الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي و البحث العلمي
Ministry of Higher Education and Scientific Research

Mohamed Khider University-Biskra
Faculty of Science and Technology
Department of Mechanical Engineering
Ref:…………

جامعة محمد خيضر بسكرة
كلية العلوم والتكنولوجيــــا
قسم الهندسة الميكانيكيـــة
المرجع:..................

Memoir presented for the award
of the diploma of:

Master in: Mechanical Engineering

Option: Mechanical Design and Manufacturing

Theme

STUDY OF THE AEROELASTIC PROPERTIES OF A ROCKET STRUCTURE

Presented by:
Hossam DJAHARA

Sustained publicly 06 June 2017

In front of the jury composed of:

Mr. Mabrouk HECINI	**Professor**	**Chairman**
Mr. Miloud ZELLOUF	**MCB**	**Supervisor**
Mr. Kamel AOUES	**MCA**	**Examiner**

College year: 2016 / 2017

الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي و البحث العلمي
Ministry of Higher Education and Scientific Research

Mohamed Khider University-Biskra
Faculty of Science and Technology
Department of Mechanical Engineering
Ref:…………

جامعة محمد خيضر بسكرة
كلية العلوم والتكنولوجيـــا
قسم الهندسة الميكانيكيـــة
المرجع:..................

Memoir presented for the award
of the diploma of:

Master in: Mechanical Engineering

Option: Mechanical Design and Manufacturing

Theme

STUDY OF THE AEROELASTIC PROPERTIES OF A ROCKET STRUCTURE

Presented by:
Hossam DJAHARA

Sustained publicly 06 June 2017

In front of the jury composed of:

Mr. Mabrouk HECINI	**Professor**	**Chairman**
Mr. Miloud ZELLOUF	**MCB**	**Supervisor**
Mr. Kamel AOUES	**MCA**	**Examiner**

College year: 2016 / 2017

To my parents and brother and sisters,

My family

And my friends

ACKNOWLEDGMENTS

First of all, I thank *ALLAH* for all the countless gifts you have offered me, thanks for guiding me and giving me the strength and the will to carry out this work.

I would like to thank my family from the bottom of my heart specially my Mother and Father, who has constantly given me support, love, encouragement and the desire to learn even more.

It is a great pleasure to acknowledge my great thanks and gratitude to **Mr. Miloud ZELLOUF**, Lecturer Professor Class (B), Faculty of Mechanical Engineering, for suggesting the topic of this essay, and his kind supervision. It is a great honor to work under his supervision.

I would like to express my deepest thanks and sincere appreciation to **Mr. Kamel AOUES**, Lecturer Professor Class (A), Faculty of Mechanical Engineering, for his encouragement, and **Mr. Mabrouk HECINI**, Full Professor, Faculty of Mechanical Engineering, for accepting the preside of the jury, and **Mr. Abdelkader KHERRAT**, Senior Engineer at Bombardier Aeronautic Company Montreal Canada, for his efforts and comprehensive advices.

I would like to express my extreme sincere gratitude and appreciation to my teachers of the Department, **Mr. Belhi GRIRA,** Lecturer Professor Class (A), Faculty of Mechanical Engineering, and all the members of the Technological Hall.

I thank all my friends for the motivation that their friendship has brought me. Their Support, their enthusiasm and their sense of humor allowed me to go to the end of this adventure which is the thesis.

CONTENT

CHAPTER II STATE OF THE ART

CHAPTER III AMATEUR ROCKETS, DEFINITION, PRINCIPLES AND FUNDAMENTALS

CHAPTER V AEROELASTICITY, FLUTTER PROBLEM AND ASSOCIATED PHENOMENA

CHAPTER VI THE FLUTTER PHENOMENA: THEORETICAL BACKGROUND AND TOOLS

CHAPTER VII THE FLUTTER PHENOMENA: THEORITICAL AND NUMERICAL ANALYSIS

CHAPTER VIII FLUTTER PREDICTION: RESULTS AND DISCUSSION

FIGURE LIST

TABLE LIST

ABBREVIATIONS LIST

VfR	Verein für Raumschiffahrt (the Spaceflight Society).
A-1	Aggregate-1.
V-1/2	Vergeltungswaffe-1/2 (Weapon of Revenge N° 1/2).
FEM	Finite Element Method.
CM	Computational Mechanics.
GFEM	Galerkin Finite Element Method.
FVM	Finite Volume Method.
CFD	Computational Fluid Dynamics.
CVFEM	Control Volume Finite Element Methods.
NACA	National Advisory Committee for Aeronautics.
NASA	National Aeronautics and Space Administration.
CAD	Computer Aided Design.
CAE	Computer Aided Engineering.
1D	One dimension.
APDL	Ansys Parametric Design Language.
FSI	Fluid Solid Interaction.
AMSEC-R v.01	Al-jazzari Mechanical Science and Engineering Club-Rocket version 01

SYMBOL LIST

A_m	Modal amplitude.
a_m	Modal amplitude (non-dimensional).
a_i	Unknowing parameters.
a	Plate length.
b	Plate width.
C	Continuity of the interpolation variable.
D	Plate stiffness.
E	Young modulus.
F	External normal force per unit area of the plate.
h	Thickness of the plate.
I	The unity matrix.
G	Shear modulus.
K	Spring constant.
k, l	Indices that take values of 1 or 2.
M	Mach number.
m	Mode number.
N_i	Interpolation functions.
N_x	In-plane force (x direction).
$N_x^{(a)}$	Applied in-plane force (x direction).
$N_y, N_y^{(a)}$	y direction.
P	Air pressure
$p - p_\infty$	Aerodynamic (perturbation) pressure.
Δp	Static pressure differential across the panel.
q_i	The degrees of freedom.
r	Mode number.
s	Mode number.
t	Time.
U	Velocity.

$\hat{u}$	approximated vector function by trail expansion.
u, v	In-plane displacements.
$V_j, \check{V}_j$	Suitable weighting (test) functions.
W	ω/h
x	Streamwise coordinate.
y	Spanwise coordinate.
z	Normal coordinate.
α	$\equiv Ka/(Ka + Eh)$, Spring stiffness parameter.
β	$\equiv (M^2 - 1)^{1/2}$
ν	Poisson ration.
ξ	x/a
ρ	Air density.
ρ_m	Plate density.
σ_{kl}	Cauchy stress tensor.
σ_x	Stress.
ω	The out-of-plat deflection of the plate.

GENERAL INTRODUCTION

Astronomy is the oldest of the natural sciences. The early civilization in recorded history, such as the Babylonians, Greeks, Indians, Egyptians, Nubians, Iranians, Chinese and Maya performed methodical observations of the night sky. Since then space travel fascinated the human and he want to discover it, and this dream became to be real until the early years when the first German V-2 missile reached an altitude of 80 km in the Second World War, after this event it became possible and revealed darkness about the machine which capable of transporting man into space and everyone is convinced that rockets are the solution.

Rockets are self propelled machines applying Newton’s third law which is:”for any action there is an equal and opposite reaction” to work in different fluid environments (air, water...etc), since those rockets are working in fluids they effected by dangerous phenomena; because of the interaction between tow domains (solid and fluid), one of those phenomena is the Aeroelasticity which is the area of applied mechanics that studies the interactions between the *Inertial*, *Elastic*, and *Aerodynamic* forces that occur when an elastic body is exposed to a fluid flow.

In this study, we will look at the interaction between solids and fluids, specifically the mutual effect of air force and the missile's fin. Because the fin is a thin plate, studying this type of plate has been a problem for scientists. The first pulse with a mathematical statement of plate problems was probably made by Euler, who in 1776 carried out an analysis of the problems of free plate vibrations. The final form of the differential equation of the great displacement theory, however, was developed by von Karman. He also researched the behavior in plate buckling.

The memoir divided into eight (8) chapters:

- In the first chapter, we discussed the history of Rockets since the birth of this technology until the Second World War, because this period was crucial and very important in understanding and enriching the knowledge base on this technology.
- In the second chapter we mentioned some of the most important associations that have played a major role in the development of rocket technology since the end of the Second World War to this day.

- Because rocket enthusiasts have also played a major role in the development of this science and technology, we have defined in the third chapter the amateur rockets and the fundamentals of this science.
- Chapter IV handles the stat of the art of both Finite Element Method and Finite Deference Method briefly.
- Turning to the history of the phenomenon of aeroelasticity enables us to understand and address the problems resulting from it, historical background and related phenomena was treated in chapter V.
- Flutter phenomena is a branch of the aeroelasticity; its theoretical background and tools was defined in chapter VI.
- We mentioned in Chapter VII the methods, approaches and procedure that used to handle fins flutter problems.
- To study the fluttering prediction of the thin plates AMSEC-Rocket v.01* fin in our case, with the consideration of the effect of the wind (longitudinal force), and the boundary conditions, the eighth chapter was devoted to the presentation of the validation tests, and some applications, with a comparison between the results obtained using a program in "Matlab" environment, and those computed by the modeling software ANSYS.

---

* AMSEC-R v.01 is a rocket was made by Al Jazzari Mechanical Science and Engineering Club which is created in 2016 to participate in the Algerian Competition between Universities in the name “Algerian Competition in Aeronautic between Universities in Mechanical Engineering”, the edition 2016/2017 titled as “Study and Design of a Competition Rocket with Deployment system”, for more see (Appendix E).

CHAPTER I

BRIEF HISTORY ON ROCKETRY

I.1. INTRODUCTION:

History, if viewed as a repository for more than anecdote or chronology, could produce a decisive transformation in the image of science by which we are now possessed [1]. Imagine not knowing how gravity works, or how disease is spread, or what Earth looks like from space. All of this was once the case, and not all that long ago. Studying the history of science allows you to have a glimpse into both the history of the world and into just how we discovered everything we know about the world. Those moments of discovery may seem anti-climactic to us now, but imagine not having discovered them at all. Imagine living without that knowledge?

I.2. CHINESE FROM FIREWORKS TO FIRE ARROWS:

The first real appearance of the rockets was in the Chinese civilization; most historians believe that the knowledge of how to make gunpowder originated in China sometime between 500 and 900 A.D, and spread westward during the 1200s. The Mongols, a nomadic people whose empire stretched from China to the plains of Hungary by the late 1200s, developed gunpowder technology after the Chinese used it against them [2].

Rockets have been around for a long time but before 1200s Chinese was using gunpowder in fireworks; festivals and for religious reasons, but did not know the right proportions to get explosions and did not achieve the necessary purification of potassium nitrate; The first Chinese book, which details the explosive proportions, was in 1412 by **Huo Lung Ching** [3].

Chinese used arrows attached into bamboo tubes filled with gunpowder and throws them with bows against the Mongols circa 1223 A.D to scare the Mongols army; the Chinese knows that it was not effecting and do not caused any damage but it works.

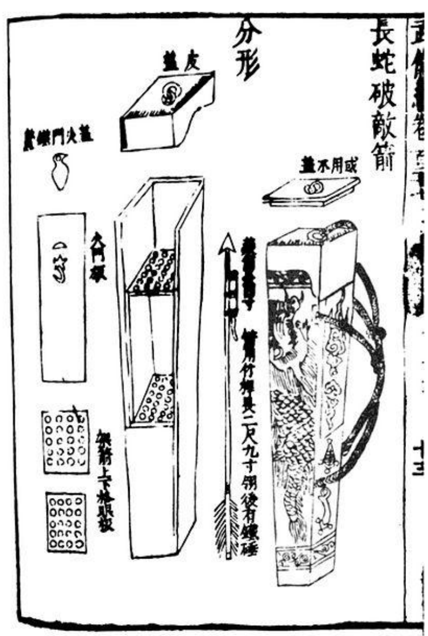


Figure I.1. An illustration of a "long serpent" fire arrow rocket launcher as depicted in the 11th century book “Wujing Zongyao” 11th century.

I.3. MUSLIMS ROCKETRY:

In the 13th century a Syrian scholar, **Hassan AL-Rammah** (born over 1280) wrote a remarkable book on military technology "*كتاب الفروسية والمناصب الحربية-Kitab AL-Furusiyya wa AL-Manasib AL-Harbiyya* i.e. *Book of Military Horsemanship and Ingenious War Devices*", which became very famous in the west.

Willey Ley (October 2, 1906 – June 24, 1969) Sad in his book "*Rockets, Missiles and Space Travel*" in 1958: *‹‹..But **Hassan AL-Rammah** adds one unsuspected novelty: a rocket-propelled Torpedo consisting of two flat pans fastened together and filled with powder or an incendiary mixture, equipped with a kind of tail to insure movement in a straight line, and propelled by two large rockets. The whole was called the "Self-moving and Combusting Egg" but no instances of its use are related››* [3].

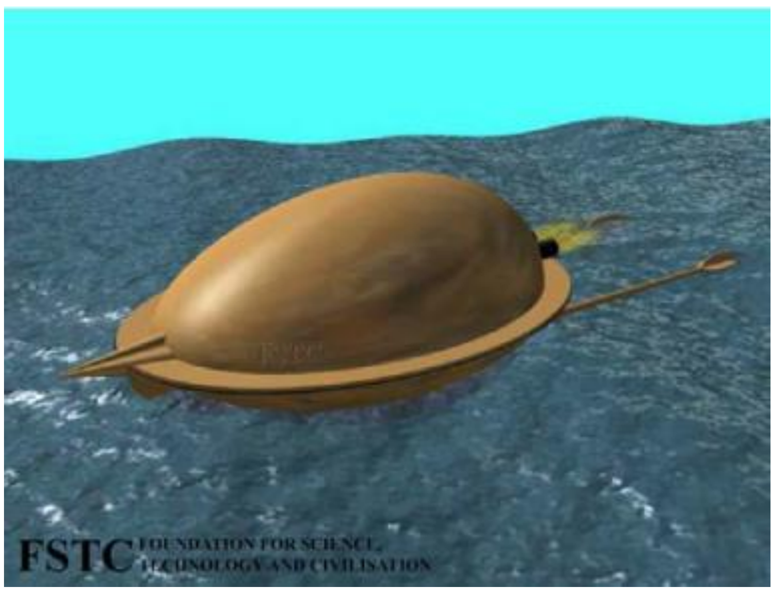


Figure I.2. A conceptual model of the floating rocket described by Hassan Al-Rammah [3].

Wherever it originated, and however it spread, rocket technology was widely known throughout Europe and Asia by the early 1400s. Handbooks of military technology, such as **Konrad Kyeser von Eichstädt's** "*Bellifortis* i.e. *Strong in War*" and **Giovanni da Fontana's** "*Belliscorim Instrumentarum Liber*", discussed rockets and their applications in detail.

I.4. INDIA SECRET WEAPONS:

Indian soldiers under **Sultan Mahmud** used rockets in their defense of Delhi against the armies of Tamerlane in 1399, Chinese armies used them against the Vietnamese near modern-day Hanoi in 1426, and French troops under **Joan of Arc** used them against the English at the siege of Orléans (1428–1429) in 1428. The use of rockets as fireworks, an established tradition in China, spread throughout South Asia in the early 1400s. It reached India and the islands of Indonesia along newly opened trade routes and became a standard form of entertainment at large, public celebrations. Understanding of how rockets worked also deepened in the early 1400s. **Eichstädt's** "*Bellifortis*", for example; noted that a rocket is pushed forward by its exhaust, and that the casing must be impervious to gas in order for the rocket to work [2].

The development of rocketry between the years 900 A.C to 1450 A.C was slow and not based on science because all the civilization was using rocket experimentally and built them of lighter materials (wood, bamboo, or even paper). The world changed profoundly in the decades around 1450. The world changed profoundly in the decades around 1450. Turkish armies captured Constantinople, erasing the last traces of the old Roman Empire and redrawing the political map of Eastern Europe and Southwest Asia [2].

I.5. THE ROLE OF THE PRINTING PRESSES IN THE DEVELOPMENT OF ROCKETRY KNOWLEDGE:

A German goldsmith named **Johannes Gutenberg** (1398 – February 3, 1468) gave Europe the printing press, the first tool for mass-producing knowledge. In northern Italy, a once-in-a-century flowering of artistic talent set the Renaissance in motion.

The rise of the printing press and the spread of printed books encouraged this standardization by making the latest information about rockets widely available. Printed descriptions of rockets and instructions on how to build them were available throughout Europe in the 1500s and early 1600s. Notable works appeared not only in traditional centers of learning like Italy and Spain, but also in still-remote areas of Europe such as Romania, Poland, and northern Germany [2].

Figure I.3. Recreated Gutenberg press at the International Printing Museum, Carson, California.

In 1650, **Kazimierz Siemienowicz** (1600-1651) a Polish artillery expert published in Amsterdam "*Artis Magnae Artilliae* i.e. *The Complete Art of Artillery*" and translated into English in 1729, the book contained a large chapter on caliber, construction, production and properties of rockets including multistage; three-stage rocket and the use of fins to provide stability as **AL-Rammah** did in his Torpedo.

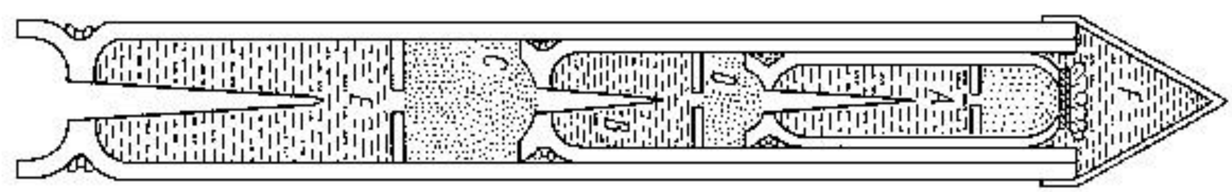


Figure I.4. Two stage rocket design by Siemenowicz, 17th century [Artis Magnae Artilleriae pars prima].

I.6. ROCKETRY IN THE INDIAN CIVILIZATION:

During the eighteenth Century, both the French and British began wrestling for control of the riches of India. In addition to fighting one another, they also found themselves frequently engaged against the Mongol forces of Tippoo Sultan of Mysore during the two battles of Seringapatam in 1792 and 1799.

Rockets were used against the British. One of **Tippoo Sultan's** (10 November 1750 – 4 May 1799) also known as the **Tiger of Mysore**, and **Tipu Sahib**, was a ruler of the Kingdom of Mysore. **Tippoo Sultan's** father; **Hyder Ally**, had incorporated a 1,200 men contingent of Rocketeers into his army in the year 1788. **Tippoo Sultan** increased this force to about 5,000 men, about a seventh of his total Army's strength, profiting from their Indian experience.

Figure I.5. The Last Effort and Fall of Tippoo Sultan by Henry Singleton.

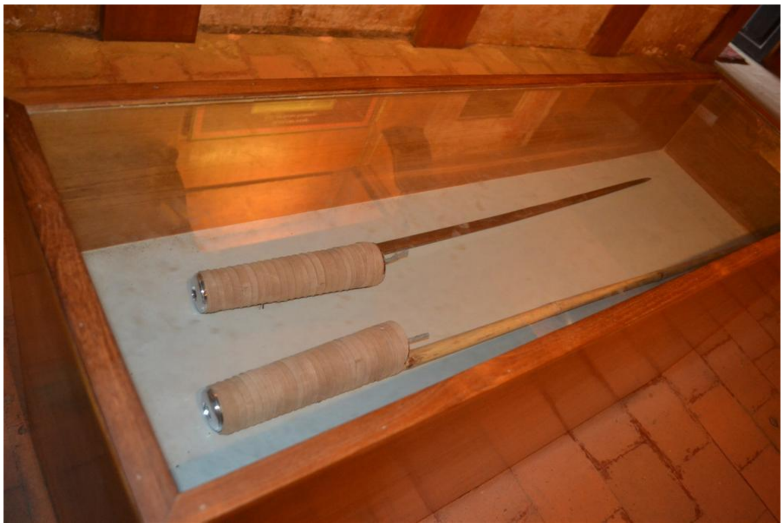


Figure I.6. Model of the Mysorean rockets [Royal Ordnance Museum].

Figure I.7. A Mysore rocketeer of Haidar Ali, carrying a war rocket, late-eighteenth-century water colour. [Copyright © V&A Images/Victoria and Albert Museum, London; http://www.vam.ac.uk].

Their rockets, built in two standardized sizes, had tubes of cast iron rather than the then-standard bamboo or pasteboard (Figure I.6). The use of iron added weight but also lent strength, allowing designers to make the rockets more powerful without fear that the added pressure from the expanding exhaust gasses would burst them. The extra thrust that iron tubes allowed more than compensated for the extra weight. According to Indian sources, **Tippoo Sahib's** rocket troops could bombard targets as much as a mile and a half away [2].

I.7. BRITISH ADOPTION OF THE TECHNOLOGY:

After the fall of Seringapatam, **Tippoo Sahib's** secret weapon did not remain secret for long. 600 launchers, 700 serviceable rockets and 9,000 empty rockets were found. The British shipped hundreds of rockets home to the Royal Arsenal as spoils of war. Some of the rockets had pierced cylinders, to allow them to act like incendiaries, while some had iron points or steel blades bound to the bamboo. By attaching these blades to rockets they became very unstable towards the end of their flight causing the blades to spin around like flying scythes, cutting down all in their path.

I.7.1. BRITISH MILITARY ROCKET DEVELOPMENT PROGRAM START:

These experiences eventually led the Royal Woolwich Arsenal to start a military rocket research and development program in 1801, based on the Mysorean technology. Several rocket cases were collected from Mysore and sent to Britain for analysis. Their first demonstration of solid-fuel rockets came in 1805 and was followed by publication of *"Concise Account of the Origin and Progress of the Rocket System"* in 1807 by **Sir William Congreve** (20 May 1772 – 16 May 1828), son of the Arsenal's commandant. Congreve rockets were systematically used by the British during the **Napoleonic** Wars and the War of 1812. They were also used in the 1814 Battle of Baltimore (Figure I.8), and are mentioned in The Star Spangled Banner, the national anthem of the United States: « *And the rockets' red glare, the bombs bursting in air* ».

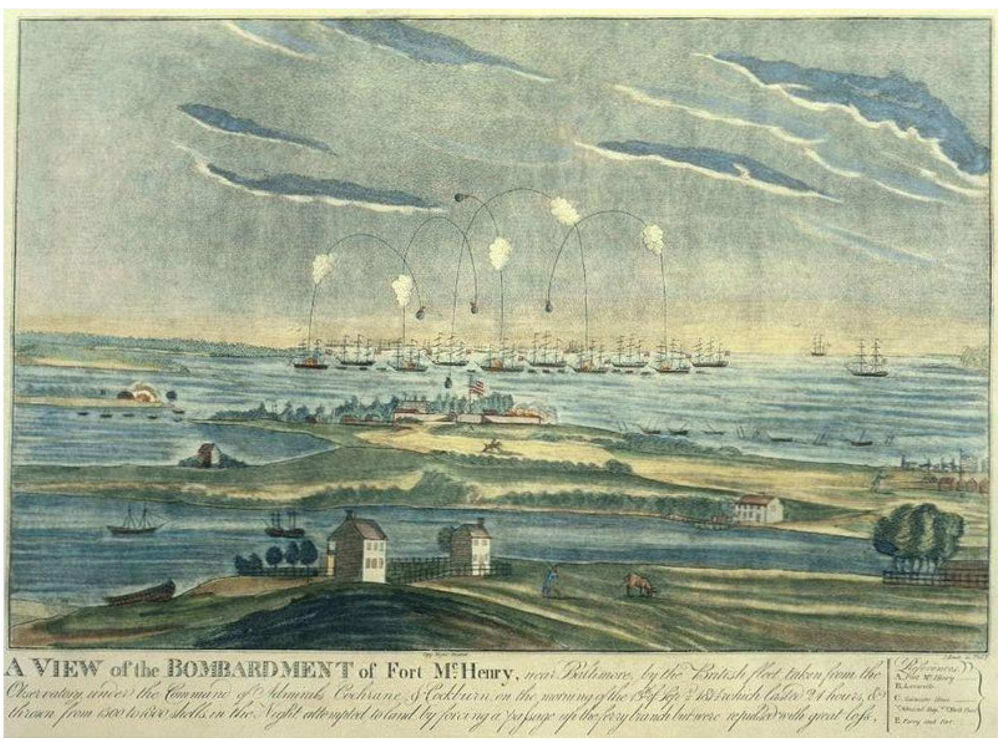


Figure II.8. Bombardment of Fort McHenry by the British. Engraved by John Bower [Laura Rich. Maryland History In Prints 1743-1900. p. 45].

I.7.2. WILLIAM CONGREVE ROCKETS ADVANCED:

Congreve made three critical innovations in rocket design. The first, borrowed straight from the Rocketeers of Mysore, was to use metal rather than pasteboard (or any other organic material) for the tube. The second was to use a mass-produced black powder mixed according to a standardized formula and prepared with mechanical grinding mills that produced particles of uniform size. The third was to use a device like a small pile driver—a heavy weight, lifted by ropes and pulleys and then dropped—to pack the powder into the tube [2].

It is surprising that **Napoleon** seems to have made no use of rockets in the French Army but it must be remembered **Napoleon** was an artillery officer and may have simply been too hide-bound a traditionalist to favor new-fangled rockets over more familiar cannons. The scope of the British use of the Congrieve rocket can be ascertained from the 1807 attack on Copenhagen. The Danes were subjected to a barrage of 25,000 rockets which burnt many houses and warehouses. An official rocket brigade was created in the British Army in 1818.

