특별기고

Birth of Science and Naval Architecture; through Galileo's *Two New Sciences*

Seung-Joon Lee (Chungnam National University)

It is well known that the birth of modern science was much benefitted from the Newton's Principia, and also that he was indebted to various works of Galileo, especially to 'Two new sciences', however, it is less known or almost unknown that the motivation of the Galileo's work has to do with his job as a consultant to the Arsenale of Venezia, while he was a professor at the University of Padua for 18 years (For timeline see Table 1).

After building the new Arsenale in the early fourteenth century, Venezia was still the strongest naval power in the Mediterranean Sea at Galileo's time, although the arena of the global trade was being gradually moved to the Atlantic Ocean. It is interesting to note that the word 'Arsenale' was borrowed from Arabic dar as-sina'ah, meaning house of manufacture, in the early twelfth century. When Galileo was 7 years old, Venezia played the decisive leading role for the Catholic victory in the famous naval Battle of Lepanto, which resulted in the legend of the Invincible Armada of Spain. The University of Padua was then under the auspices of Venezia, and was famous for her openness and academic freedom. The Arsenale was the national maritime research center as well as the navy and commercial shipyard of Venezia, to which Galileo became a consultant in 1593, and he was asked to solve problems faced by the engineers there then [Valleriani (2010)].

Among those problems, the following three became his lifetime questions, namely;

1) How long can a wooden ship be?
2) What is the trajectory of the cannon ball?
3) How big is the propulsion produced by an oar?

All of these, each of which will be considered in turn below, were closely connected to the situation around the turn of the century into the seventeenth.

Table 1. Timeline

When	Who	What
c. BC220	Archimedes	Principle of lever
1320	Republic of Venezia	Arsenale Nuovo
1492	Columbus	Navigate to West Indies
1564	Galileo	Born
1571	Catholic vs. Islamic powers	Battle of Lepanto
1592-1610	Galileo	Professor, University of Padua
1633	Galileo	Inquisition, House arrest
1638	Galileo	*Two New Sciences*
1642	Galileo[Newton]	Died[Born]
1686	Mariotte	Deflection of cantilever; Strength of materials
1687	Newton	*Principia*; Dynamics Mathematical Principles of Natural Philosophy
1738	Bernoulli, Daniel	*Hydrodynamica*
1856	Saint-Venant	Pure bending of beams
1902[1906]	Kutta[Joukowski]	Mechanism of lift
1903	Wright brothers	First heavier-than-air flight
1904	Prandtl	Boundary layer theory; Fluid dynamics
1914	Buckingham	pi-theorem

While Venezians always wanted bigger and thus longer ships to get ahead in the increasingly severe competition against the Atlantic trading countries, namely, Portugal, Spain, Holland, and England, it was found that, even if the size of cross-section of a ship is increased in proportion, longer ships were broken eventually in the middle during the construction due to their own weight. In modern terminology, they were experiencing that the geometrical similitude was not sufficient to guarantee the mechanical similitude. Galileo pointed out this rightly and accurately, and, to derive the relation between the resistance to fracture and the ship' s length and her weight, replaced the ship by a cantilever. The resistance to fracture (of a fiber) could be obtained from the experiments as shown in Fig. 1, and the breaking of a ship due to its own weight was idealized as the breaking of a weightless cantilever under loading at its free end, as shown in Fig. 2. It is noted that both of these figures are taken from his book, 'Two new sciences'.

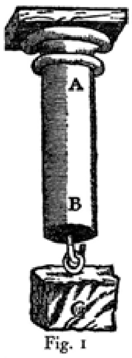

Fig. 1 Resistance to fracture

Fig. 2 Cantilever replacing ship

Applying the principle of lever, expounded by Archimedes earlier, Galileo could give an answer in the following form [Drake (1989)]. ;

Prisms and cylinders differing in length and thickness have their resistances to fracture in the ratio compounded from the ratio of the cubes of the diameters of their bases and from the inverse ratio of their lengths.

This is his Proposition V in the Second day, and we note that in his time the concept of function was not known yet, and that 'Two new sciences' consist of talks among three scholars in four days, and the first two days are for the first question and the last two days for the second. It is true that his formulation of and the solution to the problem had many faults, however, his contribution originated from the treatment of the first question is at least threefold. Application of mathematics and the known physical principles to the solution of practical problems was exemplarily shown, the quest for the dimensional analysis including model tests were first rightfully raised, and finally his simplified model for a ship by a cantilever showed the way how a body in its essence should be treated for scientific and engineering thinking. His treatment was the primary basis for applied mathematics, dimensional analysis, and the statics in general and the strength of materials in particular in the coming centuries. Newton created calculus to define velocity and acceleration, Mariotte and Saint-Venant cultivated the field of strength of materials by correcting the result of Galileo, and Buckingham established the pi-theorem for justifying dimensional analysis.

