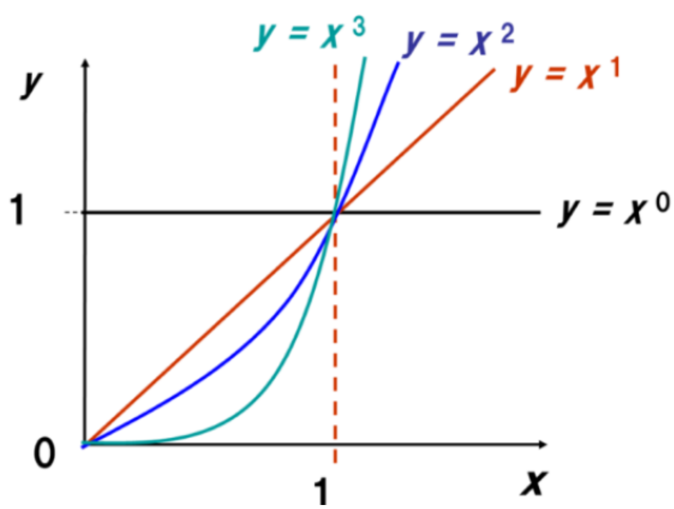
Keio University

CALAMVS GLADIO FORTIOR 1858

Onoe Hiroaki & Takahashi Hidetoshi's course - 2020

Biomimetic Micro/Nano Engineering
Report 2 : Assignment 1



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Contents

1 Introduction

While traditional physical models describing mechanical forces, heat transfers or electrostatic forces are well developed, those will induce drastically different behavior depending on the size of the elements considered. This dependency of the physical properties on the scale of the material or device is called "scale effect" or "size effect".

Low-scale behavior and properties of physical quantities are interesting in the framework of Biomimetics engineering as it allows to explain the characteristics, the behaviors or the operating principles of small scale living organism. Indeed, as can be seen in figure 1, the magnitude of the amplitudes of the power functions of the distance are reversed at small scales compare to large scales. This also means that the physical quantities depending on those different powers of the distance will also see their magnitudes change significantly. Even more important, the global behavior of a quantity, resulting form the interaction of many forces, transfers, ect., can be very impacted as one force or transfer at small scale can take over another one which dominated at large scale. As examples, for living organism, the interactions between the Surface Tension (L^1) and Weight (L^3) at small scale allows some living organism to stand on the water as the amplitude of the force resulting form the surface tension becomes more important than the Weight. Another example is the interaction between Heat capacitance (L^3) and Heat dissipation (L^2), because the amplitude of Heat dissipation becomes larger than the Heat capacitance small scale organism tend to loose their heat faster than macro-scale organism, to prevent this heat loss they usually use a particular mechanism such as an exoskeleton.

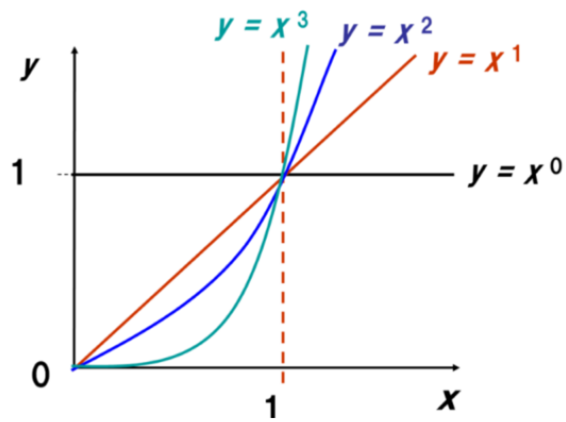

Figure 1: Schematic behavior of the distance raised to different powers as a function of the scale (distance) [1]

2 Case study : What if a human would be the same size as an ant?

Given the following parameters for the ant :

- Size : 5 mm
- Body Weight : 5 mg
- Muscle strength : 50 mgf

$\Longrightarrow$ The ant is able to lift object 10 times heavier than itself.