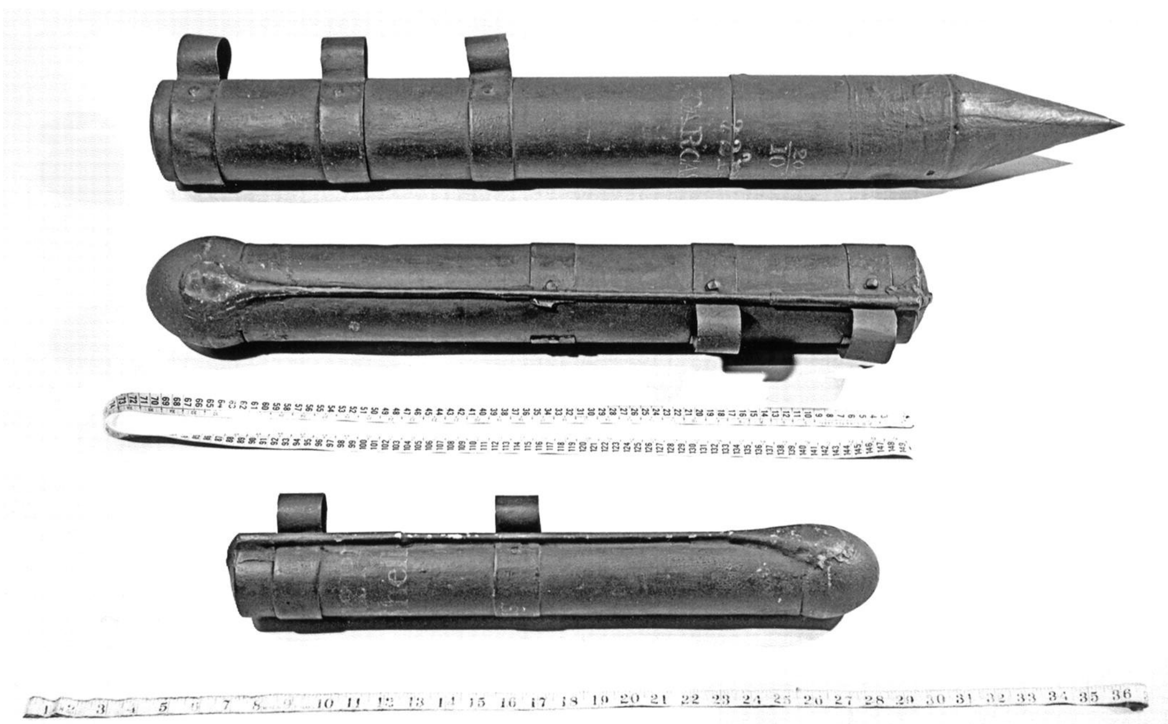


Figure III.9. Congreve 32-pounder incendiary rocket (top); explosive rockets with side-mounted sticks (bottom). These are larger than Congreve's earliest rockets, which weighed from six to eight pounds. [Copyright © National Air and Space Museum, Smithsonian Institution (SI 2008-2099)].

By the time **Congrieve** notes a problem in his rockets; when the rocket ignited the reducing of the propellant in front of the rocket makes it lose the center of gravity which led it to shift steadily forward. The largest part of the problem, however, was the stick. Like the Indian rockets on which they were based (and virtually all other rockets that came before them), **Congreve** reduced the balance problem in 1815 by mounting the stick in the center of the rocket's base plate and directing the exhaust through a ring of small nozzles around the edge of the plate. Even when centered, however, the stick was never perfectly centered, perfectly stiff, or perfectly straight, and the rockets continued to have a reputation for erratic flight.

I.8. WHEN SPACE TRAVEL WAS SCIENCE FICTION:

Dreamers came and went, but the vision remained. Man developed the tools of civilization, science, and art; and his dream slowly, incrementally approached reality. The astronomers defined the concepts of space and stars and planets. **Leonardo da Vinci** designed and built models of flying machines. **The Montgolfier brothers** devised the hot air balloon, and **F. Pilatre de Rozier** used it to lift man above the earth. The **Wright brothers** built the first powered aircraft and made air travel practical. It was only a matter of time before someone asked the question: What kind of machine could take man into the space and to the moon? [4]

At the late of the 19th Century, there was a burst of scientific investigation into interplanetary travel, largely driven by the inspiration of fiction by writers such as **Jules Verne** (8 February 1828 – 24 March 1905) and **Herbert George Wells** known as **H.G.Wells** (21 September 1866 – 13 August 1946). Scientists seized on the rocket as a technology that was able to achieve this in real life.

Jules Verne and **H.G. Wells** were the grandfathers of modern science fiction. Over the half-century between the end of the American Civil War and the beginning of World War I, they produced a steady stream of novels featuring exotic technology and fantastic journeys [2]. Some of **Wells** stories are; "*scientific romance*", "*The Land Ironclads*" (1904), "*The War in the Air*" (1908), and nuclear weapons in "*The World Set Free*" (1914). About **Verne's**, in "*From the Earth to the Moon*" (1865) and its sequel "*Round the Moon*" (1869).

Figure I.10. Jules Verne Photograph by Nadar, 1878.

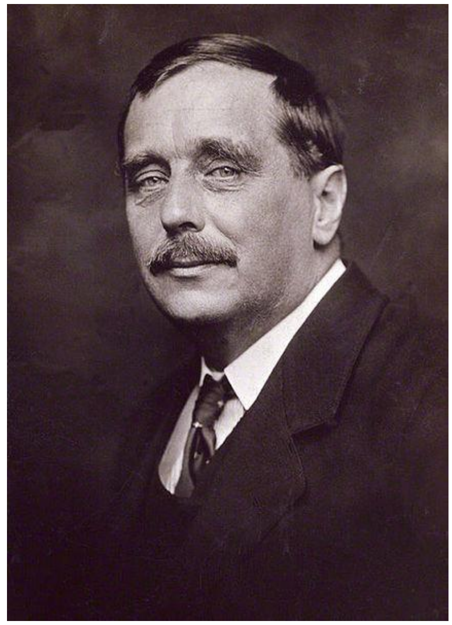


Figure I.11. H.G. Wells Photograph by George Charles Beresford, 1920.

Wells also wrote about sending heroes to space in *"The First Men in the Moon"* (1901), but the most famous one which inspired lot of minds was **Verne's** "*From the Earth to the Moon"* it was a well-researched science fiction story describing many technologies and observations. This work would inspire future rocket scientists, such as **Konstantin Tsiolkovsky** (1857-1935), **Robert Goddard** (1882-1945), and **Hermann Oberth** (1894–1989) [5]. They all admitted to having been inspired by **Verne's** book.

The favor of transition from science fiction to rocket science back to those three scientists who lived in different worlds and never met, they came up with the same answer driven by the dreams created by **Jules Verne** and others.

I.9. THE FATHERS OF ROCKETRY:

I.9.1. KONSTANTIN EDVARDOVICH TSIOLKOVSKY (1857-1935):

Konstantin Tsiolkovsky, an obscure high school teacher. At the age of ten, he became almost deaf as the result of scarlet fever. Because of his hearing impairment, he turned inward and became a scholar. Tsiolkovsky supported himself by teaching mathematics and physics in high school for 40 years, but he spent his free hours theorizing about and designing ways of being free of the earth. He designed and built a model of a flying machine powered by flapping wings. He designed dirigibles.

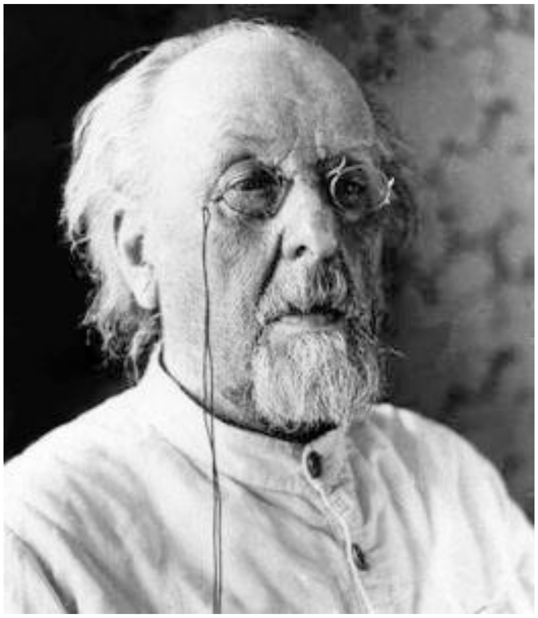


Figure IV.12. Konstantin Tsiolkovsky (September 1857 – 19 September 1935).

In 1883 **Tsiolkovsky** began to think seriously about space travel. Twenty years later, in 1903, he finally described his studies in a paper titled *"Investigation of Cosmic Space by Reactive Machines"* which he published in the Russian journal Scientific Survey. A reactive machine exploited **Isaac Newton's** third law of motion, which states that ‹‹ *for every action there is an equal and opposite reaction* ››. In **Tsiolkovsky's** mind, a reactive machine was a rocket. His later work included the modern concepts of the multistage rocket and a rocket motor fueled by liquid hydrogen and liquid oxygen. Unfortunately, because of his virtually nonexistent financial resources, **Tsiolkovsky** never built a rocket. His theoretical studies and speculations were all published in Russian. They were untranslated, unavailable, and unread outside his native land [4].

I.9.2. ROBERT HUTCHINGS GODDARD (1882-1945):

Robert Goddard has been recognized as the father of American rocketry and as one of the pioneers in the theoretical exploration of space. He was a professor of physics at Clark

University in Worcester, Massachusetts, who as a teenager was thrilled by **H.G. Wells'** "*The War of the Worlds"*, did research on ways to reach altitudes beyond the limit of balloons. Between 1914 and 1919, he received 70 patents for rockets and rocket apparatuses, including such fundamental patents on the design of the nozzle combustion chamber that allows the introduction of liquid fuel into the chamber and the design of a multistage rocket for high-altitude flight. He published his research in "*A Method of Reaching Extreme Altitudes"* in the Smithsonian Collection in 1919. It was a description of how to build a two-stage solid-propellant rocket and included a discussion of the feasibility of reaching the Moon with a rocket [5].

Figure I.13. Robert Hutchings Goddard (1882-1945) [NASA].

On December 30, 1930, one of Goddard's rockets reached an altitude of 2,000 ft. and a speed of 500 mi/h, and in 1934, he launched the first rocket equipped with a gyroscope to a height of 4,800 ft, a horizontal distance of 13,000 ft. Unfortunately, Goddard's research was not fully recognized, and his work not seriously studied by American scientists until years later [5].

Figure I.14. Robert H. Goddard and a liquid oxygen-gasoline rocket at Auburn, Massachusetts [NASA].

I.9.3. HERMANN JULIUS OBERTH (1894–1989):

Hermann Julius Oberth, fascinated by the books of **Jules Verne**, constructed a model rocket and conceived the first multistage model rocket. After World War I, he went back to study physics in Munich, Germany in 1922. His PhD thesis "*Die Rakete zu den Planetenräume* or *By Rocket into Planetary Space*" was rejected [5], he told the Heidelberg faculty that he would "become a greater scientist than some of you, even without the title of doctor" then he used the power of money and he published his thesis in 1923 as a slender ninety-two-page book titled "*The Rocket into Interplanetary Space"*. It sold well enough to cover another printing in 1925.

In 1929 he published the visionary work privately. This book and the expanded 429-page version entitled "*Wege zur Raumschiffahrt* or *Ways to Space flight*", are probably the most influential books on the future of space flight [5].

He formed informal contacts with science writers like **Max Valier** (1895 -1930) and **Willy Ley** (1906 –1969) , who used his ideas as the basis for popular, nontechnical works, and served as chief technical consultant on *"Frau im Mond* i.e. *The Woman in the Moon"*; a 1929 science fiction film by noted director **Fritz Lang** (1890 –1976) [2].

Figure I.15. Hermann Julius Oberth (1894–1989).

I.10. THE SPACEFLIGHT SOCIETY (VfR):

Following the writings of **Goddard**, **Oberth**, and others, a number of rocket research organizations were created. In part, the members were enthusiasts of space flight, and with some government support had a goal to develop guided missiles. In Germany, the "*Verein für Raumschiffahrt* – VfR- i.e. *the Spaceflight Society*", an amateur rocket group, was founded in 1927 by **Johannes Winkler** (1897 – 1947). Its member list included the who's who in rocket engineering in Germany: **Max Valier**, **Willy Ley**, and **Walter Neubert**. They were later joined by **Klaus Riedel** (1907 – 1944), **Rudolf Nebel** (1894 – 1978), **Wernher von Braun**, **Hermann Oberth**, **Walter Hohmann** (1880 – 1945), **Kurt Heinisch**, **Eugen Sänger** (1905 – 1964), **Rolf Engel** (1912 – 1993), and up to five hundred other members who produced a periodical called "*Die Rakete* or *The Rocket"*. Hohmann's book, "*Die Erreichbarkeit der Himmelskorper* or *The Attainability of Celestial Bodies*" was published in 1925 and was so technically advanced that it was consulted years later by the National Aeronautics and Space Administration (NASA) [5]. The group had a formal charter and serious objectives from the beginning. The charter set forth two principal purposes: first one is to popularize the idea of rocket flight to the moon and planets, and the second to conduct serious experiments in the development of rocket propulsion.

I.10.1. REASERCHES START AT ROCKET AIRFIELD:

The VfR's first important launches took place at the "*Raketenflugplatz* or *rocket airfield*" in May 1930. A rocket powered by gasoline and liquid oxygen made two flights within three days, reaching nearly 200 m on the first and close to 650 m on the second. Two years, 270 static tests, and 87 flights later, rockets launched by the VfR had reached altitudes of a mile and covered horizontal distances of three miles [2].

The VfR began to test different types of liquid propelled rockets with different success and minimum budgetary resources, the made different version of the "Mirak or Minimumrakete", based on the same principle, were tested in 1930 and 1931 using carbon dioxide as a pressurizer. In 1931 and 1932 the Huckel-Winkler HW-1 and HW-2 were tested. This time oxygen and liquid methane were used and for the first time an electrical ignition system.

Also in 1931 several rockets of the Repulsor series, formed by one or two sections which worked with petrol and liquid oxygen were lunched, water was used as a refrigerant, and recovery parachute was employed.

I.10.2. WERNHER Von BRAUN (MARCH 23, 1912 – JUNE 16, 1977):

Von Braun one of the members of the VfR how will became the father of the American rocketry, He joined the VfR in 1930, where he assisted **Willy Ley** in his liquid-fueled rocket motor tests in conjunction with **Hermann Oberth**. He attended the *Technische Hochschule Berlin* now (Technical University of Berlin) and he graduated from it with a diploma in mechanical engineering.

Von Braun entered the *Friedrich-Wilhelm University* of Berlin for post-graduate studies and graduated with a doctorate in physics in July 27, 1934 for a thesis entitled "*About Combustion Tests"*; his doctoral supervisor was **Erich Schumann** (1898-1985). However, this thesis was only the public part of **von Braun's** work. His actual full thesis was "*Construction, Theoretical, and Experimental Solution to the Problem of the Liquid Propellant Rocket"* (dated April 16, 1934) was kept classified by the army, and was not published until 1960.

He parlayed his practical experience with the VfR and his theoretical knowledge of physics into full-time work as a rocket designer for the German army. He rose quickly to project management and director, as a civilian. As Germany plunged into the dark days of war and the terrorizing years of war crimes, **von Braun** found himself a key player in developing what the Nazi dictator **Adolf Hitler** (1889 –1945) called the "secret weapon"—the V-2 rocket [6].

A German army officer, **Colonel Karl Becker** (1879 – 1940) chief of the army weapons bureau (*Heereswaffenamt,* or HWA), he was interested in field of artillery and ballistics, he start several researches on rocket for long range artillery as a means to deliver poison gas against an enemy, he advance the use of solid fueled rockets as short-range weapons.

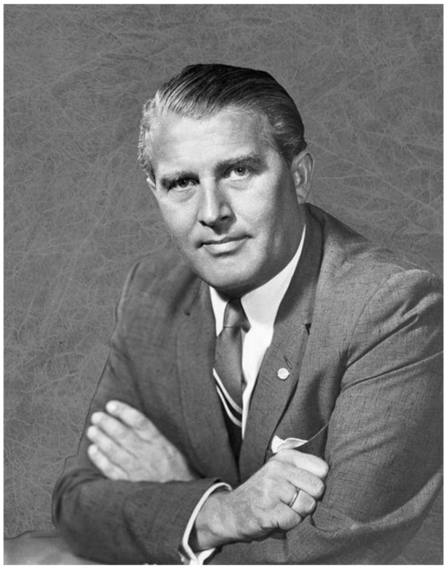


Figure I.16. Wernher Magnus Maximilian Freiherr von Braun, picture was taken in 1960 [NASA/Marshall Space Flight Center].

I.10.2.1 VON BRAUN MEETS WALTER DORNBERGER:

Captain Walter Dornberger (6 September 1895 – 27 June 1980) was an engineer and veteran artillery officer assigned to Becker, he is one of the keys player in the V-2 development as **von Braun**. In 1930, **Dornberger** started to explore ways to use solid fueled rockets to deliver weapons to a range of about seven to eight kilometers, when the VfR was experimenting with combinations of gasoline and liquid oxygen rockets that promised greater range and payloads than solid fueled systems; Becker turned his attention to liquid fuel rockets, in mine time **Dornberger** involved with the VfR activities that included information exchanges and allowed VfR members to use the HWA's rocket test ranges for their experiments. This test range, Kummersdorf, was near Berlin a static testing site for ballistic missile weapons. **Dornberger** also recruited VfR members to work for the HWA. One of his biggest catches was a young engineer, **Wernher von Braun**, who came to work for the HWA in 1932 [7].

I.11. ROCKET DEVELOPMENT AT KUMMERSDORF:

In 1934 VfR's activity stopped and some members like **von Braun**, **Klaus Riedel**, **Major von Richthofen** (1895 – 1945), and **Ernst Heinkel** (1888 – 1958) went into the HWA as civil engineers under the direction of **Captain Dornberger**. The Kummersdorf team designed and built the A-1 (Aggregate-1) rocket it could develop a thrust of about 660 pounds. Powered by a combination of liquid oxygen and alcohol and with a gyroscope in the nose of the rocket (to provide stability during flight), but this lunch was failed because of a defective motor design and the wrong emplacement of the gyroscope caused instability in flight.

Its successor, the A-2, employed separate alcohol and liquid oxygen tanks with a gyro-flywheel in its center of gravity, In December 1934 it flew up to 2.4 km, two A-2 rockets, nicknamed Max and Moritz (after the twins in the German version of the *Katzenjammer Kids* cartoon strip), were launched from the North Sea island of Borkum and reached an altitude of about 1,700 m. **von Braun**, **Rudolph**, **Riedel**, and even **Dornberger** were jubilant.

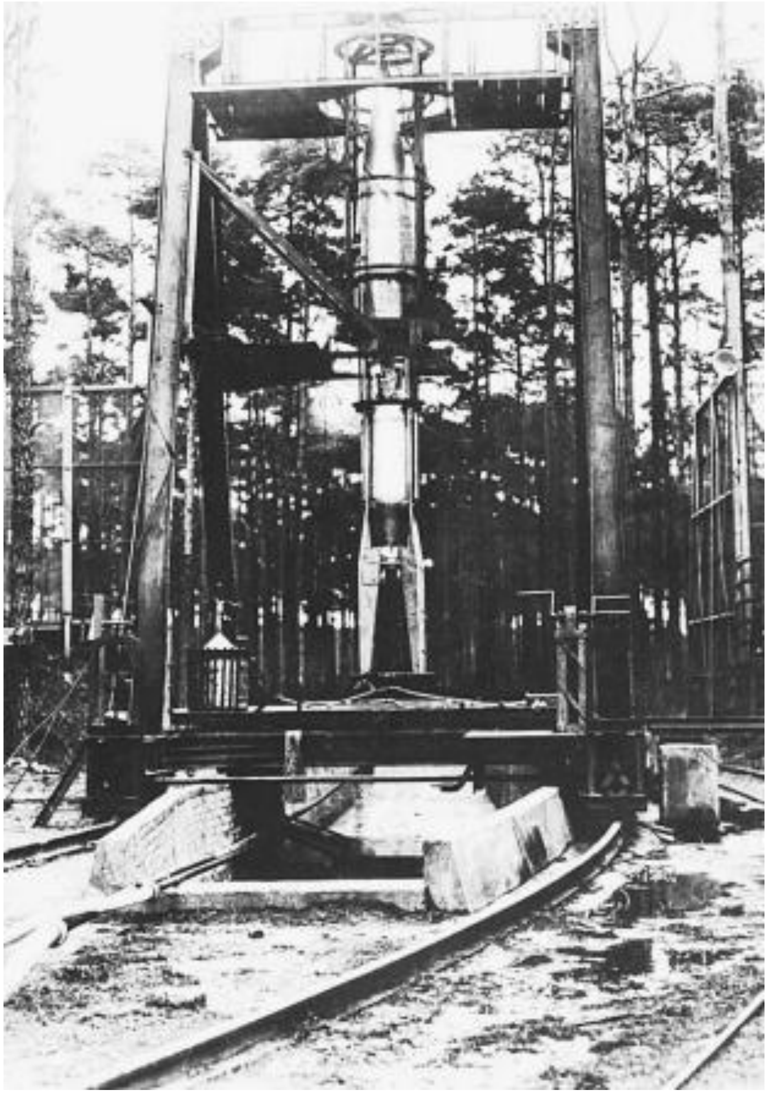


Figure I.17. Rocket testing began in the early 1930s at Kummersdorf, as shown in this photo taken about 1932–33 of an A-2 on one of the several test stands located there. [Archives, U.S. Space and Rocket Center, Huntsville, Alabama] [6].

I.12. FROM KUMMERSDORF TO PEENEMÜNDE:

In April 1937, all of the German rocket testing was relocated to a top-secret base, the "*Heeresversuchsstelle Peenemünde* or Army Experimental Station, Peenemünde" on the Baltic Coast (Figure I.18).

Figure I.18. Enlargement of part of a vertical photographic-reconnaissance aerial of Test Stand VII at the Army Research Centre Peenemunde, Usedom Island, Germany.

The German Air Ministry, the army, and the German government spent more than 70 million dollars on the construction of Peenemünde, a dream facility for the fabrication of long-range missiles. **Von Braun** assembled a team of first-rate engineers, designers, and administrators, including **Walter Thiel** (born 7 March 1949), **Rudolf Herrmann**, **Herman Steuding** (1850 – 1917), and others. As their first task, they developed the A-3 rocket, an 821 kg, 6.5 m long rocket, which burned a combination of liquid oxygen and alcohol. Its propulsion system worked very well, and great progress was made on the guidance and control systems, but it became what **von Braun** would later call "a successful failure" [5].

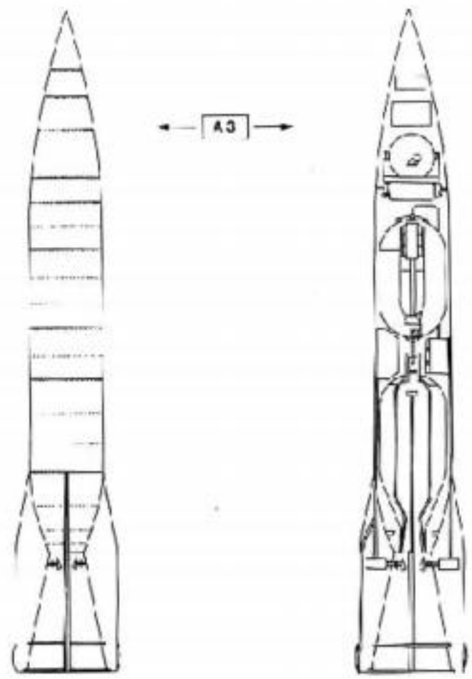


Figure V.19. Definition draw of the A3 rocket [8].

Stage	Flying test
Structure	Steel.
Cladding	Welded steel plate.
Tail unit	Fixed, steering by nozzle vanes.
Thrust	15 KN
Propellants	Liquid oxygen and alcohol.
Equipment	Thermometer, Shooting camera, gyroscopic plant and recovery parachute.
Length	6.74 m
Span	0.93 m
Max diameter	0.76 m
Launch weight	740 kg
Time of propelled flight	45 second.
Range	20 km
Test launches	four, all made in December 1944.

Table I.1. A3 Technical data [8].

I.12.2. THE AGGREGATE-4 (A-4):

By 1938, Germany had begun invading huge portions of Eastern Europe, and **Adolf Hitler** began recognizing the need for an effective ballistic missile weapon. The German Ordnance Department requested that the Peenemünde team develop a ballistic weapon with a range of 150–200 miles that could carry a 1-ton explosive warhead and could be transported on existing railways, which required size compatibility with tunnels and bends. These criteria led directly to the development of the A-4 rocket [5].

