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<u>Preface</u>: Have you ever tried a Ouija Board™ or a similar game? Did you ever wonder what causes the plastic element to move in a direction perpendicular to the direction of the applied forces? Have you tried to produce similar motions with bodies made of steel, aluminum, brass, glass, wood, or other materials? Have you tried to produce the same effect with large objects, such as, a refrigerator? Is the motion caused by innervation of your arms' muscles, or by innervation of the plastic element itself, or by mysterious spirits, as Sir Isaac Newton wrote? It took many years and countless tests to answer these questions. Physicists, biologists, biological physicists, neurologists, engineers and others will have great fun and will develop great insights modeling muscles action.

Modeling Muscles Action

Ali F. AbuTaha

Here I report how correct modeling of muscles' action led to the discovery of natural, or wave-induced, motions and to the correct dynamic analysis of the motions. Also, it is shown that the equal and opposite action-reaction force pairs can no longer be discarded in evaluating the motion and performance of biological and mechanical systems.

In wave theories, motion is restricted to the propagation of waves through matter, with only local motions, or oscillations, of the medium itself. This view is altered by the discovery[1] that modulations of waves propagating in a body can induce linear motion of the body. This paper describes a line of experimentation that led to the discovery of wave-induced motions and to the correct dynamic analyses of the motions. Also, it is shown that the action-reaction force pairs can induce motion of harmonically excited bodies (e.g., people and animals), and that the equal and opposite forces can no longer be discarded in evaluating the motions and performance of biological and mechanical systems.

Consider the situation shown in Fig. 1(a). When two vertical forces are applied with the fingers on a lightweight object resting on a smooth surface, the object moves spontaneously and mysteriously horizontally, or in a direction perpendicular to the applied forces. The effect is used in games. Classical mechanics indicates that no motion whatever results in this case, as the sum of the forces is zero. The phenomenon was tested further. Motion occurred no matter what the material, shape or size of the objects.

When a force-pair was applied horizontally with the fingers, or the hands, Fig. 1(b), the objects moved in a perpendicular direction. The effect worked with heavy objects, including refrigerators. There is a distinct time-delay in the phenomenon, which is overcome with persistence and practice.

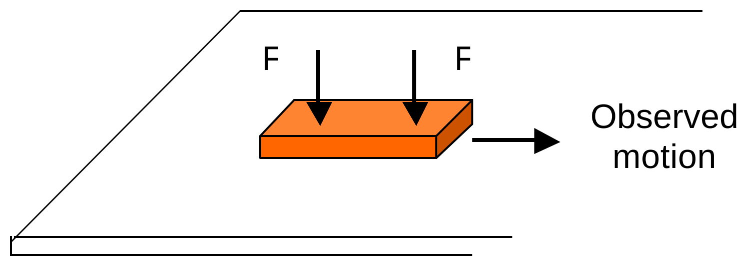

Fig. 1(a) Forces applied with fingers induce objects to move in normal direction

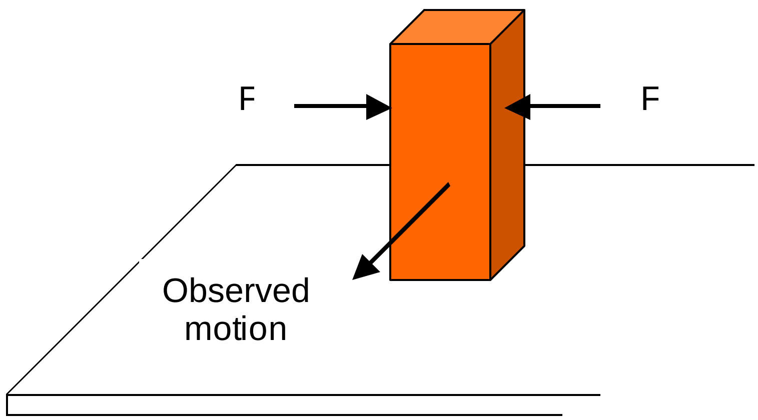

Fig. 1(b) Forces applied with fingers or hands induce objects to move in normal direction

The objects do not move if the forces in Fig. 1(a) are dead weights, or if a clamp produced the force-pair in Fig. 1(b). The motion phenomenon is strictly the result of the action of muscles. The muscles are innervated into pulse-like harmonic action by the nervous system. How the pulses turn into motion was not clear. The above tests hinted that modeling the forces generated in biological systems as static forces is wrong.