And the initial values of the parameters for the human :

- Size : 1 m
- Body Weight : 100 kg
- Muscle strength : 100 kgf

$\Longrightarrow$ What happens to the human body weight and muscle strength if its size is reduced to 5mm

2.1 Analytical resolution

2.1.1 Weight

Knowing that the body weight (kg) is a cubic function of the length (L^3), the following polynomial function for the body weight is obtained:

$$Weigth(x) = a_1x^3 + b_1 \tag{1}$$

With x being the length of the body, in m. The coefficients a_1 and b_1 must be found for the human. With the given parameters it gives:

$$Weigth(0) = 0 \Longrightarrow b_1 = 0. \tag{2}$$

And

$$Weigth(1) = 100 \Longrightarrow a_1 = 100. \tag{3}$$

Therefore,

$$Weigth\ Human(x) = 100x^3(kg). \tag{4}$$

2.1.2 Muscle Strength

Knowing that the muscle strength (kgf) is a square function of the length (L^2), the following polynomial function for the muscle strength is obtained:

$$Strength(x) = a_2x^2 + b_2 \tag{5}$$

With x being the length of the body, in m. The coefficients a_2 and b_2 must be found for the human. With the initially given parameters it gives:

$$Strength(0) = 0 \Longrightarrow b_2 = 0. \tag{6}$$

And

$$Strength(1) = 100 \Longrightarrow a_2 = 100. \tag{7}$$

Therefore,

$$Strength\ Human(x) = 100x^2(kgf). \tag{8}$$

2.2 Numerical solution

2.2.1 Weight

A human measuring x = 5 mm ($5 * 10^{-3}m$) would therefore have a weight of :

$$Weigth\ Human(5 * 10^{-3}) = 100(5 * 10^{-3})^3 = 1.25 * 10^{-5}kg \tag{9}$$

This is equal to 12.5 mg.

2.2.2 Muscle Strength

A human measuring x = 5 mm would therefore have a muscle strength of :

$$Strength\ Human(5*10^{-3}) = 100(5*10^{-3})^2 = 2.5*10^{-3}kgf \tag{10}$$

This is equal to 2500 mgf.

$\Longrightarrow$ The human would able to lift object 200 times heavier than itself.

2.3 Comparisons between ant and human

Quantity	Human	Ant
Size (mm)	5	5
Weight (mg)	12.5	5
Muscle Strenght (mgf)	2500	50

Figure 2: Comparison between the human and the ant

While the ant would be able to lift object 10 times heavier than itself, the humans at the same size would be able to lift object 200 times heavier than themselves. Proportionally, humans would be much stronger.

3 Scale effects linked to research topic

Currently studying optical networks, or photonics in general, several effects can happen depending on the size of the devices. First of all, in optical fibers in general, depending on the dimensions, the fibers will exhibit different characteristics of dispersion, losses or scattering. Here, the talk will be concentrated on dispersion and how it varies in optical fibers when the core size (or equivalently the V parameters) varies.

3.1 Optical fiber and dispersion depending on the size

3.1.1 General dependence of the propagation of light and intermodal dispersion on the core size a

An optical fiber is made-up of a core, a cladding and a jacket (around the fiber) as can be seen on figure 3. When solving the Maxwell's equation in this fiber for a given set of parameters k_0, a, n_1, n_2 the solution is non-trivial and different solutions exist, each one characterised by a different value of the propagation constant β. Those different propagation constants result in different trajectories inside one fibers, meaning that there are several spatial solution for the light to propagate in the fiber, each one corresponding to a mode. A fiber with different modes propagating at the same time is called a multi-mode fiber while fibers with only one mode are called single-mode fibers.

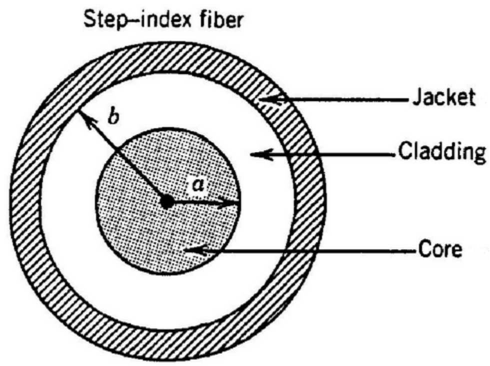

Figure 3: Section view of traditional optical fiber [2]

However, depending on the core size a, a fiber can be tuned to accept only one mode. An important parameter to design such a fiber is called the normalized frequency parameter V, depending on the core size, as can be observed in equation 11 :

$$V = k_0 a (n_1^2 - n_2^2)^{\frac{1}{2}} [2] \tag{11}$$

The representation of the modes, propagating in the fiber as a function or V (or a) can be seen on figure 4.