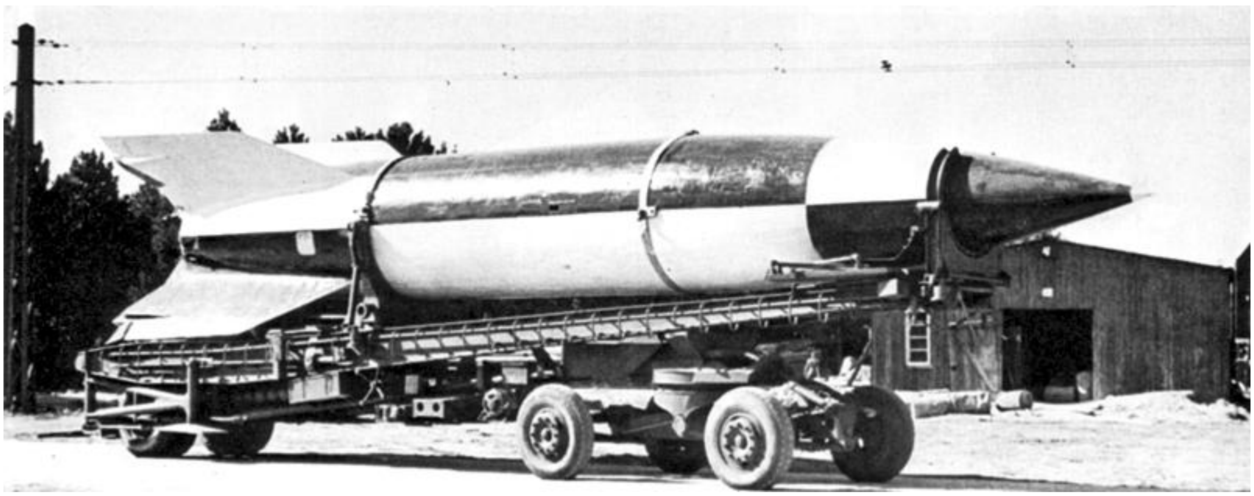


Figure I.20. V-2 rocket on Meillerwagen at Operation Backfire near Cuxhaven in 1945 [Imperial War Museum].

The A-4 was the first rocket to be built to specific performance specifications; earlier rockets were built and then tested to see how well the new design performed. A few days after **General von Fritsch's** visit in March 1936, **Dornberger** had sat down with **Riedel** and **von Braun** to outline his plans. They were developing artillery, he reminded them, for use in battle, and if they didn't come up with something useful, funding would dry up. He set out specifications for the next rocket, the A-4: It must have twice the range of the Paris Gun, a total of about 162 miles (260 km); it must be capable of carrying a warhead weighing 2204.6 pounds (1 metric ton); it could deviate only 6.5–10 feet (2–3 m) from its target; it must be transportable by rail, roadway or trails (*Meillerwagen* i.e. Meiller Vehicle) to any point within German boundaries (limiting its length and diameter to sizes that would pass through tunnels and go around curves in roads and railways) [6].

After two unsuccessful launches in June and August, on 3 October 1942 the first satisfactory flights of an A-4 were made, reaching an altitude of 85 km. The success impressed the German government, and **Hitler** himself ordered its mass production with the name of V-2, which the German propaganda declared meant "Vergeltungswaffe-2 i.e. Weapon of Revenge N° 2" [8].

I.13. WEAPONS OF REVENGE:

The most significant German missiles of the war, however, were designed not for use against ships but for use against cities. **Hitler** dubbed the V-1 and V-2 (*Verstellungswaffe* i.e. vengeance weapons), and saw them as a means of terrorizing Allied civilians and so destroying their will to fight.

Figure I.21. A-4 (V-2) rocket launch sites and ranges of missiles, 1943–1944. German A-4 (V-2) launch sites in France could strike southern England. Later, the missiles hit Antwerp and Liege. [Courtesy, Mapcraft] [7].

I.13.1. VENGEANCE WEAPON-1/BUZZ BOMB:

The V-1 was a small, unpiloted airplane powered by a jet engine and guided by a system of gyroscopes linked to its rudder and elevators (see Appendix A Figure.1). The V-1 was designed for mass production. The wings and fuselage were made of sheet metal, the engine was a simple “pulse jet” (little more than a carefully shaped tube with a fuel injector and an igniter), and the ingenious guidance system was built simply and from off-the-shelf hardware [2].

Figure I.22. Soldiers pulling flying buzz bomb.

I.13.1.1 WORK PRINCIPLE OF THE V-1 ROCKET ENGINE:

The V-1 had a fuselage of steel and wings of plywood. Essentially the power unit consists of a welded steel tube with a block of steel-spring inlet valves and nine rearward-facing fuel nozzles at the front end. The spring valves are opened by air pressure due to the forward speed of the flying bomb, and the fuel is injected and ignited the resulting explosion closes the valves so that the heated and expanded combustion gases are ejected from the rear of the tube. Pressure in the combustion chamber is reduced to below atmospheric, and the valves are re-opened by air pressure. This process is repeated about 45 times per second. To maintain the correct mixture strength, fuel feed is regulated according to speed and altitude. A single sparking plug is used for starting only. After initial starting with Butane the unit becomes self-igniting due to the heat of the chamber walls.

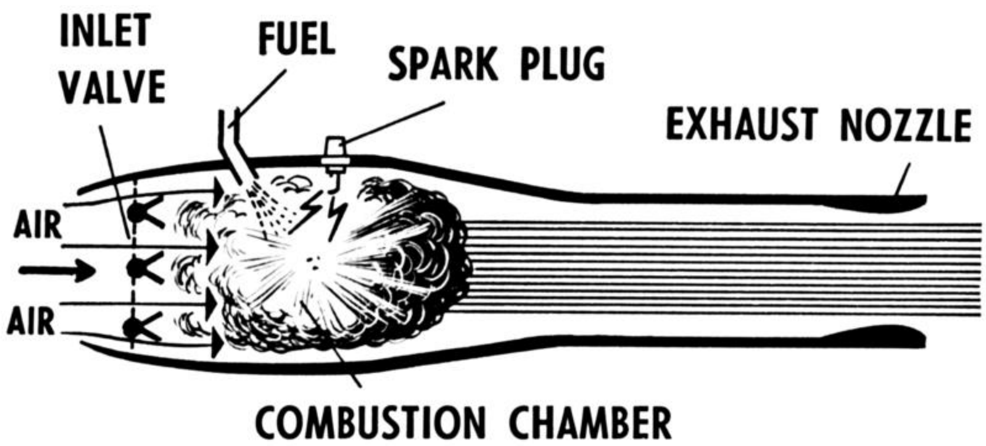


Figure I.23. Illustration of the V-1 pulse jet engine work.

The pulse jet engine gives it the characteristic sound that got it the nicknames ‘doodle bug’ and ‘buzz bomb.’ The gasoline jet engine didn’t provide enough force for takeoff, so the missile was launched with a chemical explosive that got its speed up over 800Km/h.

I.13.1.2 V-1 ROCKET LAUNCH:

Each V-1 was launched from a ramp (Figure I.24), between the rails are two covers with 1.2cm steel with 3.5cm center grow below the covers as actual price inserting a piston which propels the buzz bombs during takeoff, it was unguided. After it was launched, the V-1 flew a preset course until a switch cut off its engine, causing the V-1 to simply fall on whatever was under it.

I.13.1.3 V-1 ROCKET TROUBLES:

The V-1 mechanically complex guidance system led to its low success the airframe was also prone to failure due to engine vibration. It is believed that about 25% of all V-1 missiles launched were destroyed by airframe failure before reaching their targets.

Figure I.24. Fieseler Fi 130 Flying Bomb on the ramp.

I.13.2. VENGEANCE WEAPON V-2/A4:

The V-2 was the last version in V-weapons and it was a far more sophisticated weapon than the V-1 and therefore a far greater problem for the Allies. It was the world's first operational ballistic missile (Figure I.25), designed to be launched vertically and soar to the top of a high arc before falling toward its target. Developed by a team led by **Walter Dornberger** (**Karl Becker's** assistant) and **Wernher von Braun**, the V-2 was a development of the A-2 and A-3 rockets the team had developed in the late 1930s [2].

For the V-2, over 7 kg raw materials were needed (without the explosives and devices) of which 3.112 kg thin sheet metal (various thickness) (e.g. the outer skin). The A-4/V-2 rocket had an operational range of 374 km. The max burning time of the engine was 65-70 seconds, shortly before engine shutdown the A-4/V-2 weighed 4040 kg at a height of 35 km, starting with 1 G force, and at shutdown 8 G, after shutdown the rocket flew to a height of 97 km and fell to earth with an impact speed of 3.240-3.600 km per hour. Liftoff was straight up; 30 seconds after launch it reached speed of sound. When launched against targets close to the operational range of the vehicle, the deviation between target and impact was normally 7-17 km away from target [9].

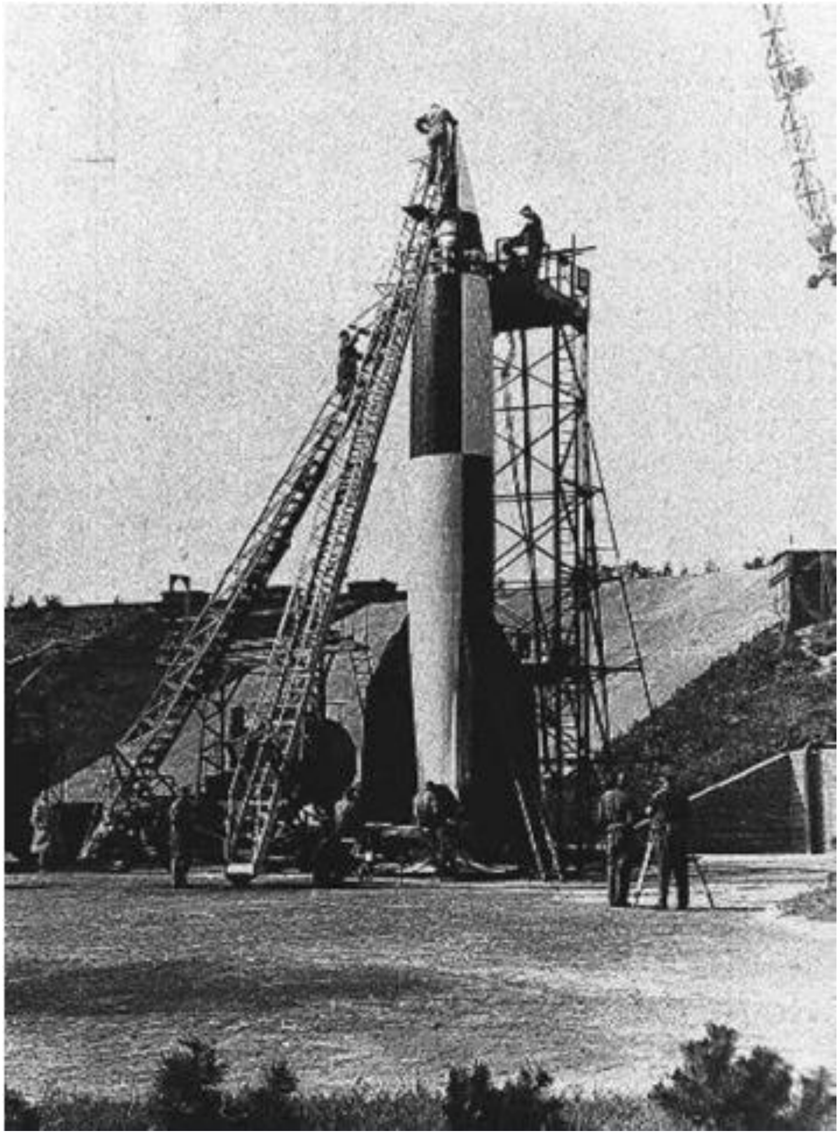


Figure I.25. Period views of one of the A-4/V-2 launch sites at Peenemünde. [Courtesy of NASA] [5].

I.13.2.1 STRUCTURE OF THE V2-ROCKET:

The V2-rocket was 14m tall with 1.65m max diameter, it was consisted of three main sections (nose, body and tail) containing the entire component (warheads, fuel tanks, motor and motor equipment), the following sections are from nose to tail:

1. NOSE:

The nose with 3.42m tall contained two parts; first one is the warhead part with 738Kg of charge explosive but not high explosives, because of frictional warmth exceeding 1200° F during flight. And the second part was for control and guidance it was divided with plywood into four rooms; each room contained such a device (see fig) (an automatic pilot, accelerometer and radio equipment). The automatic pilot was made up of two electric gyroscopes that stabilized the rocket's pitch, roll and yaw motions.

Figure I.26. American soldiers inspect a V-2 rocket captured intact in April 1945.

2. BODY:

The rocket body consists of a framework covered with a light metal fuselage and it carried three component and they are: the fuel tanks, engine (motor) equipment and the engine itself.

Because all of this heavy weights the body must be made from very strong but light weight materials, like titanium, aluminum or thin sheet steel metal, The "skin" is then attached to the stringers and hoops to form the basic shape of the rocket. The skin may be coated with a thermal protection system to keep out the heat of air friction during flight and to keep in the cold temperatures needed for certain fuels and oxidizers (Figure I.27).

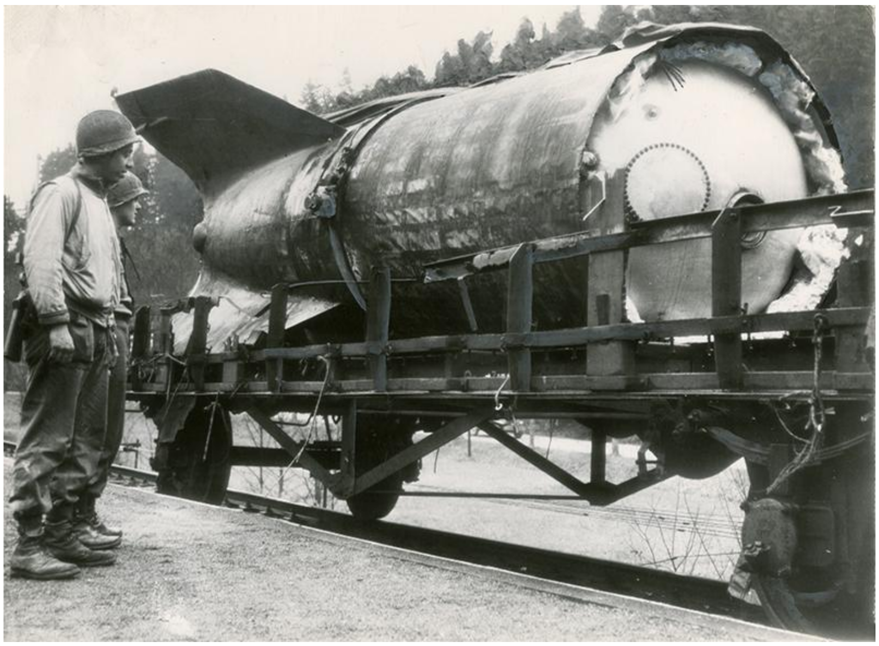


Figure I.27. American soldiers from the 1st Army examining part of a V-2 rocket after the army had captured the town of Bromskirchen, Germany. The picture shows that the rocket has not yet been paired with the upper half of the body and warhead.

a. THE FUEL TANKS:

The first tank A-Stoff carried the oxidizer liquid oxygen with a temperature of – 183°C and a dry weight 4.900 kg. The second tank called B-Stoff carried an alcohol (a mixture of 75% ethyl alcohol and 25% water) with a dry weight 3.710 kg as it is the fuel.

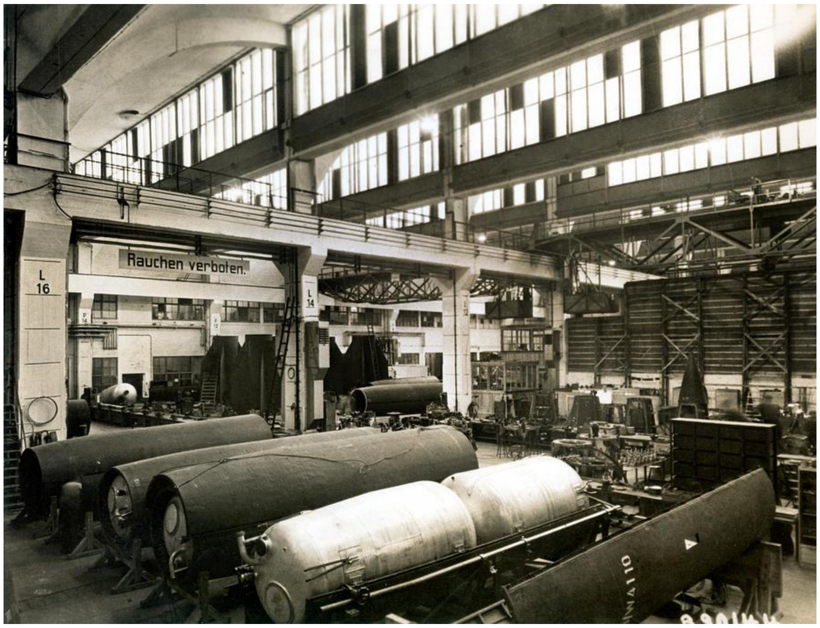


Figure I.28. German Rocket Factory, 1943 [photograph by Detlev Van Ravenswaay].

b. ENGINE:

The V-2 engine burn chamber temperature was about 2,700°C. This wall is cooled by the liquid ethyl alcohol flowing via the double wall of the beam tube and burning chamber, which also heated up the ethyl alcohol. In the burning process, first oxygen is injected, without entering air, then spontaneous burn of the fuel and liquid oxygen, then gasses flow with great speed to the nozzle end.

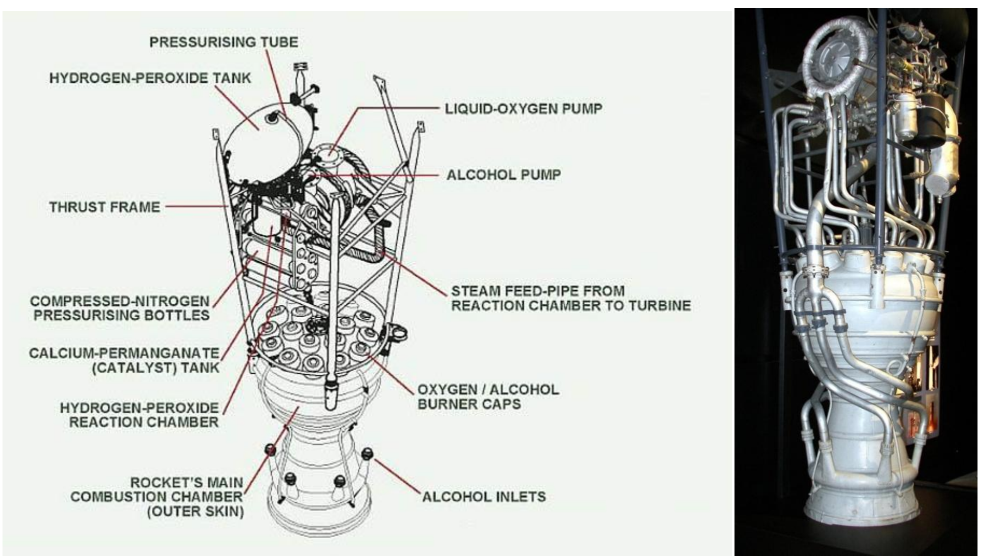


Figure I.29. Nomenclature of the V-2 rocket engine and a real view of it.

c. GAS-TURBINE PUMP:

Large liquid rocket engines require massive amounts of propellants to be fed into the combustion chamber quickly and under high pressure. This was accomplished on the V-2 by using high-speed gas-turbine pumps, or turbo-pumps. The V-2/A-4 rocket motor was the first design that successfully moved large volumes of fuel to the combustion chamber using this technology. The gas-turbine was powered by steam; pressure came from the chemical reaction of combining two liquids, sodium permanganate (tank A) and hydrogen peroxide (tank B). The thrust frame was one of the key components in the engine assembly.

The turbine developed 580 horsepower and turned the pumps at about 3,800 revolutions per minute. The cutaway on display shows some of the pumps' moving parts. The turbo-pumps forced 58 kg of alcohol and 72 kg of liquid oxygen into the V-2's combustion chamber every second.

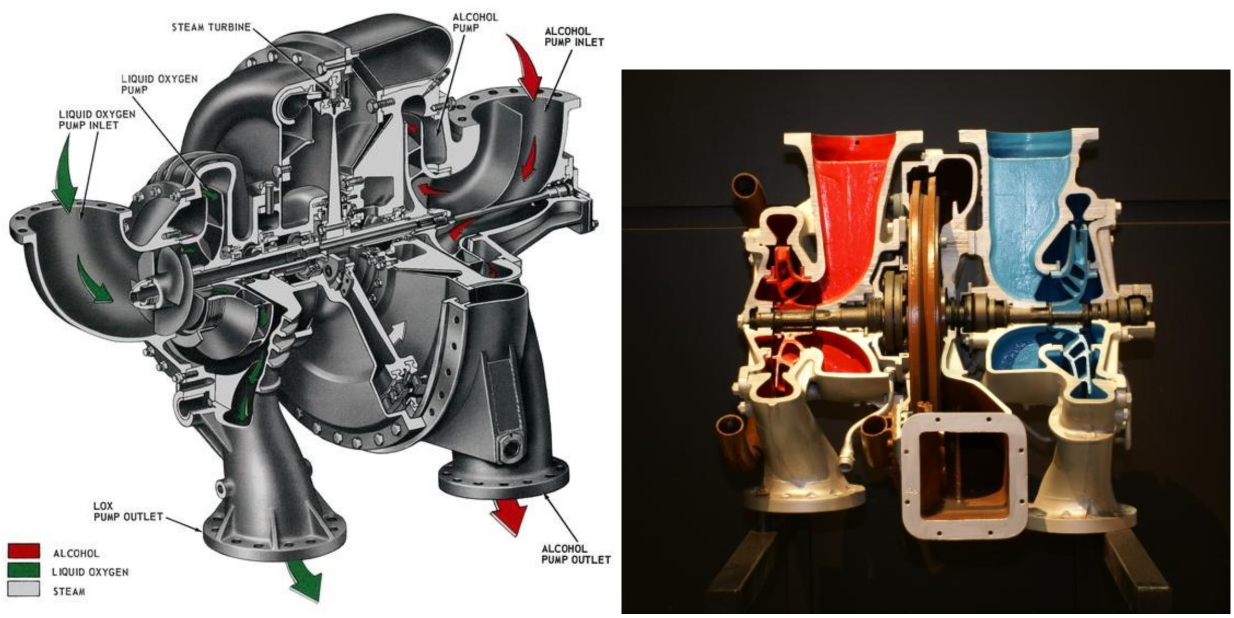


Figure I.30. Two cut view of the fuel pump; Schema (left), real view (right).

3. FINS:

The V-2 was guided by four external rudders on the tail fins, and four internal graphite vanes in the jet stream at the exit of the motor.

The V-2 rocket has 4 fins with 3.95 m long; the V-2 was steered by 4 graphite rudders and 4 vanes (at the fins). To describe the steering process, one can imagine the mechanics of the vertical vanes and rudders 1 and 3, and the horizontal vanes and rudders 2 and 4, in this manner. Vanes and rudders 1 and 3 (react together) control the oscillation and heading in the lateral movement, then the movement in the projectiles along a given axis, which stands perpendicular on the vertical movement by the same along the axis. Rudders 2 and 4 control the oscillation and heading in the vertical movement in the same manner on their axis. Vanes 2 and 4 controls roll stabilization. Vanes 1, 2, 3, and 4 are controlled by a gyroscope. They keep the axis of the V-2 vertical. Rudders 2 and 4 are controlled by another gyroscope. They take care of the angle (as from the vertical) of the rocket during burn time. The latter gyroscope is controlled by a third gyroscope that makes sure the first mile will be straight up, after that it is turning until the correct elevation is reached, This elevation is kept until the speed is high enough to reach the target, finally the last gyroscope shuts off fuel supply. After shutdown the rocket acts as regular artillery shell [9].

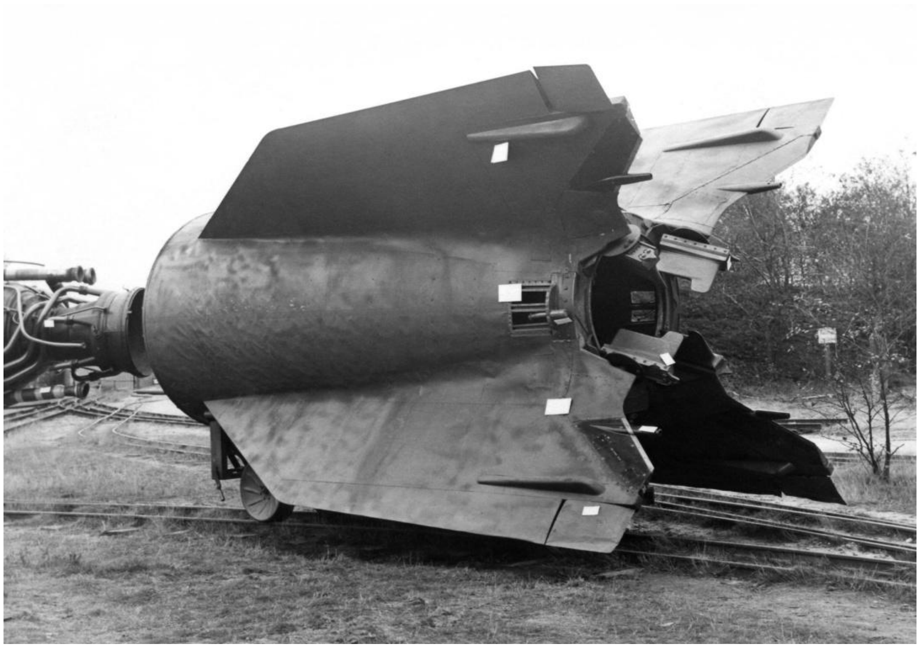


Figure I.31. Four fins attached to tail section, the parts are in an assembly rail.