The underlying action of the muscles on the object in Fig. 1 can be modeled as two harmonic disturbances traveling in the object. For simplicity, let the waves generated by the muscles be of the same amplitude and phase. Then the two disturbances, $u_1(t)$ and $u_2(t)$, produced by the fingers can be written as:

$$u_1(t) = \mathrm{A} \cos \omega_1 t \tag{1}$$

$$u_2(t) = \mathrm{A} \cos \omega_2 t \tag{2}$$

where A is the amplitude of the pulses and ω_1 and ω_2 are the frequencies of the pulses. The response to the action of the fingers is obtained by the superposition of the two waves, or,

$$u(t) = u_1(t) + u_2(t) = \mathrm{A} \cos \omega_1 t + \mathrm{A} \cos \omega_2 t \tag{3}$$

Defining average frequency, $\omega_{av} = ½ (\omega_1 + \omega_2)$, and modulation frequency, $\omega_{mod} = ½ (\omega_1 - \omega_2)$, the solution, Eq. (3), can be re-written as:

$$u(t) = \mathrm{A}_{mod}(t) \cos \omega_{av} t \tag{4}$$

where

$$\mathrm{A}_{mod}(t) = 2\mathrm{A} \cos \omega_{mod} t \tag{5}$$

It was not clear to the author how this or similar solutions apply to the motions described above. The mass of the muscles involved is not clear, the amplitude of the pulses is uncertain and the number of muscles involved is prohibitive. Nor was it clear whether the pressure applied by the fingers innervated the arm, thus the arm caused the motion, or if the superposition of the waves in the object caused the motion. To test the latter hypothesis, equivalent mechanical models were built and tested.

One way to produce harmonic pulse trains was to rotate eccentric masses on the shafts of small dc motors. It seemed that two such motors mounted on the object of Fig. 1 could act as two giant neuromuscular junctions. This configuration, described in Ref. 1, produced a variety of motions of a variety of bodies made of different materials and shapes and sizes as described in that paper.

The motion models made it possible to check out the basic characteristics of the natural, or wave-induced, motions. For example,

1. When the two motors are operated at the same rate, i.e., $\omega_1 = \omega_2 = \omega_{av}$, then, $\omega_{mod} = 0$ and the amplitude A_{mod} is constant. The models move at constant speed marked by small steps at the high frequency, ω_{av}. Increasing the input frequency increases the speed of the model. Decreasing the frequency produces the opposite effect. This behavior is restricted to a band of frequency, which depends on material and geometric characteristics of the motion model.

2. When the rotation of the two motors is varied slightly, i.e., $\omega_1 \approx \omega_2$, then the modulation frequency is much smaller than the driving frequency, or $\omega_{mod} << \omega_{av}$. Here, the models exhibit distinct stepped motion at low frequency, consistent with the beat frequency, ω_{beat}, which is defined as, $\omega_{beat} = 2\omega_{mod} = \omega_1 - \omega_2$. In essence, the motion models exhibit *amplitude-modulated* behavior at the low modulation frequency ω_{mod}. An analogy to AM radio transmission was helpful. For a motion model with input pulses of, say, 100 cps, and motion at 1 step per second; the 100 Hz input can be thought of as the carrier frequency while the step of 1 Hz is like the modulated audible frequency. This is the simplest modulation case where only one modulation frequency is present in the system.

3. It was also possible to induce motion with one motor. Apparently, the waves excited by the motor and propagated in the model reflect at the boundaries and, at least, two wave trains are set up within the body; i.e., a *forward wave* and a backward *reflected wave*. The general solution is the same as in Eqs. 1-5. Models made of hard wood or metal move at the driving frequency, as in 1 above. Here, motion is the result of superposition of the two waves; the *forward wave* and the mirror image *reflected wave*.

4. Waves change properties when reflected in a dispersive medium. In motion models made of soft materials, it was possible to produce the *beat* effect using one motor. Here, the stepped motion is the result of modulation of the *forward waves* and the *distorted reflected waves*. This condition was difficult to achieve, but it is possible.