The second question had its roots in the widening use of guns in battle fields. The Arsenale was responsible for manufacturing not only navy and commercial ships but also all the fittings and weaponry shipborne as well as on ground including guns, and hence the English word arsenal. Guns in the west were introduced through the Mongol invasion in the thirteenth century, and later the Arsenale was behind the first field usage of the lighter-weight artillery on mobile carriages.

To visualize the trajectory of cannon balls, in other words projectiles, Galileo again built a very creative field of study, namely the vector kinematics. We note that the concept of vector and the co-ordinate system were not known yet, and that mathematics then meant geometry. Pointing out the discrepancy between the result given by Aristotle' s teaching and that of his own experiments for free fall, he introduced the concept of uniform and the uniformly accelerated motions of a body. He defined the latter motion as

We shall call that motion equably or uniformly accelerated which, abandoning rest, adds on to itself equal momenta of swiftness in equal times.

This is his first definition in the Third day discussing the naturally accelerated motion. Without proper mathematics dealing with instantaneous changes, i.e. differential and integral calculi, he restricted himself to these two types of motion only and managed to prove that the trajectory is a parabola. First, decomposing the motion into two independent motions, namely the horizontal and the vertical, and he showed that the former is uniform and the latter uniformly accelerated, and finally combining these two results he could give the following theorem,

When a projectile is carried in motion compounded from equable horizontal and from naturally accelerated downward motions, it describes a semiparabolic line in its movement.

This is the first Theorem in the Fourth day dealing with the motion of projectiles, and we note that he used the word naturally accelerated downward motion for free falling. Newton' s first law of motion is in fact Galileo' s finding, however, Newton regarded it as a law, while Galileo took it as a reasonable conjecture. In any case Newton' s calculus and vector dynamics were constructed on the shoulder of Galileo' s kinematics, and since they together formed the basis of other physical sciences developed later, Galileo is often naturally called the father of modern science.

As to the third question on propulsion by an oar, as the title of his book, 'Two new sciences'(not Three), suggests, Galileo could not get far in explaining the cause of propulsion in water. Since Aristotle asked a question related to oar in his Mechanical Problems [Winter(2007)], which is now regarded as writing by Archytas of Tarentum, a contemporary of Plato who was even before Aristotle, it was a long standing problem, for which the reasonable answer including the mechanism of drag and lift was available only in the early twentieth century, after even the first heavier-than-air flight by Wright brothers.

In order to answer to this, the role of viscosity of fluid around a body had to be understood, and this was made clear only after the work of Kutta, Prandtl, and Joukowski. Early efforts by Bernoulli and Euler in the eighteenth century and by Cauchy and Stokes in the nineteenth all failed to offer a consistent and plausible description of the phenomena.

Although Galileo was not successful in answering the third question, his lifelong endeavor along this line is well described in 'Two new sciences', as evidenced by the treatment of various subjects in the First day alone such as void(rather than vacuum), motion of a body in media, weight of air, buoyancy, surface tension, viscosity, resistance of medium, terminal speed, and sensation of sound. In fact so diverse are his subjects on fluid, most readers of 'Two new sciences' get astray in the First day. Seemingly unrelated talks to the main theme, the problem of strength of materials, were in reality his precious gift to the future generation trying to answer the third question, I suppose.

If we agree to the commonly accepted idea that the fluid dynamics(not hydrodynamics) as a well established field of study began only after the Prandtl' s boundary layer theory, no wonder Galileo was not able to do much in his time, and we emphasize that it took many generations of great mind for grasping the phenomena of propulsion by lifting surfaces. After all, according to Aristotle, air and water, two most important media for the human being, were two of the four basic elements comprising the world around us. Now both of them are treated in a unified fashion within the framework of fluid dynamics, and for that we owe much to the initiation of Galileo in building up a whole new science.

Some of the basic questions asked in science are not related to engineering, for instance the origin of life, universe, and matter, however, many are stemmed from engineering practice. The fact that naval architecture as a field of engineering supplied such 'important' questions to Galileo is described above, and it is very much hoped that this trend continues in the present and future.

Acknowledgements

It is gratefully acknowledged that the permission of the Academic leave for a year from the home base, the Chungnam National University, was given to the writer.

References

DRAKE, S. (1989), Two new sciences, English translation, 2nd. Wall & Emerson, Inc., Toronto

VALLERIANI, M. (2010), Galileo Engineer, Springer: New York

WINTER, T. N. (2007), The Mechanical Problems in the Corpus of Aristotle, University of Nebraska-Lincoln, Faculty Publications, Classics and Religious Studies Department, Paper 68