Stage	Operational
Structure	Steel with internal isolation of fibre-glass.
Cladding	Riveted steel plate.
Tail unit	Movable fins controlled by electrical controls and nozzle vanes with electrohydraulic control.
Engine	Thrust of 27500 kg and a maximum acceleration of 6G.
Propellants	liquid oxygen as an oxidizer and a mixture of 75% ethyl alcohol and 25% water a fuel.
Equipment	Gyroscopic, integrated accelerometers, radio control, warhead with electrical and mechanical fuses.
Length	14.03 m
Span	3.5 m
Max diameter	1.68 m
Launch weight	12870 kg
Max speed	5760 km/h
Time of propelled flight	70 seconds.
Range	330 km
Test launches	Thirty-one in total made between 13/6/42 and 9/7/43.

Table I.2. Technical Data of the V-2/A-4 [8].

I.14. BOMBARDING PEENEMÜNDE FACILITY:

By 1943, V-2 is nearly operational but occasionally, one of the rocket out of control and landed accidently near Kalmar, Sweden, another one landed in Poland, the Polish radioed the allies who immediately sent a plan to recover the wreckage of the rocket to the headquarters in London, after assembling the parts the British government gained a small glimpse of the German missile, they toke aerial photographic reconnaissance images of Peenemünde base then on the night of 17/18 August 1943. Royal Air Force attack on the Peenemünde Army Research Center as Operation Hydra. 215 British aircrew members and 40 bombers were lost, and hundreds of civilians were killed in a nearby concentration camp. The air raid killed two V-2 rocket scientists and delayed V-2 rocket test launches for seven weeks.

I.15. MOVING FROM PEENEMÜNDE TO MITTELWERK:

Following the allied bombing of August 17, 1943 **Hitler** commanded that assembly line production of the V-2 must begin at huge new assembly production site to an underground facility at the Mittelwerk site near Nordhausen in the Harz Mountains by prisoners from Mittelbau-Dora. This site was converted from an oil depot.

After couple of launch failures, on 13 June and 16 August 1942, the A-4 performed its first successful flight on 3 October 1942. Far exceeding the performance of any previous rocket, it reached an altitude of about 90 km, travelled some 192 km from the launch site and landed within about 4 km of the target. On 7 July 1943, Dornberger and von Braun, by then technical director of the Peenemünde rocket centre, showed the film of the first successful flight to Adolf Hitler, who until then had been somewhat dismissive of rocket technology. From that point on the A-4 was given the highest priority, and renamed Vengeance Weapon or V-2.

Figure I.32. German V-2 crews attempted to knock out Antwerp, a major port, to stop the flow of supplies to Allied forces. Although there were relatively few casualties, these attacks did kill several thousand people. Supply operations were affected with a slowdown. [Courtesy, U.S. National Archives] [7].

The first two launches of the V-2 offensive were made on 6 September 1944 from a mobile battery stationed near Vielsalm, on the eastern fringe of Belgium, but both rockets failed when the fuel supply cut off prematurely. Two days later, having relocated to a point near Houffalize, the battery made its first successful launch towards Paris, which had fallen to the Allies on 25 August 1944. The world's first long-range combat rocket, now under the control of the notorious, made the 290 km flight in just a few minutes and impacted close to Port d'Italie, producing 'modest damage'. On the evening of 8 September 1944, other batteries located between The Hague and Wassenaar in Holland began their launch campaign towards London, aiming at a point near Waterloo station.

Over 3100 rockets were fired, and most of them were not against London. Only 1402 were against England, 1358 against London. The rest were against European targets: 1664 against Belgium (Antwerp being a key Allied port), 76 against France, 19 against The Netherlands, 11 against the Remagen Bridge after it was taken intact in early March 1945 (to no effect whatsoever).

I.16. THE ROCKET TEAM AND THE OPERATION PAPERCLIP:

At the end of the Second World War, the United States and USSR competed to retrieve as many of the V-2s and German rocket engineers as possible. In order to avoid capture by the Soviets, von Braun and many of his staff surrendered to the Americans and were brought to the United States through Operation Paperclip. There they began work for the U.S. Army on the Hermes missile program, an attempt to copy and then expand the capabilities of the V-2. The Soviets had a similar program employing many of the German rocket engineers who did not go with the Americans. Von Braun and his team moved to the Redstone Arsenal in Huntsville, Alabama, to work for what would become the Army Ballistic Missile Agency. It was there that the Redstone missile was developed under von Braun's leadership.

Figure I.33. Von Braun (center, with cast) talked persuasively at the time he and his team surrendered to the U.S. Army and convinced them that the German rocket team would be a great asset [NASA Marshall Space Flight Center] [6].

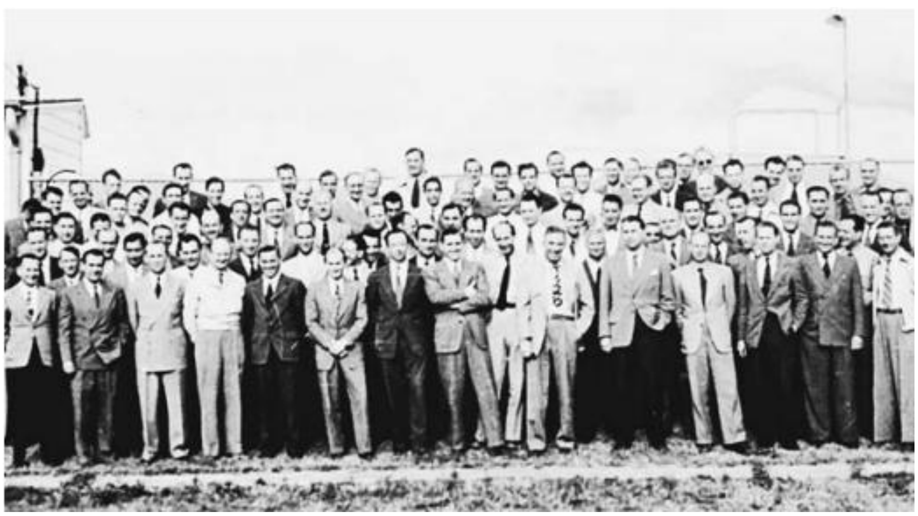


Figure I.34. Operation Paperclip brought about 100 members of von Braun's team of scientists and technologists to Fort Bliss, Texas, by the end of 1945 [NASA, Marshall Space Flight Center] [6].

In the USSR, development of the R-7 Semyorka began in the early 1950s under the leadership of Sergei Korolev (1907–1966), regarded by many as the father of the Russian space program [5].

Several rocket programs had began after the defeating of the German giant which was acquiring the technology of rocketry in that time; USSR space program (first man in space and orbit the earth, first satellite), USA (first orbital flight, first spacewalk), after those tow programs Many countries have adopted their missile programs such as UK, EUROP countries, China, India.

REFERENCES BIBLIOGRAPHY

[1] Thomas S. Kuhn, "The Structure of Scientific Revolutions", Third Edition, University of Chicago Press, Chicago 60637, 1996.

[2] A. Bowdoin Van Riper, "Rockets and Missiles: The Life Story of a Technology". (GREENWOOD PRESS, 88 Post Road West,Westport, CT 06881, 2004).

[3] Mohamed Mansour, "Foundation for Science Technology and Civilisation", 4 (July 2002).

[4] Dennis Piszkiewicz, "The Nazi Rocketeers Dreams of Space and Crimes of War". (Praeger 88 Post Road West, Westport, CT 06881, 1995).

[5] Ann Garrison Darrin, "Handbook of Space Engineering, Archaeology and Heritage". (CRC Press, United States of America, 2009).

[6] Ray Spangenburg & Diane Kit Moser, "Wernher von Braun Rocket Visionary", Revised edition ed. (Chelsea House, 132 West 31st Street New York NY 10001, 2008).

[7] Clayton K. S. Chun, "Thunder over the Horizon: From V-2 Rockets to Ballistic Missiles". (Praeger Security International, Westport, Connecticut • London, 2006).

[8] J. Miranda & P. Mercado, "Secret Wonder Weapons of the Third Reich German Missiles 1934-1945". (Schiffer Publishing, 1996).

[9] http://www.v2rocket.com/start/makeup/design.html.

CHAPTER II

STATE OF THE ART

II.1. INTRODUCTION:

The development that happened in the modern rocket technology is due to many efforts of associations and persons who spent their time and money to serve and to accelerate the wheel of rocketry science.

In the late 1920s, the rocket spaceflight idea attracted enthusiasts worldwide, especially in Germany, France, the USA, the USSR and the United Kingdom. In these countries, national and international societies for spaceflight or astronautics were set up, with mission studies and experimental tests being carried out [1].

II.2. SOCIETY FOR SPACE TRAVEL:

The first rocket society was the *"Verein für Raumschiffahr* –VfR- *or Society for space travel"* which was founded in 1927 by Johannes Winkler, with Max Valier and Willy Ley and German amateur rocketeers, prior to World War II that included members outside Germany. The VfR had two goals: raising public awareness of space travel, and advancing the state of the art in rocketry.

Figure II.1. This group shot shows members and supporters of the VfR, including, among others: Rudolf Nebel (far left), Hermann Oberth to the right of the standing rocket, Klaus Riedel (in white coat holding a Mirak I rocket), and Wernher von Braun on the right in front of an unidentified onlooker. (Library of Congress) [2].

In pursuit of the first, they published a widely read newsletter, "*Die Rakete* or *The Rocket*", and by 1930 were organizing rocket exhibitions. In pursuit of the second, they took over an abandoned (and rent-free) army post on the outskirts of Berlin: 300 acres of open space for test flights, along with buildings for workshops and -for some members- living space. With one eye on the future that they hoped to create, they give it the name "*Raketenflugplatz Spaceport*" [2]. It was an ambitious agenda, and the VfR was tireless in its diverse but dedicated activities—publishing posters, giving lectures, and holding public demonstrations, all of which met with enormous success initially [3].

The VfR gives a huge push to German rockets, and it helped to discover new and genius characters like Wernher von Braun, Klaus Riedel,Major von Richthofen, and Ernst Heinkel whom traveled to work in (*Heereswaffenamt* or HWA) under the direction of Captain Walter Dornberger at Kummersdorf site.

II.3. THE AMERICAN ROCKET SOCIETY:

The American Rocket Society was founded in 1930 as the American Interplanetary Society (AIS) by G. Edward Pendray, David Lasser, Laurence Manning, and others. Parallel to Goddard's efforts, they performed work in the testing and design requirements of liquid-fueled rockets and successfully launched multiple rockets up to 382 ft. in altitude and a distance of 1,338 ft. Their work was discontinued in World War II, and was renamed the American Rocket Society (ARS) in 1934[2]. And the AIS were absorbed into the American Institute of Aeronautics and Astronautics (AIAA) in 1963 [4].

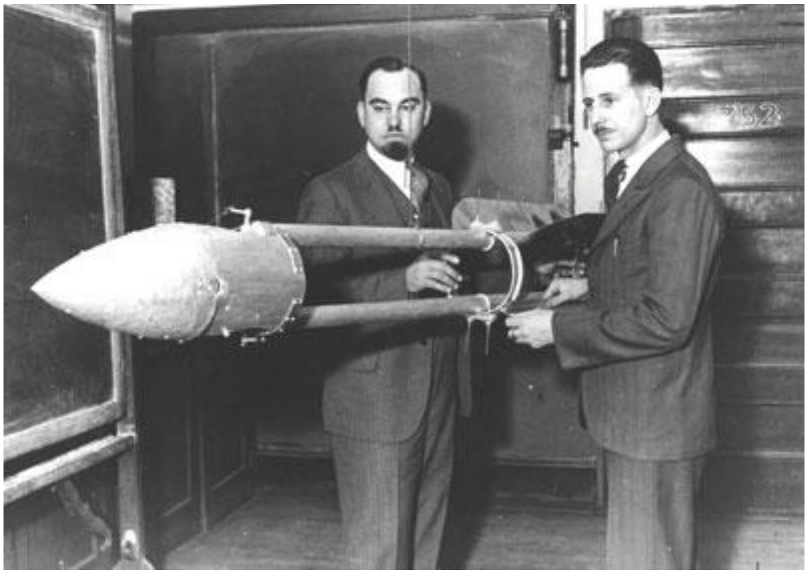


Figure II.2. American Rocket Society members G. Edward Pendray at the left, and Hugh Franklin Pierce, explain the ARS No. 1 rocket during a "lecture at New York University (Washington Square Campus) in spring of 1932" [Image Credit: Smithsonian Institution/NMMSH Archives].

II.4. UNITED KINGDOM ROCKETRY ASSOCIATION:

The United Kingdom Rocketry Association (UKRA) represents high power, mid power, model and amateur/experimental rocketry in the United Kingdom. UKRA is also the specialist body to the BMFA (British Model Flying Association) with responsibilities for High Power Rocketry, and is the United Kingdom body recognized by the Civil Aviation Authority.

During a meeting of rocketeers at the International Rocket Weekend in Largs in Scotland, in August 1996, it was discussed and agreed by all UK rocketry groups and individuals present, that the UK rocketry community needed a national association dedicated to rocketry. One that would provide insurance, safety guidelines and liase on rocketeers behalf with government bodies. UKRA was the result [5].

II.5. TRIPOLI ROCKETRY ASSOCIATION:

The Tripoli Rocketry Association (TRA) and National Association of Rocketry (NAR) are the two major organizing bodies for high power rocketry.

In December 1964 a group of high school students in Irwin, Pennsylvania formed a high school science club, with Francis (Glenn) Graham being one of the key founding members. The club was geared to all areas of science, but centered on astronomy and rocketry. Members of the club came from three cities in the area: East Pittsburgh, North Braddock, and Irwin. To help finance experiments and projects, one of the members donated some gold coins he had received from his father. These coins came from Tripoli, Lebanon during World War II. Since the members came from three towns, and Tripoli (roughly) meant "three cities," the name was accepted and they were known as the Tripoli Science Club.

After Tom Blazanin joined the group, the members of the Tripoli Rocket Club reorganized with the help of Tom and Francis. Members interested in astronomy separated to form the "American Lunar Society," which would be headed by Francis. The remaining members, about eighteen of them, renamed the group the "Tripoli Rocketry Society," along the lines set by the Advanced Rocketry Society, and geared themselves toward what was becoming the new area of high-powered "model rocketry".

Good things come slow and steady, and Tripoli grew slowly and steadily. A fellow Tripoli member, Darrel Gardner from Alaska, offered his services as an attorney to incorporate the Association as a non-profit business for the advancement and operation of non-professional rocketry. On July 18th, 1986 the Tripoli Rocketry Association, Inc. came into existence [6].

II.6. NATIONAL ASSOCIATION OF ROCKETRY:

The National Association of Rocketry (NAR) was founded in 1957, and is the oldest and largest spacemodeling organization in the world with over 6100 members and 125 affiliated clubs across the U.S. It was established in 1957 by Orville Carlisle and G. Harry Stine and is currently headed by President John Hochheimer. It supports all aspects of safe consumer sport rocket flying, from small model rockets with youth groups to very large high power rockets flown by adult hobbyists [7].

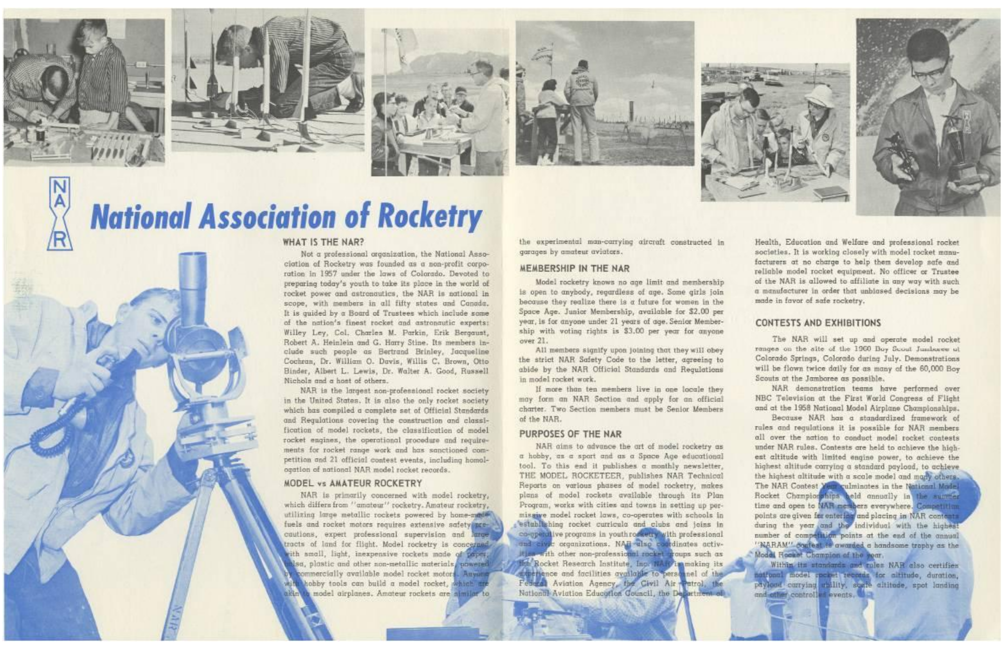


Figure II.3. NAR brochure from about 1960 [7].

The NAR is the author of a Model Rocket Safety Code for consumer model rocketry and a High Power Rocket Safety Code for high power sport rocketry that are recognized and accepted by manufacturers and public safety officials nationwide. The NAR plays a strong role in the establishment of national rocketry safety standards for public safety officials through its participation in the National Fire Protection Association (NFPA).

II.6.1. PURPOSES OF THE NAR:

NAR aims to advance the art of model rocketry as a hobby, as a sport and as Space Age educational tool. To this end it publishes a monthly newsletter “The Model Rocketeer”, publishers NAR Technical reports on various phases of model rocketry, makes plans of model rockets available through its plan program, works with cities and towns in setting up permissive model rocket laws, co-operates with schools in establishing rocket curricula and clubs and joins in co-operative programs in youth rocketry with professional and civic organizations.

II.7. MODEL VS AMATEUR ROCKETRY:

NAR is primarily concerned with model rocketry, which differs from “amteur” rocketry. Amateur rocketry, utilizing large metallic rockets powered by home-made fuels and rocket motors requires supervision and large tracts of land for flight. Model rocketry is concerned with small, light, inexpensive rockets made of paper balsa, plastic and other non-metallic materials, powered by commercially available model rocket motor. Anyone with hobby tools can build a model rocket, which are skin to model airplanes. Amateur rockets are similar to the experimental man-carrying aircraft constructed in garages by amateur aviators.

II.8. HIGH POWER ROCKETRY:

Also known as HPR, is similar to model rocketry with differences that include the propulsion power and weight increase of the model. They use motors in ranges over “G” power and/or weigh more than laws and regulations allow for unrestricted model rockets. Like model rockets, High Power rockets are typically made of safer, non-metallic materials such as cardboard, plastic, and wood, however, construction and recovery techniques usually differ somewhat, due to the requirements imposed by the use of HPR motors. This means that these models must be constructed in such a way that they have the ability to safely fly under these higher stress conditions.

REFERENCES BIBLIOGRAPHY

[1] Günther Seibert, The History of Sounding Rockets and Their Contribution to European Space Research. (November 2006).

[2] A. Bowdoin Van Riper, Rockets and Missiles: The Life Story of a Technology. (GREENWOOD PRESS, 88 Post Road West,Westport, CT 06881, 2004).

[3] Ray Spangenburg & Diane Kit Moser, Wernher von Braun Rocket Visionary, Revised edition ed. (Chelsea House, 132 West 31st Street New York NY 10001, 2008).

[4] Ann Garrison Darrin, Handbook of Space Engineering, Archaeology and Heritage. (CRC Press, United States of America, 2009).

[5] http://www.ukra.org.uk/aboutus.

[6] http://www.tripoli.org/History.

[7] http://www.nar.org.

CHAPTER III

AMATEUR ROCKETS,

DEFINITION, PRINCIPLES AND FUNDAMENTALS

III.1. INTRODUCTION:

The reason for creating this kind of association is to establish space science in people's minds from children to adults and making from space travel a goal to new generations by building their ones rockets. The popular response to this type of activity led to the establishment of competitions between clubs from all countries, whether they are amateur, model or height power rocketeers.

The grown in this domain makes it useful in many fields such as education (children, adults…), scientific researches (materials, space exploration, and weather states), Application in engineering, astronomy (sending satellites) and photography.

III.2. WHAT ARE AMATEUR ROCKETY?

Amateur rocketry, experimental rocketry or amateur experimental rocketry is a hobby in which amateurs experiment with fuels and make their own rocket motors, launching a wide variety of types and sizes of rockets with different material such as (Aluminum, Steel sheet, PVC or composite material). Amateur rocketeers have been responsible for significant research into hybrid rocket motors, and have built and flown a variety of solid, liquid, and hybrid propellant motors.

Figure III.1. Launch site for Amateur Rocketeers.

III.3. ROCKETS DEFINITION:

- A rocket is simply a machine that exploits Newton's third law of motion. It propels itself forward by "throwing" a steady stream of matter out behind it.
- A rocket is a self-contained, self propelled projectile that carries its own supplies of fuel and oxygen. The word applies equally to projectiles for military use (bombardment) and civilian use (signaling, lifesaving, fireworks). It has, since World War II, been applied only to self-propelled projectiles without onboard guidance systems [1].

- Rocket is cylindrical projectile that can be propelled to a great height or distance by the combustion of its contents.

III.4. ROCKET COMPONENTS:

A rocket design can be as simple as a cardboard tube filled with black powder like the early civilizations, but to make an efficient, accurate rocket or missile involves overcoming a number of difficult problems like the instability, aerodynamic forces or structure weight effect; rocket designers use components in order to eliminate those obstacles (e.g. to tackle the instability they use Fins and to penetrate the air they use nose (cone, warhead or ellipsoid)). The nose cone and fins of a rocket are designed to minimize drag (air resistance) and to provide stability and control (keep it pointing in the right direction without wobbling).

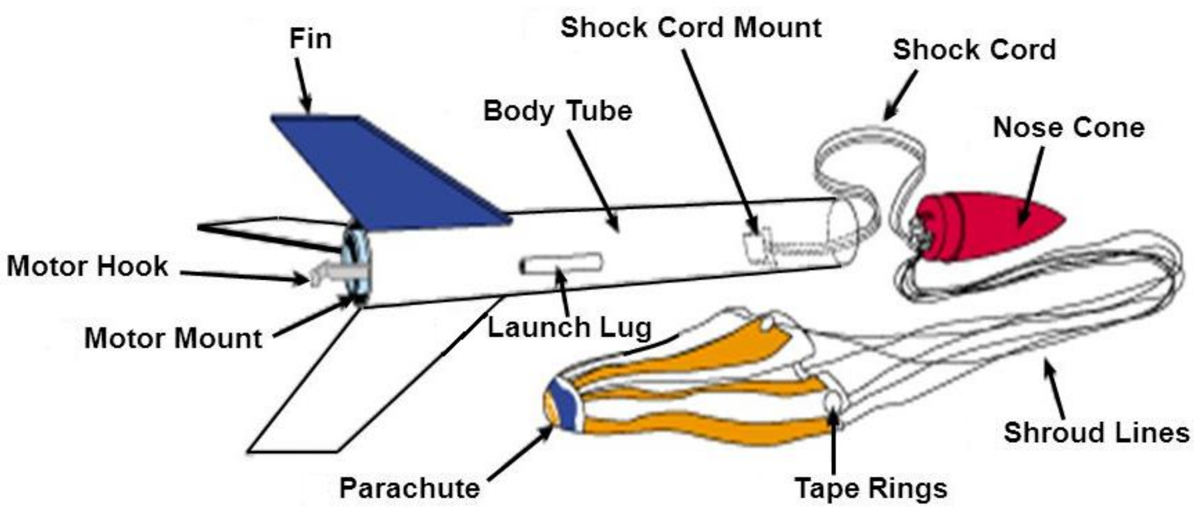


Figure III.2. Typical model rocket component.

Rockets consist of a place to put propellant such as a propellant tank in liquid fuel or case for solid fuel rockets, and a nozzle. They may also have one or more rocket motor, directional stabilization device(s) such as fins, vernier engines or engine gimbals for thrust vectoring and gyroscopes, and a strong structure typically mono-coquet to hold these components together. Rockets intended for high speed atmospheric use also have an aerodynamic fairing such as a nose cone, which usually holds the payload.

III.4.1. NOSE:

Nose is the front end of a rocket that comes into contact with the air first. It is shaped to reduce the aerodynamic drag.

Figure III.3. Nose cone made of carbon fiber.

The amount of air resistance that opposes a rocket's motion depends mainly on the shape of the nose cone, the diameter of the rocket and the speed of the rocket.

