{3,} \ldots \Pi_{k-r})$$

❑ Buckingham π - Theorem

- ***Example***

$$\Delta p_l = f(D, \rho, \mu, V)$$

$$\Delta p_l = FL^{-3}$$
$$D = L$$
$$\rho = FL^{-4}T^2$$
$$V = LT^{-1}$$
$$\mu = FL^{-2}T$$

$$K = 5; \quad r = 3 \quad \Rightarrow \quad 2\,\pi - terms\ is\ needed$$

$$\Pi_1 = \Delta p_l D^a V^b \rho^c$$

$$(FL^{-3})(L)^a(LT^{-1})^b(FL^{-4}T^2)^c = F^0T^0L^0 \quad \Rightarrow \quad \begin{cases} 1 + c = 0 \\ -3 + a + b - 4c = 0 \\ -b + 2c = 0 \end{cases} \Rightarrow \quad \begin{cases} a = 1 \\ b = -2 \\ c = -1 \end{cases} \Rightarrow \quad \Pi_1 = \frac{\Delta p_l D}{\rho V^2}$$

$$\Pi_2 = \mu D^a V^b \rho^c$$

$$(FL^{-2}T)(L)^a(LT^{-1})^b(FL^{-4}T^2)^c = F^0T^0L^0 \quad \Rightarrow \quad \begin{cases} 1 + c = 0 \\ -2 + a + b - 4c = 0 \\ 1 - b + 2c = 0 \end{cases} \Rightarrow \quad \begin{cases} a = -1 \\ b = -1 \\ c = -1 \end{cases} \Rightarrow \quad \Pi_2 = \frac{\mu}{D\rho V}$$

Commonly used dimensionless parameters

$$\text{Mach Number, M} = \frac{V}{c} \propto \frac{\text{inertial force}}{\text{compressibility force}}$$

$$\text{Reynolds number, Re} = \frac{\rho VL}{\mu} \propto \frac{\text{inertial force}}{\text{viscous force}}$$

$$\text{Euler number, Eu} = \frac{\Delta p}{\frac{1}{2}\rho V^2} \propto \frac{\text{pressure force}}{\text{inertial force}}$$

$$\text{Drag Coefficient}: C_D = \frac{D}{\frac{1}{2}\rho V^2 S} = \frac{\text{Drag}}{\text{inertial force}}$$

$$\text{Lift Coefficient}: C_L = \frac{L}{\frac{1}{2}\rho V^2 S} = \frac{\text{Lift}}{\text{inertial force}}$$

$$\text{Prandtl Number}: \text{Pr} = \frac{V}{\gamma} = \frac{\text{momentum diffusion}}{\text{heat diffusion}}$$

$$\text{Schmidt Number}: Sc = \frac{U}{\gamma_c} = \frac{\text{momentum}}{\text{mass}}$$

$$\text{Froude Number, Fr} = \frac{V}{\sqrt{\lg}} \propto \frac{\text{inertial force}}{\text{gravity force}}$$

$$\text{Strohal Number, Str} = \frac{l\varpi}{V} \propto \frac{\text{centrifugal force}}{\text{inertial force}}$$

$$\text{Weber Number, We} = \frac{V^2 l\rho}{\sigma} \propto \frac{\text{inertial force}}{\text{surface tension force}}$$