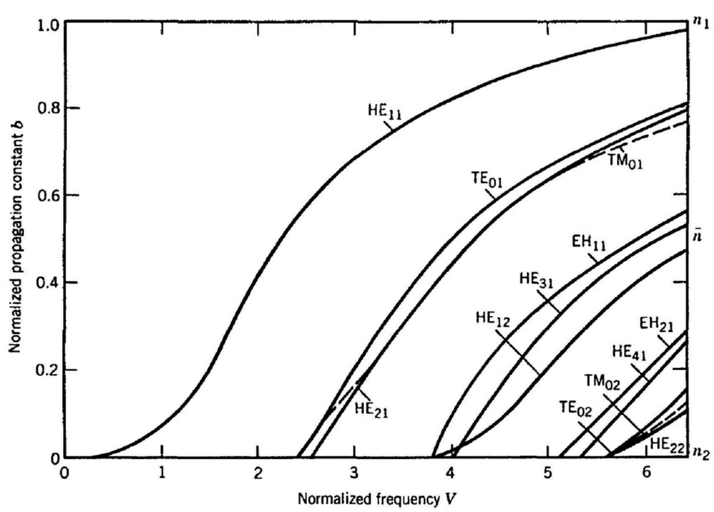

Figure 4: Modes existing in optical fibers depending on the value of V [2]

A scale effect which can be interpreted here is that if the fiber core a is made small enough, only one mode can propagate and therefore no intermodal dispersion is seen in optical fibers. In other word if V = 10, the energy inside the fiber is distributed into many modes while if the core size a is around 10 times smaller (then V is 10 times smaller), with V around 1 or 2, the energy is concentrated into the fundamental mode and no intermodal dispersion appears. When someone organises an experiment, or just wants to create optical fibers it will adapt the V parameters to include the number of modes desired in his design. For example, if for an experiment it is required to lower dispersion (intermodal) in the fibers, it should make the value of V (or a) so that only the fundamental mode propagates (V = 2.4).

3.1.2 Dependence of the core size a on the waveguide dispersion

The waveguide dispersion D_W in optical fibers is given by equation 12 [2] :

$$D_W = -\frac{2\pi\Delta}{\lambda^2}\left[\frac{n_{2g}^2}{n_2\omega}\frac{Vd^2(Vb)}{dV^2} + \frac{n_{2g}}{n_2\omega}\frac{d(Vb)}{dV}\right] \tag{12}$$

In this last equation, n_{2g} is the group index of the cladding material, V is the V parameter and b is the normalized propagation constant.

The point is that depending on the value of V (or the fiber core size a) the different terms in equation 12 will have different values as displayed on figure 5.

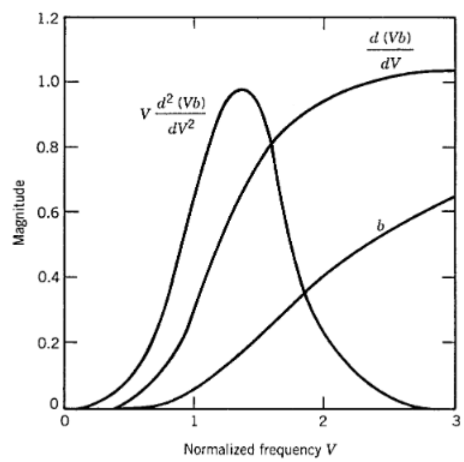

Figure 5: Dependence of the value of different the terms contributing to the material dispersion on the V parameter [2]

A scale effect considered here is that the contribution and magnitude of the terms in the material dispersion are different depending on the core size a of the design. For small core size, let's say V around 1, the main term is the first term $\frac{Vd^2(Vb)}{dV^2}$ while for higher values of V, let's say around 10, the term $\frac{d(Vb)}{dV}$ becomes more important, therefore resulting in different behavior of dispersion depending on the type of fiber (large or small core).

4 Conclusion

In this report, the scale effect where extensively studied.. While the introduction described the principle in general, the second part was dedicated to a case study of comparing the properties of human an ants having the same size through their weight and muscle strength. Finally, the scale effect principle was applied to optical fiber to determine how the properties of light, and more particularly the dispersion, changes when the core size "a" varies.

References

[1] Miki Norihisa & Takahashi Hidetoshi's slides of "MEMS: design and fabrication" course. Course #2, slide #7.

[2] Godvind P. Agrawal. *Fiber-Optic communication system - Third edition, Chapter 2.* John Wiley Sons, Inc., 2002.