The first point that meets the air is the nose cone at the front end of the rocket. If the speed of a rocket is less than the speed of sound (1200 km/h in air at sea level), the best shape of a nose cone is a rounded curve. At supersonic speeds (faster than the speed of sound), the best shape is a narrower and sharper point.

III.4.1.1 DIAMETER AFFECTS ON ROCKET DRAG:

Rockets with a larger diameter have more drag because there is more air being pushed out of the way. Drag depends on the cross-sectional area of the object pushing through the air. Making a rocket as narrow as possible is the best way to reduce drag. The speed of a rocket through the air similarly increases drag. As speed doubles, drag increases four times as much.

III.4.2. FINS:

The stability of a rocket is its ability to keep flying through the air pointing in the right direction without wobbling or tumbling.

Fins are used on smaller rockets to provide this stability and control direction. It works in the same way as placing feathers at the tail of an arrow. The greater drag on the feathers keeps the tail of the arrow at the back so that the point of the arrow travels straight into the wind.

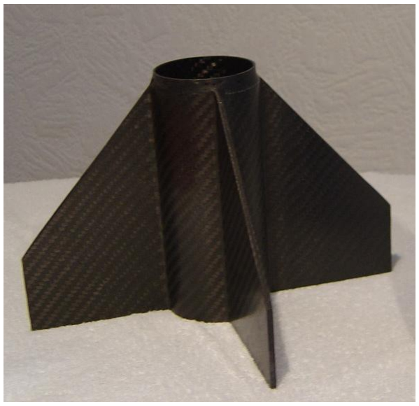


Figure III.4. Rocket fins made of carbon fiber.

III.4.3. BODY:

Body tubes used in order to connect members with each other, as longer is the tube it increase rocket moment of inertia, or its resistance to rotation. (e.g. If we have two rockets that each have the same mass, fins, body tube sizes, etc., but one is 20% longer, the longer rocket will have approximately a 40% higher moment of inertia in the directions normal to the long axis of the rocket. This leads to greater resistance to rotating due to wind loads than the shorter rocket.

Figure III.5. One of the members of Yale Undergraduate Aerospace Association holding multi-stage roket body tube.

III.4.4. MOTOR:

The rocket motor is the device in the model that creates the thrust force that propels the rocket into the air. Amateur rocketeers build their own motor (solid or liquid propellant), however, the model or height power rockets should bay certificated motors according to their Associations. In amateur rocket the thrust is limited as the other types.

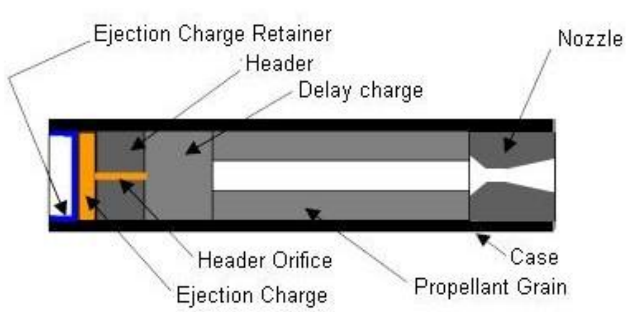


Figure III.6. Solid propellant rocket motor.

III.5. THE FLIGHT OF THE ROCKET:

The flight of a rocket breaks down into three phases:

- The propelled phase.
- The ballistic phase.
- The descent under parachute.

III.5.1. THE PROPELLED PHASE:

The period from the instant of firing to the end of combustion of the propellant. It comprises a part where the rocket is guided by the launching ramp and a part where the rocket is delivered to itself.

III.5.2. THE BALLISTIC PHASE:

The ballistic phase starts after the extinguishing of the thruster, solely subject to its weight and to the resistance of the air, exploits the speed acquired during the propulsion to reach its maximum altitude.

III.5.3. THE DESCENT UNDER PARACHUTE:

After the culmination, when the engine begins to fall, the ballistic phase continues until the parachute opens.

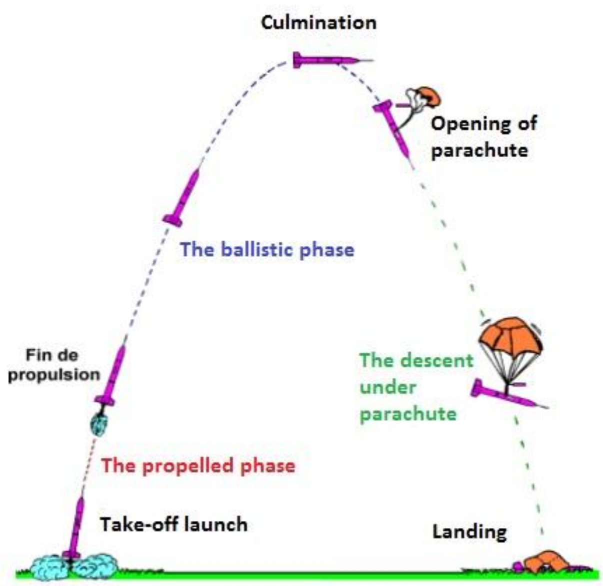
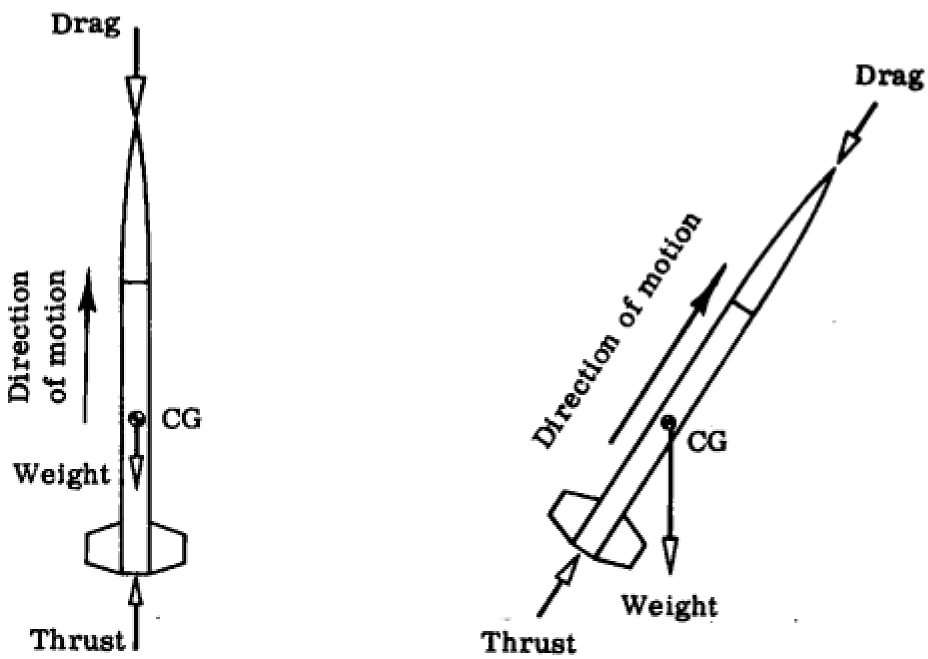


Figure III.7. Flight phases of a rocket [2].

Of course, one can encounter aborted ballistic phases when the parachute opens before the culmination, or complete ballistic flights without opening parachute (but it is less desirable!) [2].

III.6. FORCES EXERTED ON THE ROCKET:

The forces associated with translation are the rocket's weight, the engine's thrust and the resistance of the air to the rocket's motion; called the aerodynamic drag. These forces are shown schematically in (figureIII.8). Notice that thrust is along the length of the rocket of the rocket, and weight always points down toward the ground [3].



(a) (b)

Figure III.8. Translational forces in; **(a).** vertical flight, **(b).** Slanted flight [3].

The rocket is subjected, during its flight, to three forces:

- Its **weight P**, vertical force applied to the center of gravity (C.G. ) .
- The **thrust F** of the motor, axial force applied to the thrust plate.
- **Air resistance R**, applied to the Center of pressure (C.P ).

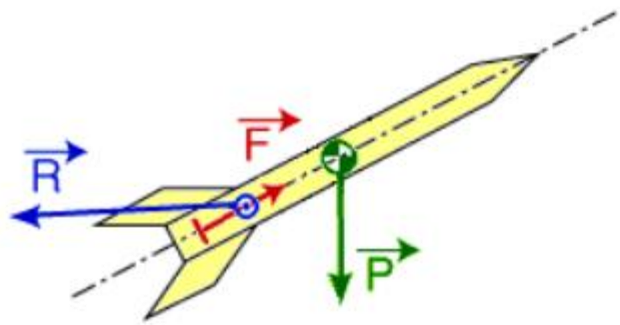


Figure III.9. Effective Forces on the Rocket [2].

III.7. FLIGHT DYNAMICS

The evolution of these three forces will govern the behavior of the rocket:

- the movement of the rocket around its center of mass will define its stability.
- the movement of the rocket center of mass in space will define its trajectory.

III.7.1. ROCKETS STABILITY NOTION:

To be stable, the rocket must maintain the same attitude during its flight by maintaining its longitudinal axis aligned as well as possible with the direction of its speed.

III.7.2. THE FORCES THAT ROTATE OUR ROCKETS:

The forces that are capable of rotating the rocket on itself and make it instable are those that create a Moment in relation to the Mass Center.

The Weight, Engine thrust and Drag are always aligned with the Center of Mass (C.M.), and do not contribute to the rotation of the rocket on itself.

Thus, the rocket rotates around its center of mass under the sole action of the normal component of the resistance of the air (RN), called Force of Portance.

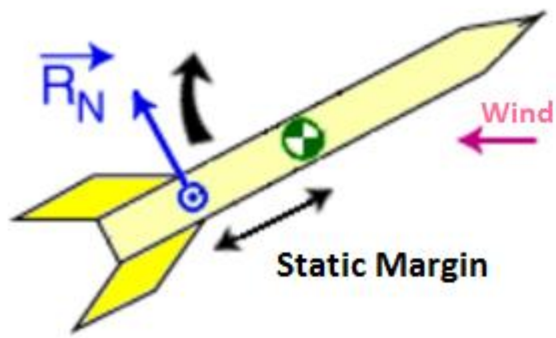


Figure III.10. Static Margin ilustration [2].

The distance between the C.P. and the C.M. is called Static Margin (SM); It represents the "lever arm" of this force of Portance. Expressed in Calibres (diameter of the body of the rocket).

The rotation of the rocket therefore depends only on the value of the moment of lift (Force of Portance × Static Margin) [2].

REFERENCES BIBLIOGRAPHY

[1] A. Bowdoin Van Riper, “Rockets and Missiles: The Life Story of a Technology”. (GREENWOOD PRESS, 88 Post Road West,Westport, CT 06881, 2004).

[2] Planète-Sciences, “Le Vol de la Fusée, Stabilité et Trajectographie”, v2.0, juillet 2008.

[3] Jim Barrowman, “Stability of a Model Rocket in Flight”, Techni Inf Report 30, CENTURI ENGINEERING COMPANY, 1970.

CHAPTER IV

REVIEW OF NUMERICAL METHODS

IV.1. INTRODUCTION:

In the pre-computer era, solving engineering problems often demanded vast amount of time to derive analytical or exact solutions. Although these solutions often provided excellent insight into the behavior of some systems, analytical solutions could be derived for only a limited class of problems. Since the late 1940s, the widespread availability of digital computers has led to a veritable explosion in the use and development of numerical methods. These techniques can greatly enhance the capabilities to confront and solve complex problems, and to handle large systems of equations, nonlinear behavior and complicated geometries that are often difficult or impossible to solve analytically [1].

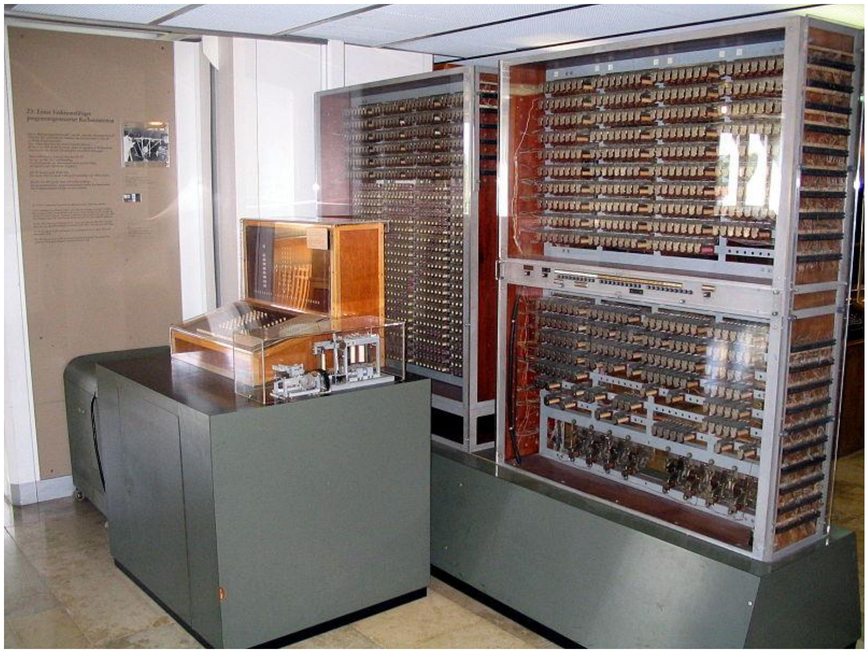


Figure IV.1. Replica of Zuse's Z3, the first fully automatic, digital (electromechanical) computer [Deutschen Museum in München].

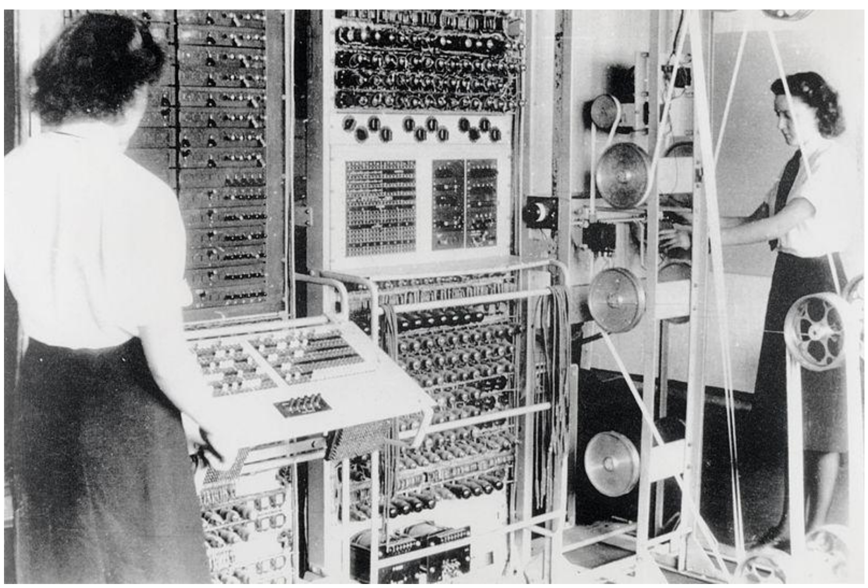


Figure IV.2. Colossus was the first electronic digital programmable computing device, and was used to break German ciphers during World War II [The National Archives (United Kingdom), Record: FO850/234].

IV.2. COMPUTATIONAL MECHANICS AND COMPUTER:

The development of computational mechanics clearly owes much to the presence of the electronic computer which came on the scene only in the middle of the last century. However, the words *computer* and *computations* are much older. In the very first paper on finite differences in the 20th century, Richardson, in 1910, uses the word *computers* to describe his assistants who were boys from the local high-school, employed to do the numerical calculations at each iteration.

It is interesting to note that Richardson paid a price of *N*/18 pence per co-ordinate point calculation in which *N* was the number of digits used and, as his note says, he did not pay if the computers committed errors [2].

The programmable digital computer (simply called the computer in the following) enabled numerical simulation to take its place as an equal alongside the interaction between theory and experimentation that had characterized the natural sciences since the time of Galileo and later the engineering sciences. Today, numerical simulation, theory and experimentation are the three supporting pillars of Computational Mechanics in particular. Theory formation therefore takes place not only on the theory–computer–experiment level, but on the experiment–computer–simulation and the theory–computer–simulation levels as well. This latter level, which Argyris described splendidly in 1965 in his prophetic essay *The Computer shapes the theory* [Argyris (1965)], forms the outer framework in which the formation of structural mechanics theories has been mainly taking place since the middle of the innovation phase of structural theory (1950 – 1975) [3].

The historico-logical development of the computer goes hand in hand with the formation of Finite Element Method and therefore forms the beginning and the end of the innovation phase of structural theory (1950 – 1975).

The finite element method (FEM), or the weighted residual method, today forms the basis of computational mechanics (CM) see [2]. As, in principle, every field problem, e.g. Electro-dynamic, Elasto-mechanical or Fluid-mechanical, can be solved numerically with FEM [3].

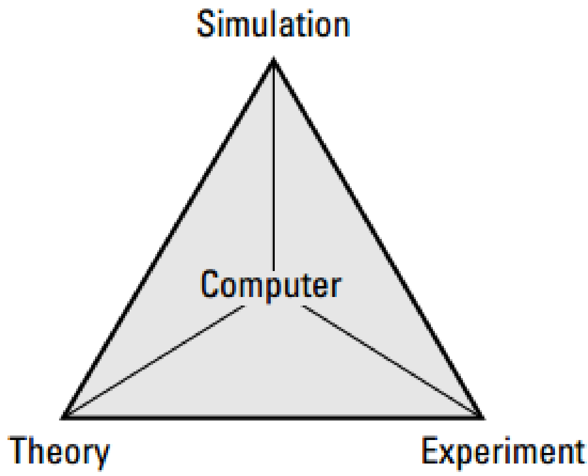


Figure IV.3. The tetrahedron of computer, theory, experiment and simulation [3].

IV.3. FINITE ELEMENT METHOD:

The finite element method solves a problem where analytical solution cannot possibly be determined. It provides an approximate solution to the exact solution. The environment studied is *discretized* in several elements connected together by *nodes*. The geometry of an element is characterized by a finite number of nodes on its perimeter. The solving of a problem by the finite element method consists in finding the displacements (e.g. translations and rotations) of these nodes. The displacement field at any point is determined by *interpolation* between the values determined at the nodes. The interpolation is based on the use of *shape functions* [4].

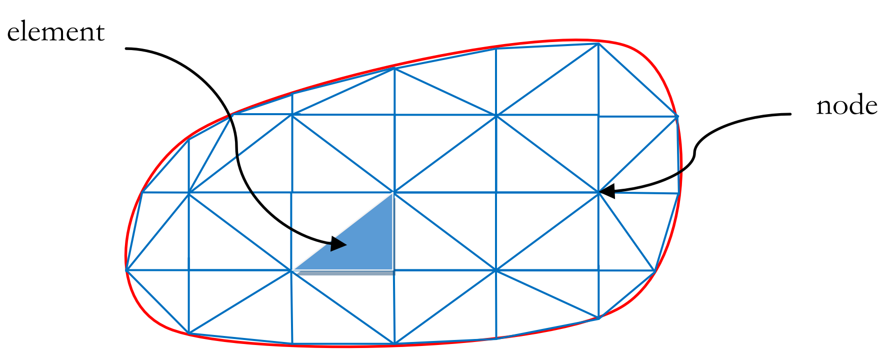


Figure IV.4. Discretized environment with triangle elements.

IV.3.1. HISTORICAL BACKGROUND [5]:

The modern development of the finite element method began in the 1940s in the field of structural engineering with the work by Hrennikoff [6] in 1941 and McHenry [7] in 1943, who used a lattice of line (one-dimensional) elements (bars and beams) for the solution of stresses in continuous solids. In a paper published in 1943 but not widely recognized for many years, Courant [8] proposed setting up the solution of stresses in a variational form. Then he introduced piecewise interpolation (or shape) functions over triangular subregions making up the whole region as a method to obtain approximate numerical solutions. In 1947 Levy [9] developed the flexibility or force method, and in 1953 his work [10] suggested that another method (the stiffness or displacement method) could be a promising alternative for use in analyzing statically redundant aircraft structures. However, his equations were cumbersome to solve by hand, and thus the method became popular only with the advent of the high-speed digital computer.

In 1954 Argyris and Kelsey [11, 12] developed matrix structural analysis methods using energy principles. This development illustrated the important role that energy principles would play in the finite element method. The first treatment of two-dimensional elements was by Turner et al. [13] in 1956.

They derived stiffness matrices for truss elements, beam elements, and two-dimensional triangular and rectangular elements in plane stress and outlined the procedure commonly known as the direct stiffness method for obtaining the total structure stiffness matrix. Along with the development of the high-speed digital computer in the early 1950s, the work of Turner et al. [13] prompted further development of finite element stiffness equations expressed in matrix notation. The phrase finite element was introduced by Clough [14] in 1960 when both triangular and rectangular elements were used for plane stress analysis.

A flat, rectangular-plate bending-element stiffness matrix was developed by Melosh [15] in 1961. This was followed by development of the curved-shell bending element stiffness matrix for axisymmetric shells and pressure vessels by Grafton and Strome [16] in 1963.

Extension of the finite element method to three-dimensional problems with the development of a tetrahedral stiffness matrix was done by Martin [17] in 1961, by Gallagher et al.

[18] in 1962, and by Melosh [19] in 1963. Additional three-dimensional elements were studied by Argyris [20] in 1964. The special case of axisymmetric solids was considered by Clough and Rashid [21] and Wilson [22] in 1965.

Most of the finite element work up to the early 1960s dealt with small strains and small displacements, elastic material behavior, and static loadings. However, large deflection and thermal analysis were considered by Turner et al. [23] in 1960 and material nonlinearities by Gallagher et al. [18] in 1962, whereas buckling problems were initially treated by Gallagher and Padlog [24] in 1963. Zienkiewicz et al. [25] extended the method to visco-elasticity problems in 1968.

In 1965 Archer [26] considered dynamic analysis in the development of the consistent-mass matrix, which is applicable to analysis of distributed-mass systems such as bars and beams in structural analysis.

With Melosh's [19] realization in 1963 that the finite element method could be set up in terms of a variational formulation, it began to be used to solve nonstructural applications. Field problems, such as determination of the torsion of a shaft, fluid flow, and heat conduction, were solved by Zienkiewicz and Cheung [27] in 1965, Martin [28] in 1968, and Wilson and Nickel [29] in 1966.

Further extension of the method was made possible by the adaptation of weighted residual methods, first by Szabo and Lee [30] in 1969 to derive the previously known elasticity equations used in structural analysis and then by Zienkiewicz and Parekh [31] in 1970 for transient field problems. It was then recognized that when direct formulations and variational formulations are difficult or not possible to use, the method of weighted residuals may at times be appropriate. For example, in 1977 Lyness et al. [32] applied the method of weighted residuals to the determination of magnetic field.

In 1976, Belytschko [33, 34] considered problems associated with large-displacement nonlinear dynamic behavior, and improved numerical techniques for solving the resulting systems of equations. For more on these topics, consult the texts by Belytschko, Liu, Moran [35], and Crisfield [36, 37].

A relatively new field of application of the finite element method is that of bioengineering [38, 39]. This field is still troubled by such difficulties as nonlinear materials, geometric nonlinearities, and other complexities still being discovered.

From the early 1950s to the present, enormous advances have been made in the application of the finite element method to solve complicated engineering problems. Engineers, applied mathematicians, and other scientists will undoubtedly continue to develop new applications. For an extensive bibliography on the finite element method, consult the work of Kardestuncer [40], Clough [41], or Noor [42].

IV.3.2. FINITE ELEMENT METHOD APPROACHES:

There are two general direct approaches traditionally associated with the finite element method as applied to structural mechanics problems. One approach, called the force, or flexibility, method, uses internal forces as the unknowns of the problem. To obtain the governing equations, first the equilibrium equations are used. Then necessary additional equations are found by introducing compatibility equations. The result is a set of algebraic equations for determining the redundant or unknown forces.

The second approach, called the displacement, or stiffness, method, assumes the displacements of the nodes as the unknowns of the problem. For instance, compatibility conditions requiring that elements connected at a common node, along a common edge, or on a common surface before loading remain connected at that node, edge, or surface after deformation takes place are initially satisfied. Then the governing equations are expressed in terms of nodal displacements using the equations of equilibrium and an applicable law relating forces to displacements [4].

IV.3.3. DEGREE OF CONTINUITY OF THE INTERPOLATION FUNCTION:

If the interpolation variable is continuous, it is said to have C^0-continuity.if first derivatives are continuous, the interpolation function is said to have C^1-continuity. Continuous second derivatives imply C^2-continuity, and so on.

Suppose the functions appearing under the integral of the element equations contain derivatives up to the $(r + 1)st$ order. To satisfy the compatibility requirement, the interpolation functions must be C^r-continuous at element boundaries. The completeness requirement is met if the interpolation functions are C^{r+1}-continuous within each element. These requirements for interpolation functions representing the behavior of a field variable are usually sufficient to ensure convergence to the solution as element size decreases.

IV.3.4. INTERPOLATION FUNCTIONS:

The form functions or interpolation functions are the functions N_i which connect the displacements from any interior point to an element to the n nodal displacements q_i which are the degrees of freedom in the case of the kinematic approach: An element as many functions of form as degrees of freedom in the element.

$$u(x) = \sum_{i=1}^{n} N_i(x) q_i \qquad (IV.1)$$

They ensure the passage from the continuous problem to the discrete problem, the knowledge of the displacement in a few discrete nodes allowing reconstructing the field of displacement in the element. The displacement at any point of the element is a linear combination of the nodal displacements whose coefficients are the values of the shape functions at this point [42].