…

Table 2.5 Nondimensional parameters

Name	Symbol	Definition	Comparison ratio
Biot number	Bi	$\frac{h}{\kappa/L}$	Convection heat transfer/conduction heat transfer
Bond number	Bo	$\frac{g(\rho-\rho_f)L^2}{\sigma}$	Buoyancy force/surface tension force (geometric length/capillary length)^2
Capillary number	Ca	$\frac{\mu V}{\sigma}$	Viscous effect/surface tension effect
Cavitation number	Cav	$\frac{p-p_v}{\rho V^2}$	Pressure difference from vapor pressure/dynamic pressure
Drag coefficient	C_D	$\frac{F_D}{1/2\rho V^2 A_x}$	Drag force/dynamic pressure times cross section area (for aircraft planform area)
Eckert number	Ec	$\frac{V^2}{c_p \Delta T}$	Kinetic energy/enthalpy change
Ekman number	E	$\frac{\nu}{f_R L^2}$	Viscous force/Coriolis force (Coriolis frequency $f_R = 2\sin\theta\Omega$ for earth rotation)
Fourier number	F	$\frac{\alpha t}{L^2}$	Heat conduction rate/energy storage rate
Friction coefficient	C_f	$\frac{\tau}{1/2\rho V^2}$	Shear stress/dynamic pressure
Friction factor	f	$\frac{h_L D/L}{1/2V^2}$	Head loss (viscous dissipation) in pipe of length D/incoming kinetic energy
Froude number	Fr	$\frac{V^2}{gL}$	Kinetic energy/gravity potential Inertia force/gravity force
Grashof number	Gr	$\frac{g\alpha\Delta T L^3}{\nu^2}$	Bouyancy force/viscous force
Head loss coefficient	K	$\frac{h_L}{1/2V^2}$	Head loss (viscous dissipation)/incoming kinetic energy
Knudsen number	Kn	$\frac{\lambda}{L}$	Mean free path/flow length
Lift coefficient	C_L	$\frac{F_L}{1/2\rho V^2 A_x}$	Lift force/dynamic pressure times cross section area (for aircraft planform area)
Mach number	M	$\frac{V}{a}$	Velocity/speed of sound
Marangoni number	Ma	$\frac{L}{\mu\alpha}\partial\sigma/\partial x$	Thermocapillary flow/thermal conduction
Nusselt number	Nu	$\frac{hL}{k}$	Nondimensional heat convection coefficient
Peclet number	Pe	$\frac{VL}{\alpha}$	= Re Pr bulk heat transfer/conduction heat transfer
Prandtl number	Pr	$\frac{\mu c_p}{k}$	Viscous diffusion effect/thermal diffusion effect
Pressure coefficient (Euler number)	C_p	$\frac{p-p_{Ref}}{1/2\rho V^2}$	Pressure change/dynamic pressure
Rayleigh number	Ra	$\frac{g\alpha\Delta T L^3}{\nu k}$	Modified Grashof number Gr Pr
Reynolds number	Re	$\frac{VL}{\nu}$	Inertia effects/viscous effects
Richardson number	Ri	$\frac{g\alpha\Delta T L}{V^2}$	Bouyancy force/inertia force
Rossby number	Ro	$\frac{V}{f_R L}$	Rotation time/flow time (Coriolis frequency $f_R = 2\sin\theta\Omega$ for earth rotation)
Stanton number	St	$\frac{h}{\rho c_p V}$	Heat transfer/thermal capacity of fluid
Strouhal number	St	$\frac{fL}{V}$	Frequency/(flow time)$^{-1}$
Weber number	We	$\frac{\rho V^2 L}{\sigma}$	Dynamic pressure/surface tension

❑ SIMILITUDE

- ***Geometric similarity:*** ***the model has the same shape as the prototype.***