5. The mechanical motion models made it possible to examine how the input pulse energy compares with the output motion energy of the models. For the method I selected to produce the pulse trains, i.e., rotating eccentric masses, the input kinetic energy of the

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two eccentric elements, of mass m each, and the kinetic energy of motion of the model, of mass M, are:

$$E = m A^2 \omega^2 \tag{6}$$

$$E = ½ Ms^2 \tag{7}$$

where s is the speed of the motion model. The speed, s, is then:

$$s = 2(m/M)^{1/2} A\omega \tag{8}$$

Generally, the calculated speed is always greater than the measured speed, which indicates that full conversion of pulse energy into motion was not attained. Defining C as an efficiency factor of energy conversion and substituting N for $2(m/M)^{1/2}$, then the speed, s, is given as,

$$s = CNA\omega \tag{9}$$

The author built, tested and recorded on video thousands of motion models to verify the characteristics of the motion described above. Typical study models move in the range of about 2 cm/s to 30 cm/s. Consider a typical motion model where, $m \approx 2g$, $M \approx 200g$, $A \approx 0.01m$ and $\omega_{av} \approx 100$ rad/sec. For this model, the calculated speed is 20 cm/s, which compares very well with the measured speeds, of about 10 cm/s. In this case, the efficiency factor C is about 50%.

It is thus seen that the basic mathematical analysis of natural, or wave-induced, motions is straightforward. The motion mechanism explains how muscles directly convert pulse trains into motion, without ropes, gears, pulleys or linkages. The antagonistic action of muscles, i.e., the ability to push and pull, is also clarified with our motion models. The ropes and rubber band models, used by other researchers, do not explain the antagonistic action.

Many motions in biological systems are rhythmic. The analysis and experiments described above show that locomotor rhythms could be generated at the muscle level, and not necessarily at the neural level. Modulation of the waves in the muscles can produce the rhythmic beat effect in nature. This finding greatly alters our understanding of the mind-body interaction. To produce start-stop, start-stop motion of a car requires repeated pushing of the accelerator (excitatory neuron action), brake (inhibitory neuron action), intelligence (or computers), feedback circuits, etc. Our research shows that only excitatory neural action is required to produce stepping, or rhythmic, motions; whether walking, breathing, heart beats, etc.

Muscle exertion is primarily characterized by pulse frequencies. When running, versus walking, only the pulse frequency is increased. This behavior is consistent with the analytical and experimental observations described above.

The equal forces normal to the direction of motion are usually discarded in the study of motion and performance of biological and mechanical systems. An experiment was devised to test the effect of the action-reaction force pair on the motion of harmonically excited models. Models were excited such that spontaneous motion did not result. A set of pegs was placed on both sides of the model. When the pegs were pressed against the model, the model moved readily in the normal direction, see Fig. 2. This and similar experiments demonstrated the importance of the normal forces exerted by birds in flight or by fish in the water.

The last experiment was inspired by tests conducted at reputable research centers, in the last 3 decades, which study the phenomenal motions of fish, dolphins, and whales. Fish placed between pegs out of water, as shown with our lifeless wooden motion model in Fig. 2, move swiftly forward. In describing their work, the researchers completely ignore the sideways forces that the fish exert on the pegs! Only the force components in the direction of motion are considered, mathematically and empirically. Those researches seem to produce more questions than answers. Those and similar research efforts will greatly benefit from our results.

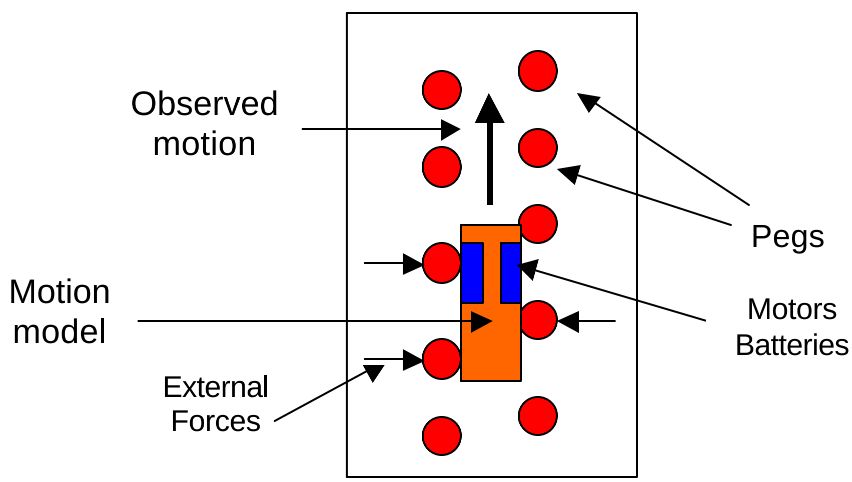

Fig. 2 Harmonically excited motion model moves normally to externally applied forces

[1]A. AbuTaha, “Discovery of Self-Motion,” Aug. 30, 1999