IV.4. THE GENERALIZED FINITE ELEMENT METHOD (GFEM):

All problems of mechanics (and indeed of many other areas of physics) can be cast in the form of differential equations (generally partial) which require satisfaction in a particular domain, together with their ancillary conditions on the boundary. Thus required to solve [43]:

$$\begin{aligned} A(u) + q &= 0 \qquad in\ \Omega\ (domain) \\ B(u) + b &= 0 \qquad in\ \Gamma\ (boundary) \end{aligned} \qquad (IV.2)$$

Where:

- A, B Appropriate operators.
- q, b Known vector valued functions.
- u Unknown (vector) function.

In the generalized finite element method, the vector function u approximated by a trial expansion writing as:

$$u \approx \hat{u} = \sum_{i=1}^{n} N_i a_i \qquad (IV.3)$$

Where:

- $\boldsymbol{N_i}$ Basic functions.
- $\boldsymbol{a_i}$ Unknown parameters.

The approximating algebraic equations are obtained in the generalized finite element method by simply writing the weak (weighted residual) or variational forms:

$$\int_{\Omega} V_j^T (Au + q)\, d\Omega + \int_{\Gamma} \breve{V}_j^T (Bu + b)\, d\Gamma = 0 \qquad (IV.4)$$

$$j = 1,2, \dots, n$$

Where:

- $\boldsymbol{V_j}, \boldsymbol{\breve{V}_j}$ Suitable weighting (test) functions.

There are many possibilities of choices for the shape function N and the weighting functions $V, \breve{V}$.

The weighting process of approximation was, it is believed, first proposed and used by Galerkin [44]. In his works he uses a variety of weight functions though at times the only possibility of $V_j = N_j$ is attributed to him. This widely used choice (called by some the Galerkin F.E. Method or GFEM) [43], it is the optimal weighting in self adjoint problems [45].

Each of the subclasses of the GFEM possesses their relative merits, although standard FE is without a doubt the most popular. Some of the salient characteristics of the two procedures [43]:

IV.4.1. (STANDARD) FINIT ELEMENT:

1. Ease of dealing with non-homogeneous situations by separate element considerations.

2. Ease of dealing with irregular domains and local refinement;

3. Natural incorporation of boundary conditions.

4. Ease of incorporating nonlinear behavior at element level.

5. Need for assembly of final equations.

6. "Average" rather than "pointwise" equation approximation.

7. "Mass" matrices of consistent nature require lumping for iterative or dynamic computation.

IV.4.2. (STANDARD) FINIT DIFFERENCE:

1. Regular meshes unless mapping of whole domain used.

2. No need for equation assembly.

3. "Pointwise" satisfaction of equations has merits in nonlinearity introduction.

4. "Mass" matrices naturally lumped.

5. Equation systems frequently non-symmetric (unless energy type formulation used, which in fact returns to standard FE). Iterative solutions used largely for this reason.

IV.5. FINITE VOLUME METHOD (FVM):

The finite volume method appears to be a particular case of finite elements with a non Galerkin weighting. It is of course less accurate for self adjoint problems but has some computationally useful features for first order equations involving only surface integrals. For certain problems this is a substational economy and leads to computationally useful approximations [45].

The finite volume method evolved in the early seventies via finite difference. It was first applied to solve two-dimensional, time-dependent Euler equations in fluid dynamics by McDonald [46], and then extended to three-dimensional flows by Rizzi and Inouye [47]. Numerical heat transfer and fluid flow by Patankar. The finite volume procedure is in fact a special case of the weighted $eq.(IV.4)$ in which [45, 1]:

$$V_j = I \quad in \quad \Omega_c \quad (V_j = 0 \quad elsewhere)$$

Where:

- **I** Is the unity matrix.
- Ω_c Is a control volume which can be discretised in different ways.

IV.5.1. FINITE VOLUME METHOD IN FLUID FLOWS:

The advantage of FVM is that, for example in fluid flow, the fluxes calculated only on two dimensional surfaces of the control volume instead of on three-dimensional space. Also, this method allows the shape and location of the finite volumes, as well as the rules and accuracy for the evaluation of the fluxes through the control surface, to vary, thus giving considerable flexibility to the method [1].

Traditionally, computational structural mechanics was based on FEM, while FVM appeared to be most widely used and arguably most successful in CFD. Because of its success in fluid flow, FVM for structural analysis started attracting attention [48]. The concept of FVM was enhanced by Baliga [49] in the form of CVFEM. In the report detailed by Minkowycz et al. [50], examples of thick plate bending and welding, compressible flow on a plane nozzle, and flow in a model gas turbine combustor by FVM were described. Further, solution procedures by CVFEM on problems in multidimensional steady, incompressible fluid flow and heat transfer were illustrated.

The coupling of different versions of FEM and FVM has also provided extra dimension in solution methodology. For example, the common features of GFEM and CVFEM in CFD, such as domain discretization, interpolation, and the same matrix form for the resulting systems of discretised equations, have allowed successful coupling of these two methods [51]. The hybrid methods have been proved to be very effective and successful, and it is obvious that they have great potential for further investigation.

Comparisons between FEM and FVM have been regularly featured in many engineering applications, including CFD and heat transfer, by numerical tests. It has been found that in some occasions, FVM can be readily confined to element assemblies and can be more efficient to approximate coefficients on interfaces, and, higher order elements can be implemented without much complication [1].

REFERENCES BIBLIOGRAPHY

[1] T.Y. Chao and W.K. Chow, “A review on the applications of finite element method to heat transfer and fluid flow”, Int. J. Arch. Sci, Volume 3, Number 1, p.1-19, 2002.

[1] O. C. Zienkiewicz. “The birth of the finite element method and of computational mechanics.”, Int. J. Numer. Meth. Engng 2004; **60**:3–10.

[2] Karl-Eugen Kurrer, “The History of the Theory of Structures From Arch Analysis to Computational Mechanics”, 2008 Ernst & Sohn, technische Wissenschaften GmbH & Co. KG, Berlin.

[3] ___________________AIDE-MÉMOIRE, *MÉCANIQUE DES STRUCTURES - Résistance des matériaux*. (DUNOD, Paris, 2008).

[4] Daryl L. Logan, A First Course in the Finite Element Method, Fifth Edition ed. (Cengage Learning, 200 First Stamford Place, Suite 400 Stamford, CT 06902 USA, 2012).

[5] Hrennikoff, A., ‘‘Solution of Problems in Elasticity by the Frame Work Method,’’ Journal of Applied Mechanics, Vol. 8, No. 4, pp. 169–175, Dec. 1941.

[6] McHenry, D., ‘‘A Lattice Analogy for the Solution of Plane Stress Problems,’’ Journal of Institution of Civil Engineers, Vol. 21, pp. 59–82, Dec. 1943.

[7] Courant, R., ‘‘Variational Methods for the Solution of Problems of Equilibrium and Vibrations,’’ Bulletin of the American Mathematical Society, Vol. 49, pp. 1–23, 1943.

[8] Levy, S., ‘‘Computation of Influence Coefficients for Aircraft Structures with Discontinuities and Sweepback,’’ Journal of Aeronautical Sciences, Vol. 14, No. 10, pp. 547–560, Oct. 1947.

[9] Levy, S., ‘‘Structural Analysis and Influence Coefficients for Delta Wings,’’ Journal of Aeronautical Sciences, Vol. 20, No. 7, pp. 449–454, July 1953.

[10] Argyris, J. H., ‘‘Energy Theorems and Structural Analysis,’’ Aircraft Engineering, Oct., Nov., Dec. 1954 and Feb., Mar., Apr., May 1955.

[11] Argyris, J. H., and Kelsey, S., Energy Theorems and Structural Analysis, Butterworths, London, 1960 (collection of papers published in Aircraft Engineering in 1954 and 1955).

[12] Turner, M. J., Clough, R. W., Martin, H. C., and Topp, L. J., ‘‘Stiffness and Deflection Analysis of Complex Structures,’’ Journal of Aeronautical Sciences, Vol. 23, No. 9, pp. 805–824, Sept. 1956.

[13] Clough, R. W., ‘‘The Finite Element Method in Plane Stress Analysis,’’ Proceedings, American Society of Civil Engineers, 2nd Conference on Electronic Computation, Pittsburgh, PA, pp. 345–378, Sept. 1960.

[14] Melosh, R. J., ‘‘A Stiffness Matrix for the Analysis of Thin Plates in Bending,’’ Journal of the Aerospace Sciences, Vol. 28, No. 1, pp. 34–42, Jan. 1961.

[15] Grafton, P. E., and Strome, D. R., ‘‘Analysis of Axisymmetric Shells by the Direct Stiffness Method,’’ Journal of the American Institute of Aeronautics and Astronautics, Vol. 1, No. 10, pp. 2342–2347, 1963.

[16] Martin, H. C., ‘‘Plane Elasticity Problems and the Direct Stiffness Method,’’ The Trend in Engineering, Vol. 13, pp. 5–19, Jan. 1961.

[17] Gallagher, R. H., Padlog, J., and Bijlaard, P. P., ‘‘Stress Analysis of Heated Complex Shapes,’’ Journal of the American Rocket Society, Vol. 32, pp. 700–707, May 1962.

[18] Melosh, R. J., ‘‘Structural Analysis of Solids,’’ Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, pp. 205–223, Aug. 1963.

[19] Argyris, J. H., ‘‘Recent Advances in Matrix Methods of Structural Analysis,’’ Progress in Aeronautical Science, Vol. 4, Pergamon Press, New York, 1964.

[20] Clough, R. W., and Rashid, Y., ‘‘Finite Element Analysis of Axisymmetric Solids,’’ Journal of the Engineering Mechanics Division, Proceedings of the American Society of Civil Engineers, Vol. 91, pp. 71–85, Feb. 1965.

[21] Wilson, E. L., ‘‘Structural Analysis of Axisymmetric Solids,’’ Journal of the American Institute of Aeronautics and Astronautics, Vol. 3, No. 12, pp. 2269–2274, Dec. 1965.

[22] Turner, M. J., Dill, E. H., Martin, H. C., and Melosh, R. J., ‘‘Large Deflections of Structures Subjected to Heating and External Loads,’’ Journal of Aeronautical Sciences, Vol. 27, No. 2, pp. 97–107, Feb. 1960.

[23] Gallagher, R. H., and Padlog, J., ‘‘Discrete Element Approach to Structural Stability Analysis,’’ Journal of the American Institute of Aeronautics and Astronautics, Vol. 1, No. 6, pp. 1437–1439, 1963.

[24] Zienkiewicz, O. C., Watson, M., and King, I. P., ‘‘A Numerical Method of Visco-Elastic Stress Analysis,’’ International Journal of Mechanical Sciences, Vol. 10, pp. 807–827, 1968.

[25] Archer, J. S., ‘‘Consistent Matrix Formulations for Structural Analysis Using FiniteElement

Techniques,'' Journal of the American Institute of Aeronautics and Astronautics, Vol. 3, No. 10, pp. 1910–1918, 1965.

[26] Zienkiewicz, O. C., and Cheung, Y. K., ''Finite Elements in the Solution of Field Problems,'' The Engineer, pp. 507–510, Sept. 24, 1965.

[27] Martin, H. C., ''Finite Element Analysis of Fluid Flows,'' Proceedings of the Second Conference on Matrix Methods in Structural Mechanics, Wright-Patterson Air Force Base, Ohio, pp. 517–535, Oct. 1968. (AFFDL-TR-68-150, Dec. 1969; AD-703-685, N.T.I.S.)

[28] Wilson, E. L., and Nickel, R. E., ''Application of the Finite Element Method to Heat Conduction Analysis,'' Nuclear Engineering and Design, Vol. 4, pp. 276–286, 1966.

[29] Szabo, B. A., and Lee, G. C., ''Derivation of Stiffness Matrices for Problems in Plane Elasticity by Galerkin's Method,'' International Journal of Numerical Methods in Engineering, Vol. 1, pp. 301–310, 1969.

[30] Zienkiewicz, O. C., and Parekh, C. J., ''Transient Field Problems: Two-Dimensional and Three-Dimensional Analysis by Isoparametric Finite Elements,'' International Journal of Numerical Methods in Engineering, Vol. 2, No. 1, pp. 61–71, 1970.

[31] Lyness, J. F., Owen, D. R. J., and Zienkiewicz, O. C., ''Three-Dimensional Magnetic Field Determination Using a Scalar Potential. A Finite Element Solution,'' Transactions on Magnetics, Institute of Electrical and Electronics Engineers, pp. 1649–1656, 1977.

[32] Belytschko, T., ''A Survey of Numerical Methods and Computer Programs for Dynamic Structural Analysis,'' Nuclear Engineering and Design, Vol. 37, No. 1, pp. 23–34, 1976.

[33] Belytschko, T., ''Efficient Large-Scale Nonlinear Transient Analysis by Finite Elements,'' International Journal of Numerical Methods in Engineering, Vol. 10, No. 3, pp. 579–596, 1976.

[34] Belytschko, T., Liu W. K., and Moran, B., Nonlinear Finite Elements For Continua and Structures, John Wiley, 1996.

[35] Crisfield, M.A., Non-linear Finite Element Analysis of Solids and Structures, Vol. 1: Essentials, John Wiley & Sons, Chichester, UK, 1991.

[36] Crisfield, M.A., Non-linear Finite Element Analysis of Solids and Structures, Vol. 2: Advanced Topics, John Wiley & Sons, Chichester, UK, 1997.

[37] Huiskies, R., and Chao, E. Y. S., ''A Survey of Finite Element Analysis in Orthopedic Biomechanics: The First Decade,'' Journal of Biomechanics, Vol. 16, No. 6, pp. 385–409, 1983.

[38] Journal of Biomechanical Engineering, Transactions of the American Society of Mechanical Engineers, (published quarterly) (1st issue published 1977).

[39] Kardestuncer, H., ed., Finite Element Handbook, McGraw-Hill, New York, 1987.

[40] Clough, R. W., ‘‘The Finite Element Method After Twenty-Five Years: A Personal View,” Computers and Structures, Vol. 12, No. 4, pp. 361–370, 1980.

[41] Noor, A. K., ‘‘Bibliography of Books and Monographs on Finite Element Technology,’’ Applied Mechanics Reviews, Vol. 44, No. 6, pp. 307–317, June 1991.

[42] Jean-Charles Craveur, “Modelisation des Elements Finis’’, 3e édition, DUNOD , 30 septembre 2008.

[43] O. C. Zienkiewicz, “The Generalized Finite Element Method—State of the Art and Future Directions”, *J. Appl. Mech* 50 4b, pp. 1210-1217 Dec 01, 1983.

[44] Galerkin, B. G., "Series Solution of Some Problems of Elastic Equilibrium of Rods and Plates, (Russian) Vestn. Inzh. Tech., Vol. 19, 1965, pp.897-908

[45] O C Zienkiewicz, E Oñate, “Finite volumes vs finite elements: is there really a choice?”, publication N°8, November 1990.

[46] P.W. McDonald, “The computation of transonic flow through two-dimensional gas turbine cascades”, ASME Paper 71-GT-89 (1971).

[47] A.W. Rizzi and M. Inouye, “Time split finite volume method for three-dimensional blunt-body flows”, J.A.I.A.A., Vol. 11, pp. 1478-85 (1973).

[48] I. Demirdžić and D. Martinović, “Finite volume method for thermo-elasto-plastic stress analysis”, Comput. Methods Appl. Mech. Engrg., Vol. 109, pp. 331-349 (1993).

[49] B.R. Baliga, “A control-volume based finite element method for convective heat and mass transfer”, Ph.D. Thesis, University of Minnesota, Minneapolis, USA (1978).

[50] W.J. Minkowycz and E.M. Sparrow (editors), Advances in numerical heat transfer, Vol. 1, Taylor & Francis (1997).

[51] C.R. Swaminathan and V.R. Voller, “Streamline upwind scheme for control-volume finite elements, Part I – Formulations”, Numer. Heat Transfer, Part B, Vol. 22, pp. 95-107 (1992).

CHAPTER V

AEROELASTICITY, FLUTTER PROBLEM AND ASSOCIATED PHENOMENA

V.1. INTRODUCTION:

Aeroelasticity is the area of applied mechanics that studies the interactions between the *Inertial*, *Elastic*, and *Aerodynamic* forces that occur when an elastic body is exposed to a fluid flow. Although aeroelasticity was originally studied in connection with aeronautical applications, the study of aeroelasticity may be broadly classified into two fields: static aeroelasticity, which deals with the static or steady response of an elastic body to a fluid flow; and dynamic aeroelasticity, which deals with the body's dynamic (typically vibrational) response. Aeroelastic phenomena have also played a very important role in other fields of applied science. For instance, civil engineering has a history of undertaking projects with ever bolder designs and ever higher flexibility (buildings, bridges, towers, power lines, etc.). Similarly, when designing turbo-machines. Aeroelasticity draws on the study of fluid mechanics, solid mechanics, structural dynamics and dynamical systems.

V.2. HISTORICAL BACKGROUND:

After construction completed on July 1, 1940, the Tacoma Narrows Bridge was the third largest suspension bridge in the entire world, behind the Golden Gate Bridge and the George Washington Bridge. Its infamy lies not with historic length but in its nickname, Galloping Gertie. The nickname arose from the bridge's easily excitable bending mode. Drivers would watch the oncoming cars rise and fall with the violent motion of the bridge. During a particularly strong forty-mile per hour gust the newly excited torsion mode of the bridge caused a violent twisting along the centerline of the bridge. Figures below shows the bending and torsional modes of the bridge. Despite being made from carbon steel and concrete on, November 7, 1940 the growing torsional oscillations overwhelmed the natural damping of the bridge and Gertie plunged 300 ft into the ocean below. After months of research NACA engineers diagnosed the cause of the vibrations as aeroelastic flutter [1].

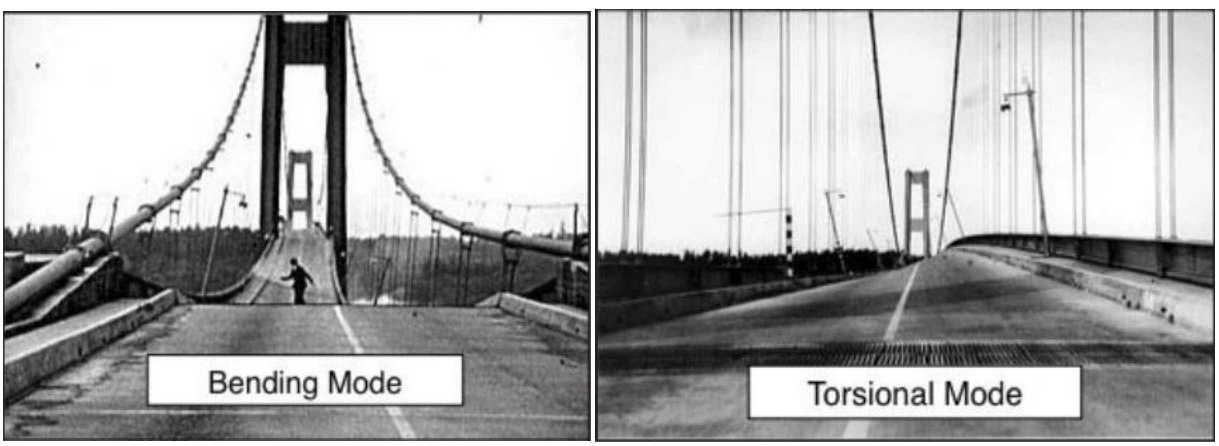


Figure V.1. Tacoma Narrows Bridge fluttering (bending and torsional modes) [1].

Aeroelasticity may therefore be defined as the study of the elastic behavior of structures whose motion within the flow generates induced stress. This topic combines three disciplines:

- Aerodynamics: to predict the forces experienced by the structure.
- Elasticity: to determine alterations to the structure (displacements and deformations).
- Structural dynamics: to determine the inertia matrices and modal properties (modes, natural frequencies) and in some cases the inertial forces (for motion involving non-uniform acceleration) [2].

V.3. AEROELASTIC PHENOMENA TYPES:

Classically, aeroelastic phenomena are classified using Collar's triangle of forces (Figure V.2). The three types of force arising from motion (elastic, aerodynamic and inertial) are represented by the three vertices of the triangle. Each aeroelastic phenomenon can be situated on this diagram according to how it relates to each vertex. For instance, phenomena relating to dynamic aeroelasticity are located at the center of the triangle, whereas effects relating to static aeroelasticity are located on the left-hand side. The right-hand side groups together phenomena that only involve aerodynamic and inertial forces, such as the dynamics of rigid aircraft studied in flight mechanics. The base of the triangle corresponds to vibrational problems from structural dynamics [2].

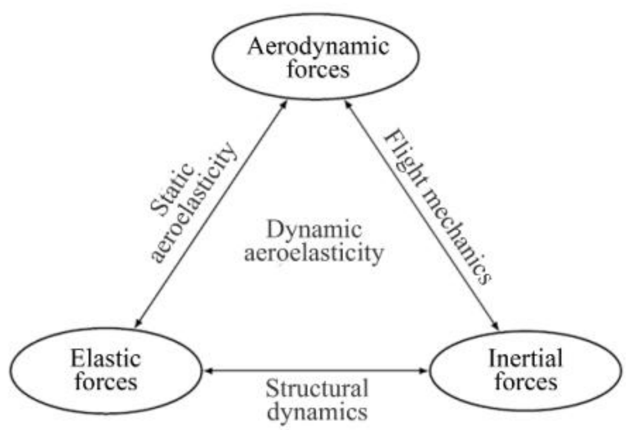


Figure V.2. Collar's aeroelastic Venn diagram [2].

V.3.1. AEROELASTICITY CASES:

Two major Aeroelasticity phenomena have been defined in this field:

V.3.1.1 STATIC AEROELASTICITY:

The structure experiences strain as a result of the aerodynamic forces that it applies to itself. Two significant static aeroelastic effects may occur:

a. DIVERGENCE:

It is a phenomenon in which the elastic twist of the wing suddenly becomes theoretically infinite, typically causing the wing to fail spectacularly.

b. CONTROL REVERSAL:

This phenomenon occurring only in wings with ailerons or other control surfaces, in which these control surfaces reverse their usual functionality

V.3.1.2 DYNAMIC AEROELASTICITY:

The fluid supplies energy to the structure, which may either amplify oscillatory motion or cause the system to break up if the maximal tolerances are exceeded. This phenomenon divided into three sub-divisions:

a. BUFFETING:

It is high-frequency instability, caused by airflow separation or shock wave oscillations from one object striking another. It is caused by a sudden impulse of load increasing. It is a random forced vibration. Generally it affects the tail unit of the aircraft structure due to air flow downstream of the wing.

b. FLUTTER:

Flutter is a dynamic aeroelastic phenomenon encountered in flexible structures subjected to aerodynamic forces. This includes aircrafts, buildings, telegraph wires, and bridges. Flutter occurrence is a combined outcome of interactions between aerodynamics, stiffness, and inertial forces on a structure. As the speed increases when the aircraft is in flight, there may be a point where the structural damping is insufficient to damp out the motions which are increasing due to aerodynamic forces being added to the structure. This introduces unwanted vibrations which can lead to structural failure and thus flutter consideration during design process is a vital part.

V.4. FLUTTER ILLUSTRATION:

Flutter phenomenon may start with a rotation of the blade section (at t=0 s in Figure V.3). The increased angle amplifies the lift such that the section undertakes an upward vertical motion. Simultaneously, the torsional rigidity of the structure recoils the profile to its zero-pitch condition (at t=T/4 in Figure V.3). The flexion rigidity of the structure tends to retain the neutral position of the profile but the latter then tends to a negative angle of attack (at t = T/2 in Figure V.3). Once again, the increased aerodynamic force imposes a downward vertical motion on the profile and the torsional rigidity of the latter tends to a zero angle of attack. The cycle ends when the profile retains a neutral position with a positive angle of attack. With time, the vertical movement tends to damp out whereas the rotational movement diverges. If freedom is given to the motion to repeat, the rotational forces will lead to blade failure [3].

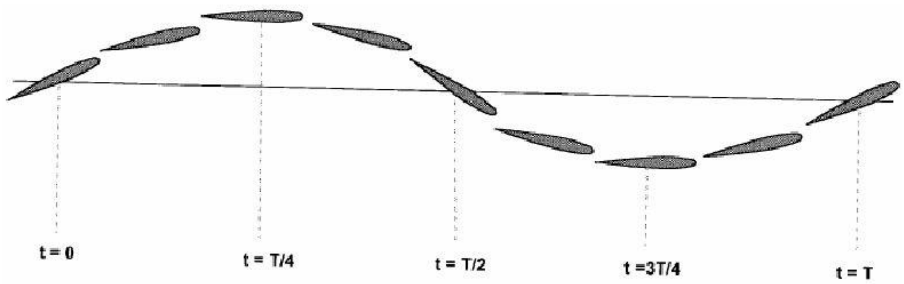


Figure V.3. Illustration of flutter movement [3].