- **F-16**

- **F-16**

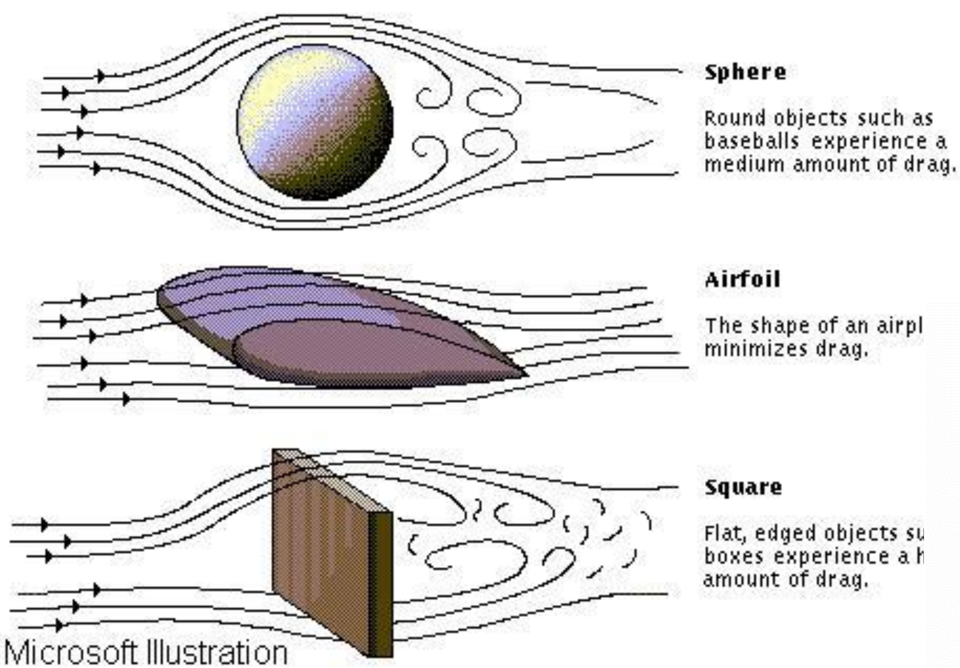
- **F-22**

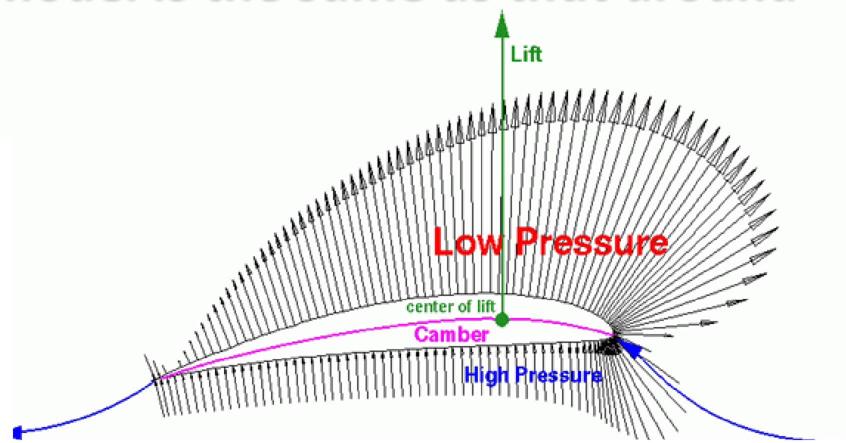
Model Analysis

Similarities and Simlitude

❑ SIMILITUDE

- ***Kinematic similarity:* condition where the velcoity ratio is a constant between all corresponding points in the flow field.**
  - ***The streamline pattern around the model is the same as that around the prototype***





Model Analysis

Similarities and Simlitude

❑ SIMILITUDE

- ***Dynamic similarity:*** *Forces which act on corresponding masses in the model flow and prototype flow are in the same ratio through out the entire flow.*

$$\frac{(F_I)_m}{(F_I)_p} = \frac{(F_p)_m}{(F_p)_p} = \frac{(F_\mu)_m}{(F_\mu)_p} = \frac{(F_g)_m}{(F_g)_p} = \text{constant}$$

$$\Rightarrow \quad \frac{(F_I)_m}{(F_I)_p} = \frac{(F_p)_m}{(F_p)_p} \quad \Rightarrow \quad \frac{(F_I)_m}{(F_p)_m} = \frac{(F_I)_p}{(F_p)_p} \quad \Rightarrow \quad Eu_m = Eu_p$$

$$\Rightarrow \quad \frac{(F_I)_m}{(F_I)_p} = \frac{(F_\mu)_m}{(F_\mu)_p} \quad \Rightarrow \quad \frac{(F_I)_m}{(F_\mu)_m} = \frac{(F_I)_p}{(F_\mu)_p} \quad \Rightarrow \quad \mathrm{Re}_m = \mathrm{Re}_p$$

$$\Rightarrow \quad \frac{(F_I)_m}{(F_I)_p} = \frac{(F_g)_m}{(F_g)_p} \quad \Rightarrow \quad \frac{(F_I)_m}{(F_g)_m} = \frac{(F_I)_p}{(F_g)_p} \quad \Rightarrow \quad Fr_m = Fr_p$$

Similitude

Model Analysis

Similarities and Simlitude