V.5. INVESTIGATING IN FLUTTER:

Scientists and engineers studied flutter, performed experiments and developed theories for the cause and mathematical tools to analyze the behavior. In the 1920s and 1930s, an unsteady aerodynamic theory was developed. Closed-form solutions to simple, academic problems were studied in the 1940s and 1950s. In the next thirty years, strip theory aerodynamics, beam structural models, unsteady lifting surface methods (e.g. double-lattice) and finite element models expanded analysis capabilities. The advent of digital computers has further supported the development of other powerful methods. Disciplines involved in analyzing flutter include aerodynamics, structural finite element modeling and structural dynamics.

V.6. NEW MATERIALS TO REDUCE FLUTTER:

The introduction of composite material in the design of aircrafts in the early 70s led to a new airframe design concepts as well as the re-evaluation of older concepts. Composites offer better specific stiffness and strength; fiber-reinforced materials have another property, anisotropic. Exploiting the directional properties of composites materials and thereby creating aerodynamic loads through controlled deformation could control aeroelastic problems such as flutter and divergence without excessive weight.

V.7. STAT OF THE ART:

• J O H N M. H E D G E P E T H (1957), [4]:

Treated theoretically the problem of panel flutter of rectangular simply supported plates subjected to supersonic flow over one surface, Two panel flutter analyses are performed using the static approximation in conjunction with thin-plate theory -one employs aerodynamic strip theory, the other aerodynamic surface theory.

• V.V. BOLOTIN (1963), [5]:

Treated the stability of elastic systems under the action of non-canservative forces. And nonlinear flutter of curved plates in his book on non-conservative problems.

• E.H. Dowell (1966), [6]:

Predicted the flutter instability occurrence. Were problem of two-and three-dimensional plates undergoing limit cycle oscillations (subsequent to the occurrence of a linear, aeroelastic instability) has been investigated. Von Karman's large deflection plate theory and quasi-steady aerodynamic theory have been employed. The effects of (constant) inplane load and static pressure differential have been included. Galerkin's method has been used to reduce the mathematical problem to a system of nonlinear ordinary differential equations in time which are solved by numerical integration.

• MERVYN D. OLSON and Y. C. FUNG (1966), [7]:

Conducted experiments and have concluded that the oscillation amplitude of flutter is of the same order of magnitude as the shell thickness; therefore, a nonlinear shell theory should be used in order to predict accurately the flutter amplitude.

• E.H. DOWELL (1969; 1970b), [8]:

Investigated the nonlinear flutter of curved plates of shallow curvature by using a modified Donnell’s nonlinear shallow-shell theory. Both simply supported and clamped plates were considered. The linear piston theory was used to describe the fluid-structure interaction. Six modes, with different numbers of stream wise waves, were included in the mode expansion.

• **M.N. BISMARCK-NASR (1992), [9]:**

Did an extensive review of the finite element method applied to the problem of supersonic aeroelastic stability of plates and shells this review is limited to linear models.

• **Marco Amabili and Francesco Pellicano (2001), [10]:**

Studied the aeroelastic stability of simply supported, circular cylindrical shells without imperfections in supersonic flow. Nonlinearities due to large-amplitude shell motion were considered by using Donnell's non-linear shallow-shell theory, and the effect of viscous structural damping was taken into account. The system was discretized using the Galerkin method.

REFERENCES BIBLIOGRAPHY

[1] Zachary Howard, “How to calculate fin flutter speed”, Apogee Journal, ISSUE 291 6 pages, JULY 19, 2011.

[2] Abdelkhalak El Hami, Bouchaib Radi, “Fluid-Structure Interactions and Uncertainties: Ansys and Fluent Tools”, Volume 6, John Wiley & Sons, March 2017.

[3] Drishtysingh Ramdenee et al., “Aeroelasticity of wind turbines blades using numerical simulation”, Chapter 4, “Advances in Wind Power”, INTECH, 2012.

[4] John M. Hedgepeth. "Flutter of Rectangular Simply Supported Panels at High Supersonic Speeds", Journal of the Aeronautical Sciences, Vol. 24, No. 8 (1957), pp. 563-573.

[5] V. V Bolotin, Nonconservative problems of the theory of elastic stability, 324 pages, Macmillan, 1963.

[6] E.H. DOWELL. "Nonlinear oscillations of a fluttering plate." AIAA Journal, Vol. 4, No. 7 (1966), pp. 1267-1275.

[7] Y. C. FUNG and M.D. OLSON. "Supersonic flutter of circular cylindrical shells subjected to internal pressure and axial compression." AIAA Journal, Vol. 4, No. 5 (1966), pp. 858-864.

[8] E. H. DOWELL. "Panel flutter - A review of the aeroelastic stability of plates and shells", AIAA Journal, Vol. 8, No. 3 (1970), pp. 385-399.

[9] Maher N. Bismarck-Nasr, “Finite element analysis of aeroelasticity of plates and shells”, Appl. Mech. Rev, Volume 45, Issue 12, Dec 01, 1992, pp. 461-482.

[10] Marco Amabili and Francesco Pellicano. "Nonlinear Supersonic Flutter of Circular Cylindrical Shells", AIAA Journal, Vol. 39, No. 4 (2001), pp. 564-573.

CHAPTER VI

THE FLUTTER PHENOMENA:

THEORETICAL BACKGROUND AND TOOLS

VI.1. INTRODUCTION:

The problem of flutter phenomena was recognized to be an important aspect of the design of high speed vehicles when Jordan [1] observed that a number of the early V-2 rocket failures were due to panel flutter, also another "catastrophe" is the "Tacoma Narrows" bridge which been collapsed in 1940. Since then, extensive theoretical, analytical and experimental research on the subject has been performed. One of the basic textbooks is the EARL H. DOWELL'S [2] discusses the theoretical aspects and the developments attained in this field.

VI.2. VON KARMAN'S LARGE DEFLECTION PLATE THEORY:

The **von Kármán** equations it is a set of nonlinear partial differential equations describing the large deflections of thin flat plates. The equation is notoriously difficult to solve, and take the following form [3]:

$$\begin{cases} \dfrac{Eh^3}{12(1-\nu^2)}\Delta^2\omega - h\dfrac{\partial}{\partial x_l}\left(\sigma_{kl}\dfrac{\partial \omega}{\partial x_k}\right) = F \\ \dfrac{\partial \sigma_{kl}}{\partial x_l} = 0 \end{cases} \qquad (VI.1)$$

Where:

- $\boldsymbol{E}$ Young's modulus of the plate material.
- $\boldsymbol{h}$ Thickness of the plate.
- $\boldsymbol{\nu}$ Poisson's ratio.
- $\boldsymbol{\omega}$ The out-of –plane deflection of the plate.
- $\boldsymbol{k}, \boldsymbol{l}$ Indices that take values of 1 or 2.
- $\boldsymbol{F}$ External normal force per unit area of the plate.
- $\boldsymbol{\sigma_{kl}}$ Cauchy stress tensor.

The 2-dimensional biharmonic operator is defined as:

$$\Delta^2\omega \coloneqq \frac{\partial^2}{\partial x_k \partial x_k}\left[\frac{\partial^2 \omega}{\partial x_l \partial x_l}\right] = \frac{\partial^4 \omega}{\partial x_1^4} + \frac{\partial^4 \omega}{\partial x_2^4} + 2\frac{\partial^4 \omega}{\partial x_1^2 \partial x_2^2} \qquad (VI.2)$$

VI.3. PISTON THEORY:

Piston theory has been used to refer broadly to a number of aerodynamic models which describe the pressure on a point of a body through analogy to the motion of a piston in a 1-dimensional cylinder. As a result, a number of flavors of piston theory exist, with variations in the basis of the pressure equation and in the reference frame used; however, all the variations assume supersonic flow at the point under consideration, with various limits of validity depending on the basis of the theory. In all cases, piston theory provides a quasi-steady, point-function relationship between the surface downwash and aerodynamic pressure at a point on a body. This renders piston theory a computationally inexpensive aerodynamic model [4].

VI.3.1. PRINCIPLE OF THE PISTON THEORY:

It is an approximate theory which works for thin wings at high speeds and small angles of attack. If the characteristic thickness of the body in question is thin, then at high Mach numbers the shock generated at the leading edge is a highly inclined weak shock. This makes the flow region between the surface and the inclined shock a thin boundary layer attached to the surface. If the surface pressure at the boundary layer is p and the vertical velocity on the surface is U, then the flow can be modeled as the wedge flow as shown in (Figure VI.1). The piston theory is based on the analogy with a piston moving a velocity U in a tube to create compression wave. The ratio of the compression pressure created in the tube to the pressure before passing of the piston becomes [3]:

$$\frac{p}{p_\infty} = \left[1 + \frac{\gamma - 1}{2}\frac{V_T}{a}\right]^{\frac{2\gamma}{\gamma-1}} \qquad (VI.3)$$

Where:

- a The speed of sound for the gas at rest.

The $Eq.(VI.3)$ can be linearized by using a series expansion to retain the first term:

$$\frac{p}{p_\infty} \cong 1 + \gamma\frac{V_T}{a} \qquad (VI.4)$$

Where:

- V_T the vertical velocity:

$$V_T = V_0 + V_1$$
$$V_T = \frac{\partial W}{\partial t} + V_{cyl}\frac{\partial W}{\partial X} \qquad (VI.5)$$

And $V_{cyl} = U$, the free flow velocity, so V_T becomes:

$$V_T = \frac{\partial W}{\partial t} + U\frac{\partial W}{\partial X} \qquad (VI.6)$$

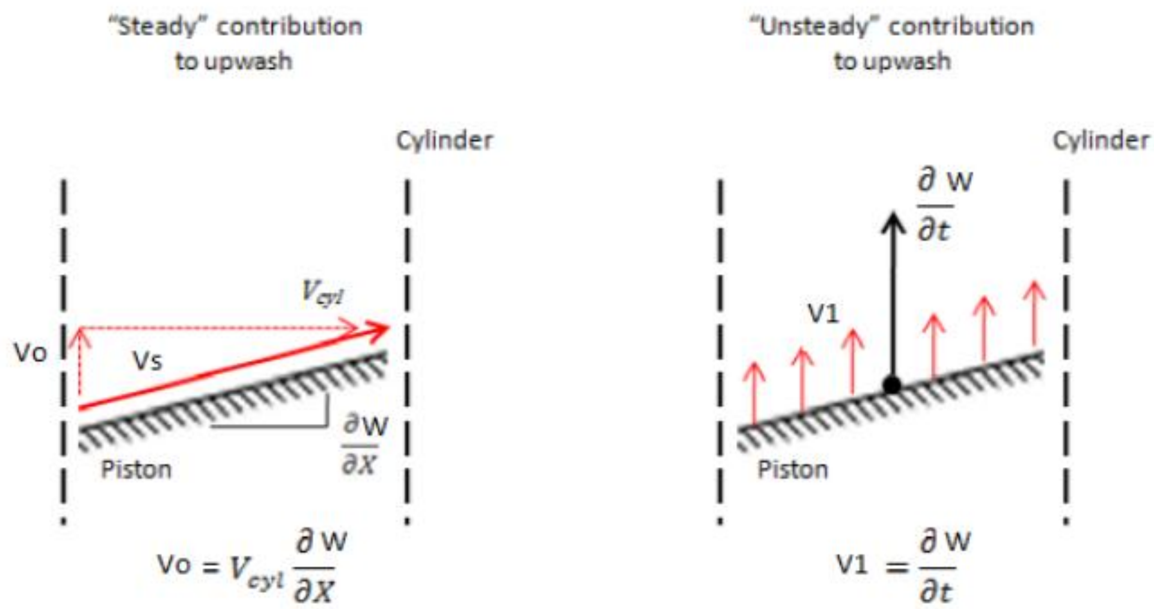


Figure VI.1. Piston theory illustration [3].

By substituting $Eq.(VI.5)$ into $Eq.(VI.4)$ we obtain:

$$\frac{p}{p_\infty} \cong 1 + \gamma\frac{1}{a}\frac{\partial W}{\partial t} + \frac{U}{a}\frac{\partial W}{\partial X} \qquad (VI.7)$$

Rearranging and using:

The Mach number $M = U/a$ and dynamic pressure $q = (\gamma/2)pM^2$

$$p - p_\infty \cong p_\infty\left[\gamma\frac{1}{a}\frac{\partial W}{\partial t} + \frac{U}{a}\frac{\partial W}{\partial X}\right] \qquad (VI.8)$$

$$p - p_\infty \cong \frac{p_\infty U}{a}\left[\frac{\gamma}{U}\frac{\partial W}{\partial t} + \frac{\partial W}{\partial X}\right] \qquad (VI.9)$$

VI.4. PROBLEM FORMULATION:

This section presents the assumption and solution methodology used to obtain the results based on the **von Karman's** large deflection plate equation and the description of **Bolotin** about the equation of small oscillations of the plate.

We assumed the fin of the rocket as two dimensional simply supported plate to be undergoing cylindrical bending with no spanwise bending (Figure VI.2). The plate is infinitely long in the direction parallel to the flow velocity. The plate is subject to pressure loading given by quasi-steady supersonic piston theory [5].

The equation of motion for a two-dimensional plate undergoing cylindrical bending (no spanwise bending) is:

$$D\left(\frac{\partial^4 \omega}{\partial x^4}\right) - \left(N_x + N_x^{(a)}\right)\left(\frac{\partial^2 \omega}{\partial x^2}\right) + \rho_m h\left(\frac{\partial^2 \omega}{\partial t^2}\right) + (p - p_\infty) = \Delta p \quad (VI.10)$$

Where:

- D Flexural rigidity of the plate.

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad (VI.11)$$

- N_x Nonlinear induced loading ;

$$N_x = \alpha Eh/2a \int_0^a (\partial\omega/\partial x)^2\, dx \quad (VI.12)$$

- $N_x^{(a)}$ (Externally) applied in-plan load.
- Δp Static pressure differential across the panel.
- $p - p_\infty$ Aerodynamic pressure loading.

$$p - p_\infty = \frac{2q}{\beta}\left[\frac{\partial\omega}{\partial x} + \left(\frac{M^2-2}{M^2-1}\right)\frac{1}{U}\frac{\partial\omega}{\partial t}\right] \quad (VI.13)$$

Where:

- M Mach number.

$$W'''' - 6\alpha(1-\nu^2)\left[\int_0^1 (W')^2 d\xi\right] W'' - R_x W'' + \frac{\partial^2 W}{\partial \tau^2} + \lambda\left\{W' + \left(\frac{M^2-2}{M^2-1}\right)\left(\frac{\mu}{\beta\lambda}\right)^{1/2}\frac{\partial W}{\partial \tau}\right\} = P \qquad (VI.14)$$

Where:

$$W' = \partial W/\partial \xi$$

$$\xi \equiv x/a' \equiv \partial/\partial \xi$$

$$\tau \equiv t(D/\rho_m h a^4)^{1/2} \qquad W \equiv \omega/h \qquad (VI.15)$$

$$\lambda \equiv 2qa^2/\beta D \qquad \mu \equiv \rho a/\rho_m h$$

$$R_x \equiv N_x^{(a)} a^2/D$$

$$P \equiv \Delta p a^4/Dh$$

For the simplicity, the notation μ/M will be used:

$$M \gg 1 \qquad [(M^2-2)/(M^2-1)]^2\,\mu/\beta \to \mu/M$$

$$W'''' - 6\alpha(1-\nu^2)\left[\int_0^1 (W')^2 d\xi\right] W'' - R_x W'' + \frac{\partial^2 W}{\partial \tau^2}$$

$$+\lambda\left\{W' + \left(\frac{\mu}{M\lambda}\right)^{1/2}\frac{\partial W}{\partial \tau}\right\} = P \qquad (VI.16)$$

Note that the function relationship:

$$\omega/h = \omega/h\,(\xi, \tau; \lambda, \mu/M, R_x, P, \alpha)$$

VI.4.1. GALERKIN METHOD:

The equation will be solved by the use of galerkin's method; comparison function for simply supported plat is [5]:

$$W(\xi,\tau) = \sum_{m=1}^{\infty} a_m(\tau)\, sin(m\pi\xi) \qquad (VI.17)$$

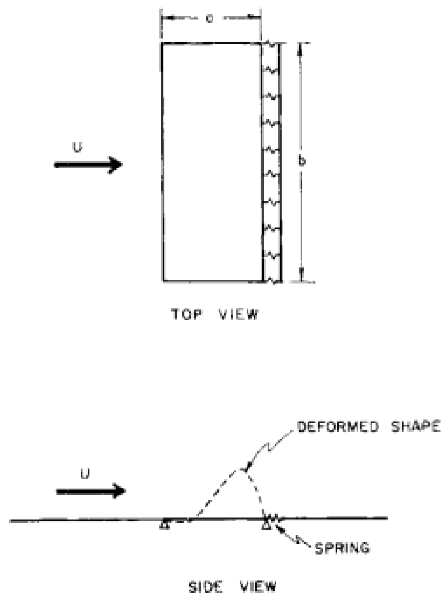


Figure VI.2. Panel geometry [5].

After substituting $Eq.(VI.17)$ into $Eq.(VI.16)$ we obtain:

$$\sum a_m(m\pi)^4 sin(m\pi\xi) + 6\alpha(1-\nu^2)\left[\sum a_r^2 \frac{(r\pi)^2}{2}\right]\sum a_m(m\pi)^2 sin(m\pi\xi) + R_x \sum a_m(m\pi)^2 sin(m\pi\xi) + \sum \frac{d^2 a_m}{d\tau^2} sin(m\pi\xi) + \lambda\left[\sum a_m(m\pi)\, cos(m\pi\xi) + \left(\frac{\mu}{M\lambda}\right)^{1/2}\sum \frac{da_m}{d\tau} sin(m\pi\xi)\right] = P \qquad (VI.18)$$

Following the Galerkin method we multiply $Eq.(VI.18)$ by $\sin s\pi\xi$ and integrate over the panel length, for the demonstration (see. Appendix C), the result is:

$$a_s\frac{(s\pi)^4}{2} + 6\alpha(1-\nu^2)\left[\sum_r a_r^2 \frac{(r\pi)^2}{2}\right] a_s\frac{(s\pi)^2}{2} + R_x a_s \frac{(s\pi)^2}{2} + \frac{d^2 a_s}{d\tau^2}\frac{1}{2} + \lambda\left\{\sum_m \frac{sm}{s^2-m^2}[1-(-1)^{s+m}]a_m + \frac{1}{2}\left(\frac{\mu}{M\lambda}\right)^{1/2}\frac{da_s}{d\tau}\right\} = P\frac{[1-(-1)^s]}{s\pi} \quad ; \qquad s = 1,2,\dots,\infty \qquad (VI.20)$$

This equation is a coupled set of ordinary nonlinear differential equations in time which solved by using available algorithms such as Euler and Runge-Kutta method. In this study 4th order Runge-Kutta method was used to solve the ODE (see. Appendix C).

VI.5. CALCULATE FIN FLUTTER SPEED:

- **Zachary Howard (2011), [6] :**

Treated the Flutter Boundary Equation based on an earlier calculation published in NACA Technical Paper 4197 [7]. And used more accurate term for torsional modulus; this accuracy was gained by the inclusion of plate theory. The true accuracy of this equation will not be known, but preliminary calculation suggest that a comfortable safety margin is anything 20% below the flutter speed.

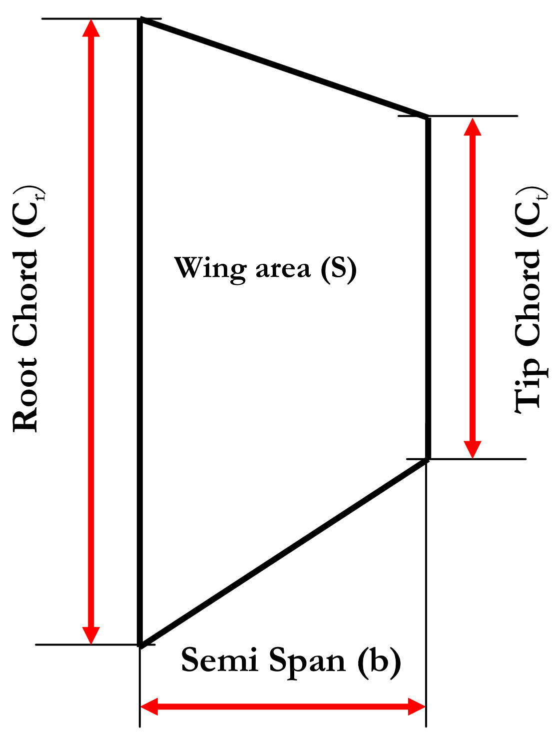


Figure VI.3. Fin geometry.

The Flutter Boundary Equation by **Zachary**:

$$V_f = a\sqrt{\frac{G}{\frac{1{,}337\, AR^3\, P(\lambda+1)}{2(AR+2)\left(\frac{t}{c_r}\right)^3}}} \qquad (VI.21)$$

Where:

- a Speed of sound.
- G Shear modulus (psi).
- AR Aspect ratio.
- P Air pressure (lbs/ft^2).
- λ Taper ratio.
- t Fin thickness (in).
- c_r Root chord (in).

Geometric equations:

$$S = \frac{1}{2}(c_r + c_t)b$$
$$AR = \frac{b^2}{S} \qquad (VI.22)$$
$$\lambda = \frac{c_t}{c_r}$$

Where:

- S Wing area (in^2).
- c_t Tip chord (in).
- b Semi span (in).

Since the rocket is flying in the Troposphere zone which is between 8-15km; temperature and pressure vary linearly with altitude according to the $Eq.(VI.23)$:

$$T = 59 - 0.00356h$$
$$P = 2116\left(\frac{T + 459.7}{518.6}\right)^{5.256} \qquad (VI.23)$$

Where:

- T Temperature (°F).

The last variable is the speed of sound:

$$a = \sqrt{1.4 \times 1716.59 \times (T + 460)} \qquad (VI.24)$$

REFERENCES BIBLIOGRAPHY

[1] P. F. Jordan, "The physical nature of panel flutter", Aero Digest, 34-38, 1956.

[2] E.H. DOWELL, "Aeroelasticity of plates and shells", Noordhoff & Sijthoff, Leyden, 1975.

[3] Naoto Kaji et al., "Non Linear Oscillations of a Fluttering Plate", MECH 6481 , April 6, 2016.

[4] Marius-Corné Meijer and Laurent Dala. "Generalized Formulation and Review of Piston Theory for Airfoils", AIAA Journal, Vol. 54, No. 1 (2016), pp. 17-27.

[5] E.H. DOWELL. "Nonlinear oscillations of a fluttering plate." AIAA Journal, Vol. 4, No. 7 (1966), pp. 1267-1275.

[6] Zachary Howard, "How to calculate fin flutter speed", Apogee Journal, ISSUE 291 6 pages, JULY 19, 2011.

[7] Dennis J. Martin, "Summary of Flutter Experiences as a Guide to the Preliminary Design of Lifting Surfaces on Missiles", NACA-TN-4197, United States, Feb 01, 1958.

CHAPTER VII

THE FLUTTER PHENOMENA:

THEORITICAL AND NUMERICAL ANALYSIS

VII. INTRODUCTION:

The progress achieved by digital and software tools in the past 40 years has allowed scientists to dramatically improve their understanding of the world. The development of mathematical models has allowed to work on increasingly sophisticated problems in a wide range of fields: predicting the behavior of production tools, transportation, the environment, etc. Managing these complex problems has been facilitated within each discipline separately but also from a cross-disciplinary perspective, allowing more general phenomena to be tackled [1].

VII.2. ANALYZING APPROACHES:

Any problem or phenomena can be analyzed by three ways:

VII.2.1. THEORETICAL APPROACH:

Using laws and/or Theories and associated equations, such as Newton's law, Navier-Stokes to solve solid or fluid flow problems, these solutions are exact.

VII.2.2. EXPERIMENTAL APPROACH:

Making experiments and trying to understand the phenomena and relation between various variables, such as wind tunnel or Post-buckling experiments which helps to design and optimize external shape of airplanes, missiles, ships and automobiles etc.

VII.2.3. NUMERICAL APPROACH:

Solving structural, thermal or fluid flow problems using numerical techniques. These solutions are approximate, not exact.

VII.3. DIFFICULTIES IN THEORETICAL & EXPERIMENTAL APPROACHES:

- **Theoretical approach:**

This approach gives exact solution which is a great advantage. But analytical solutions are only possible for a limited number of problems, usually formulated in an artificial, idealized way. For example in the case of a fixed-free beam under axial force or laminar fluid flow in uniform cannel, those two cases are easy to solve by hand, but imagine if we have a building construction problem or fluid flow over airplane wing, in those cases human cannot solve them with theoretical approaches.

- **Experimental approach:**

Those approaches are very reliable, and depict real world situations. For example, in aerospace industries Wind Tunnel experiments are very reliable. But some situations they became very expensive, and sometimes they have technical difficulties (Sometimes it takes several years before an experiment is set up and all technical problems are resolved).

And from there it will remain only the numerical approach which we can use to solve the complex issues that face us in our daily lives.

And to solve this kind of problems may take too much time (e.g. increasing in the precision lead to increasing in time) of course -from problem to another, the engineers used and still using *Numerical Analysis Software* to handle variety of mechanical problems such as Catia, Abaqus and Ansys. Add to that the development in CAD software like SolidWorks and Catia makes the challenge Numerical Analysis Software very heavy.

VII.4. ANSYS, INC.:

ANSYS is a general-purpose finite-element solving a wide variety of mechanical problems. These problems include static/modeling package for numerically dynamic, structural analysis (both linear and nonlinear), heat transfer, and fluid problems, as well as acoustic and electromagnetic problems. In general, a finite-element solution may be broken into the following three stages [2].

VII.4.1. PRE-PROCESSING*: defining the problem*

The major steps in pre-processing are (i) define keypoints/lines/areas/volumes, (ii) define element type and material/geometric properties, and (iii) mesh lines/areas/ volumes as required. The amount of detail required will depend on the dimensionality of the analysis, i.e., 1D, 2D, axi-symmetric, and 3D.

VII.4.2. SOLUTION*: assigning loads, constraints, and solving*

Here, it is necessary to specify the loads (point or pressure), constraints (translational and rotational), and finally solve the resulting set of equations.

VII.4.3. POST-PROCESSING*: further processing and viewing of the results*

In this stage one may wish to see (i) lists of nodal displacements, (ii) element forces and moments, (iii) deflection plots, and (iv) stress contour diagrams or temperature maps [2].

VII.5. PLATFORMS OR ENVIRONMENTS:

Two software environments can be used to implement Ansys code:

VII.5.1. ANSYS CLASSIC:

Chronologically, this was the first software solution offered by the developers. It is designed for constructing finite element models with simple geometries that can easily be assembled from basic operations. Within this environment, the user directly builds finite element models using the scripting language i.e. APDL. Ansys Classic is therefore oriented toward users with experience in numerical simulations [1].

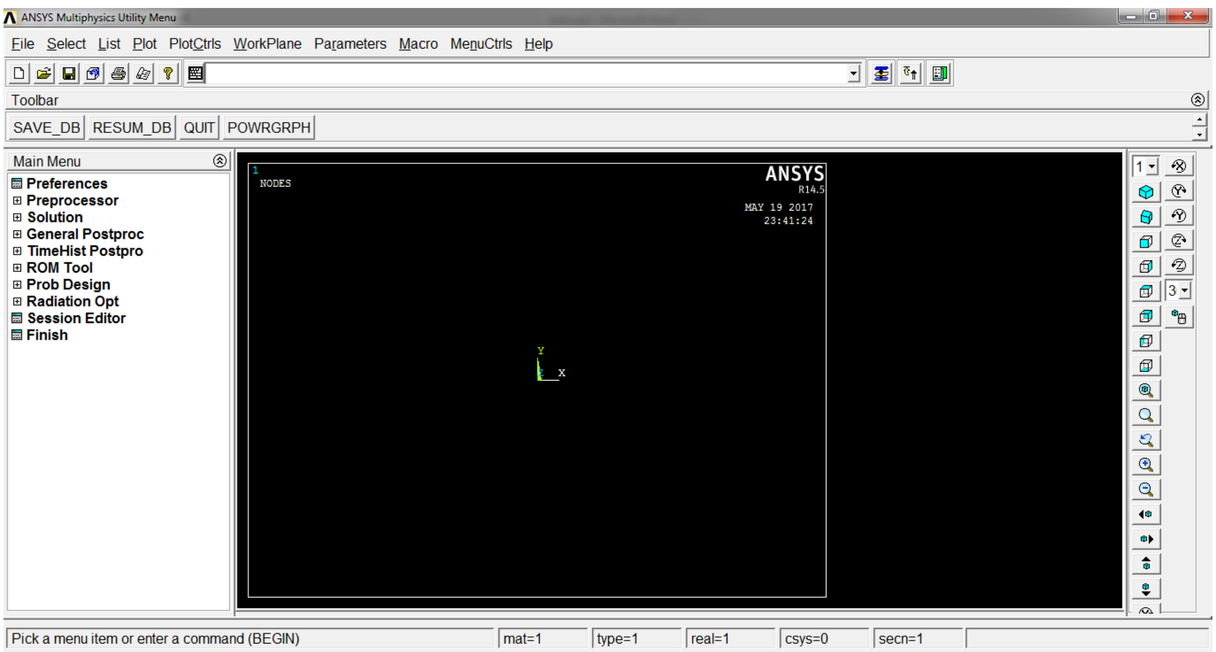


Figure VII.1. Classic platform Ansys Mechanical APDL.

VII.5.2. ANSYS WORKBENCH:

This platform takes a different approach to model building by reusing the original Ansys code. It is particularly suitable for handling problems with complex geometries (many objects with pieces) and is accessible to users without experience in performing computations. In this environment, the user essentially works on the geometry of the model and not the model itself. The platform therefore fulfills the task of converting the commands specified by the user into

Ansys code before launching the solving procedure. The finite element models generated in this way may, however, still be manipulated by inserting custom commands into the Ansys code [1].

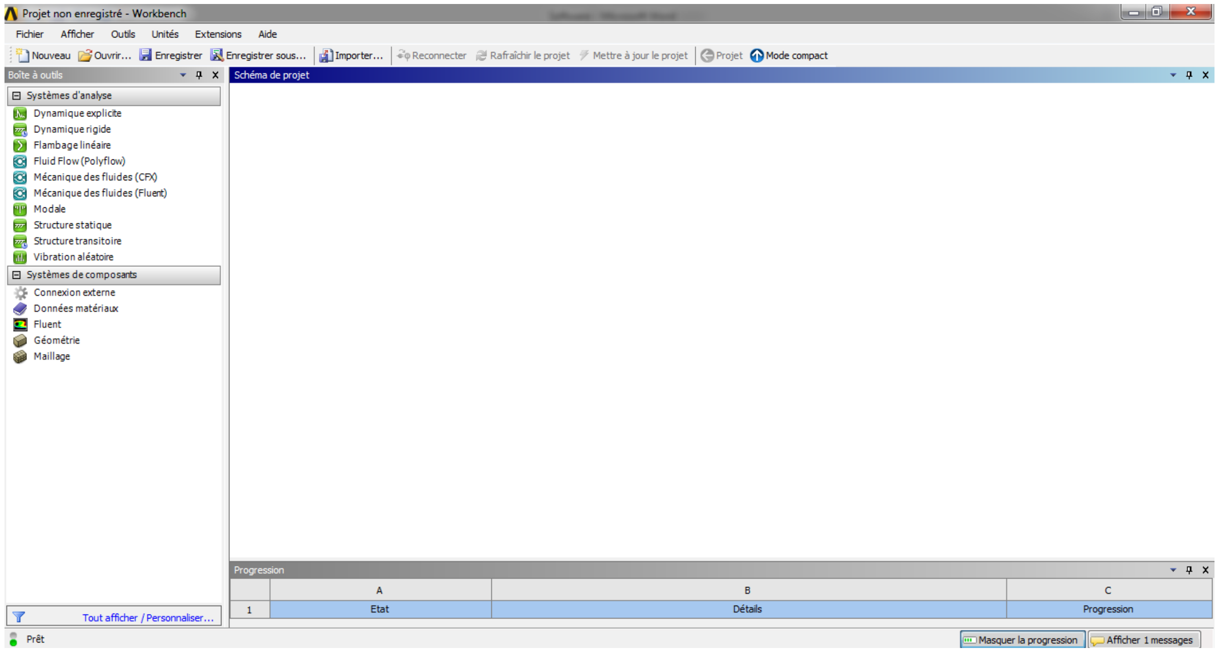


Figure VII.2. Ansys Workbench platform.

VII.6. MAJOR PRODUCTS AND CAPABILITIES:

VII.6.1. ANSYS STRUCTURAL:

This product allows carrying out mechanical simulations by calculating the structures. Its main capabilities are:

1. Static analysis
2. Modal analysis
3. Harmonic analysis (forced response)
4. Temporal or transient analysis
5. Nonlinear (contacts, plasticity of materials, large displacements or large deformations).

VII.6.2. ANSYS MECHANICAL:

This product has the same capacities as ANSYS structural, adding a thermal solution, with modeling of the radiation.

VII.6.3. ANSYS CFX & FLUENT:

Both of the software allows performing simulations in fluid mechanics. They bear the names of the companies that developed them, bought by ***ANSYS, Inc.*** in February 2003 and February 2006 respectively.

VII.6.4. ANSYS ELECTROMAGNETICS:

Electromagnetic simulation from ANSYS provides analysis tools that enable the accurate simulation of electromagnetic fields. ANSYS electromagnetic solutions enable engineers and designers to accurately predict the behavior of high-performance electrical and electromechanical devices.

VII.6.5. ANSYS MULTIPHYSICS:

Multiphysics simulation from ANSYS provides high-fidelity engineering analysis tools that enable the accurate simulation of complex coupled-physics behavior. ANSYS multiphysics solutions combine industry-leading solver technology for all physics disciplines (structural mechanics, heat transfer, fluid flow and electromagnetic) with an open and adaptive ANSYS Workbench environment, flexible coupled-physics simulation methods, and parallel scalability.

VII.7. FLUID–STRUCTURE COUPLING USING ANSYS:

Recently, several new problems have been formulated in the area of fluid–structure coupling, for example in the automotive industry with the dynamics of airbag inflation and fluid sloshing inside tanks; in aeronautics with the fluttering phenomenon affecting airplane wings, which involves a coupling between the vibrational dynamics of a structure and the flow of a fluid; and in the transportation industry with studies on noise reduction inside vehicles based on vibroacoustic analysis.

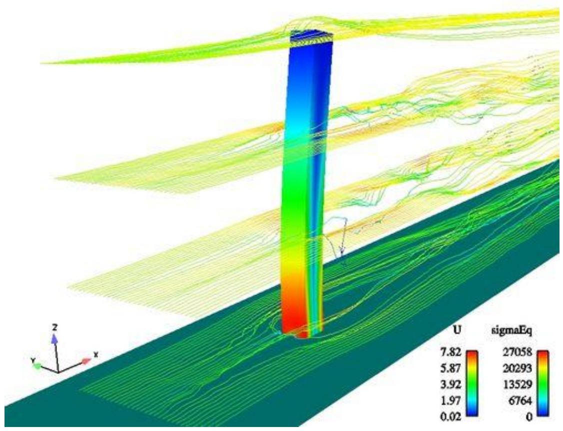


Figure VII.3. FSI simulation of flow past over cantilevered elastic square beam.

Each and every structure in contact with a fluid is subject to phenomena involving mechanical fluid–structure couplings to some extent. This kind of multi-physics coupling often significantly affects the dynamic behavior of mechanical systems. Taking it into account is one of the major challenges in calculating the dimensions of structures, especially when the objective is to ensure that their design meets the necessary safety requirements.

VII.7.1. COUPLING WITH ANSYS:

Some analysis components have unidirectional couplings. For example, in thermal stress problems, the temperature field places thermal constraints on the structure domain, but the structural deformations generally do not influence the temperature distribution. Therefore, it is not necessary to iterate between the solutions of both domains. In fluid–structure interaction (FSI) problems, the fluid pressure causes a structural deformation, which in turn modifies the solution for the fluid. In order to achieve convergence in this problem, it will be necessary to iterate between both physical domains. The coupling between the domains can be described directly or via load transfer.

VII.7.1.1 LOAD TRANSFER COUPLING METHOD - WORKBENCH-:

The coupling can be performed using a system of components called **system coupling** in Workbench. More precisely, we can implement the analysis of unidirectional or bidirectional FSIs by connecting the system coupling component to external mechanical or fluid data systems [1].

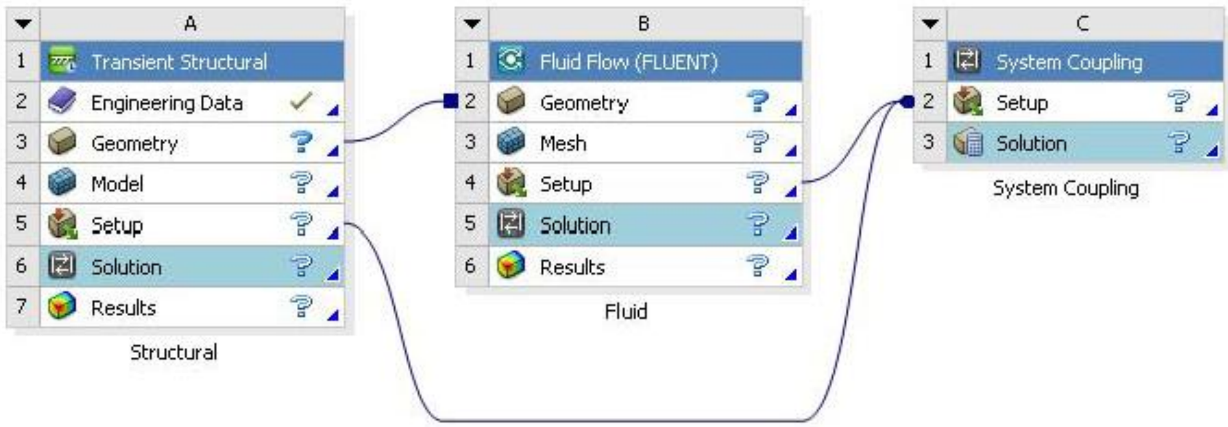


Figure VII.4. Coupling Transient Structural and Fluid flow using the system coupling.

VII.8. SOLIDWORKS:

SolidWorks is a solid modeling CAD and CAE, computer program that runs on Microsoft Windows. SolidWorks is published by Dassault Systems.

SolidWorks Corporation was founded in December 1993 by Massachusetts Institute of Technology graduate Jon Hirschtick. he recruited a team of engineers with the explicit purpose of making 3D CAD technology more accessible easy-to-use, affordable, and available on the Windows desktop. So he used $1 million to make MIT Blackjack Team to set up the company. SolidWorks released its first product *SolidWorks 95*, in November 1995.

VII.9. OPENROCKET:

The software has been published as Open Source software. The methods for calculating the aerodynamic properties of rockets follow primarily those presented by James Barrowman in his Master’s thesis.

Model rocket simulation is a powerful tool allowing rocketeers to design and simulate the flight of rockets before they are actually built. A few commercial model rocket simulators exist, but they are essentially “black-box” solutions, where the user has no clear understanding how the simulations are being performed and no possibility to extend them.

It is an Open Source rocket development and simulation environment written totally in Java. The program structure has been designed to make full use of object oriented programming, allowing one to easily extend its features. The software also includes a framework for creating user-made listener components that can listen to and interact with the simulation while it is running. This allows a powerful and easy way of interacting with the simulation and allows simulating for example guidance systems.

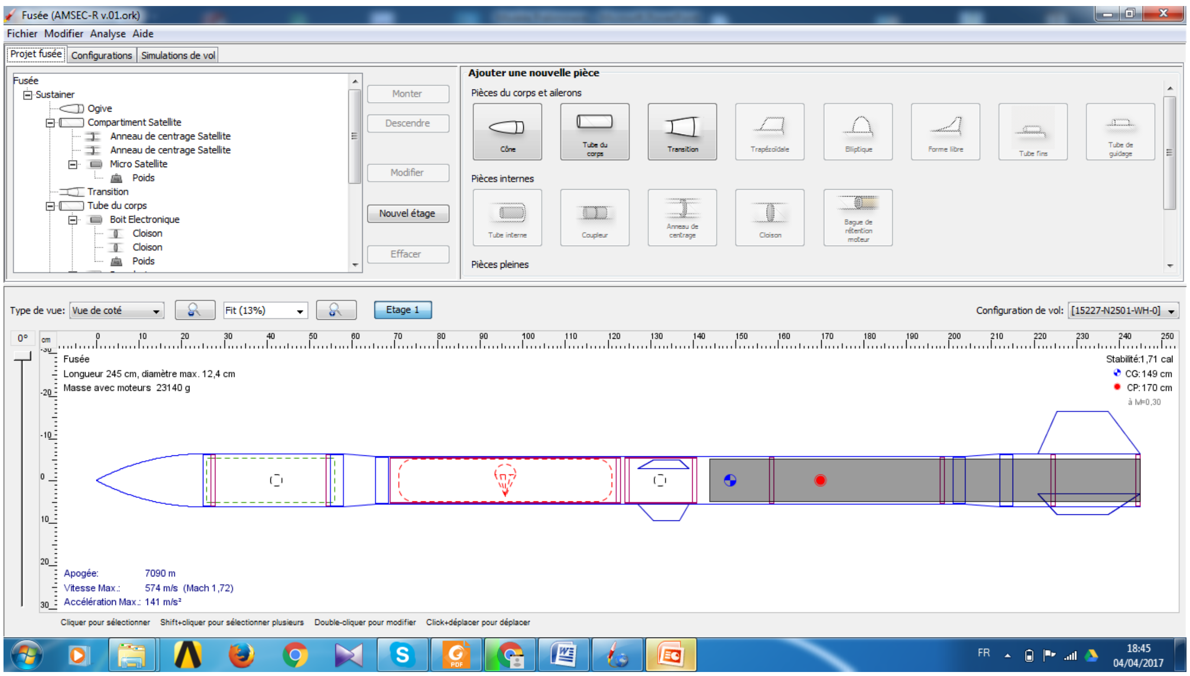


Figure VII.4. OpenRocket program platform.

REFERENCES BIBLIOGRAPHY

[1] Bouchaib Radi and Abdelkhalak El Hami, “Fluid-Structure Interactions and Uncertainties Ansys and Fluent Tools”, Volume 6, John Wiley, 111 River Street, Hoboken, NJ 07030, USA, Mar 27-2017.

[2] Tadeusz Stolarski Y. Nakasone S. Yoshimoto, “Engineering Analysis with ANSYS Software”, 1st Edition, pp. 480, Butterworth-Heinemann, 18th December 2006.

CHAPTER VIII

FLUTTER PREDICTION:
RESULTS AND DISCUSSION

I.1. INTRODUCTION:

In this chapter we are going to present a comparison between three approaches for predicting flutter boundary for fins (the point where the flutter occurs), the first one is the Flutter Boundary Equation which was mentioned in chapter VI, Second approach it is a Matlab program which is made by Naoto Kaji et al. [3] from chapter VI; it uses the derivative ODE (see Appendix C) and Rung-kutta fourth order to make the equation numeric and to solve it by the program, the last one by using numerical software such as Ansys in our case; the tool “system coupling” for FSI analyzing was used with deferent cases (velocities and geometries).

VIII.2. STARTING WITH OBENROCKET:

We begin by designing our model in OpenRocket software; this program uses two methods; the Barrowman method to calculate the center of gravity (C.G.) and center of pressure (C.P.), 6-DOF Runge-Kutta fourth order for simulation.

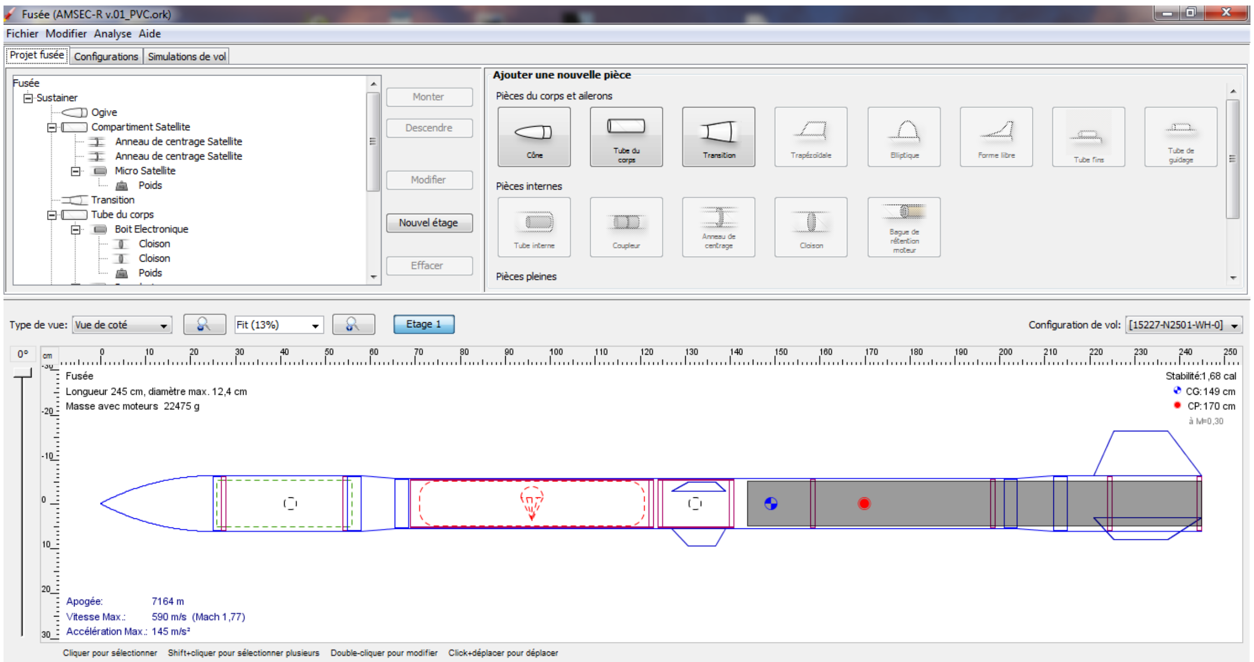


Figure VIII.1. OpenRocket platform; AMSEC-Rocket v.01.

After the simulation we got those characteristic about rocket flight:

CHARACTERISTICS	VALUE	CHARACTERISTICS	VALUE
Stages	1	**Flight time (s)**	561
Length (mm)	2450	**Time to reach apogee (s)**	33.4
MaxDiameter (mm)	124	**Optimum Delay (s)**	27.4
Weight & motor (kg)	23.140	**Ramp output speed (m/s)**	16.8
Stability (cal)	1.71	**Max speed (m/s)**	570
CG (mm)	1490	**Max Acceleration (m/s²)**	141
CP (mm)	1700	**Deployment speed (m/s)**	21.7
Altitude (m)	7064	**Speed at landing (m/s)**	11.3

Table VIII.1. Characteristic of the AMSEC-Rocket.

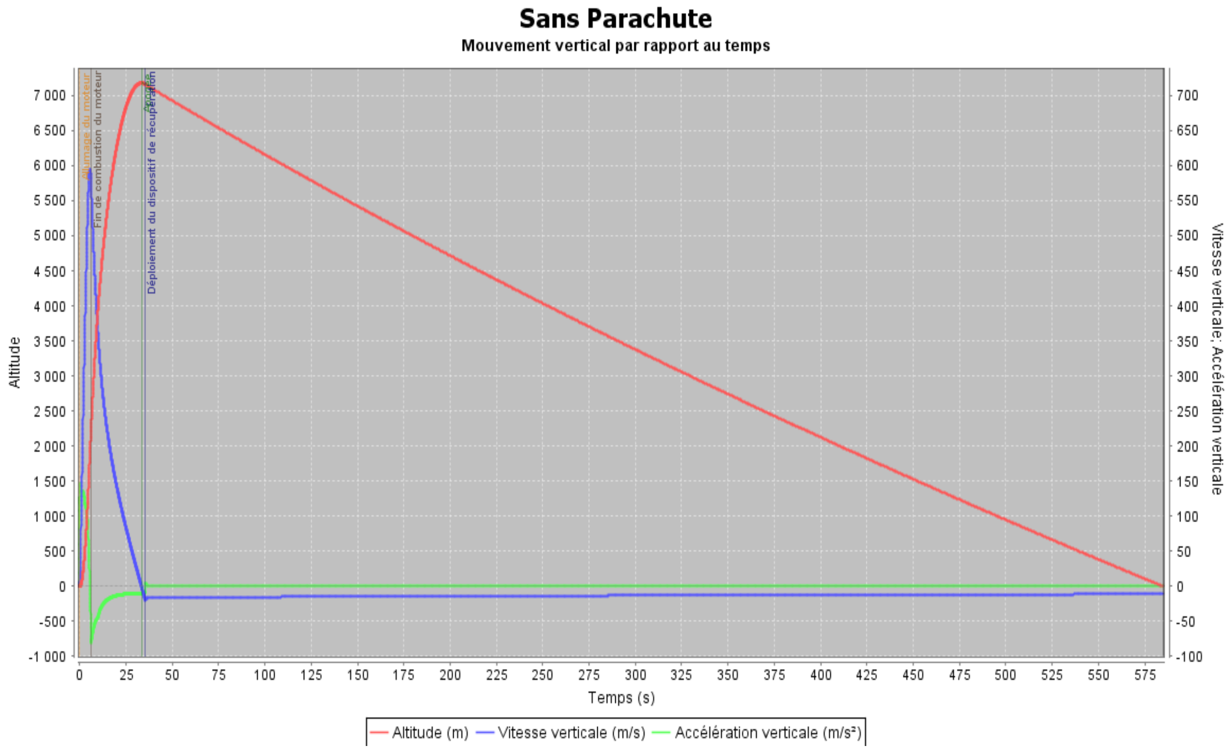


Figure VIII.2. AMSEC-R Flight simulation (Altitude vs time vs vertical velocity and acceleration).

VIII.3. ROCKET MATERIALS:

We choose The PVC (polyvinyl chloride) as main material for the body, tail and fins. The nose and transitions are made from composite material (glass fiber).

We made Tensile test on one specimen ISO 527-2 type 1A from PVC (Pipe) in the Technological Hall by tensile machine type INSTRON 5969 Series, to extract mechanical proprieties.

We get the following results:

Density: $\boldsymbol{\rho = 1380\ Kg/m^3}$

Young Modulus: $\boldsymbol{E = 2293\ MPa}$

Tensile strength: $\boldsymbol{T_s = 37,65\ MPa}$

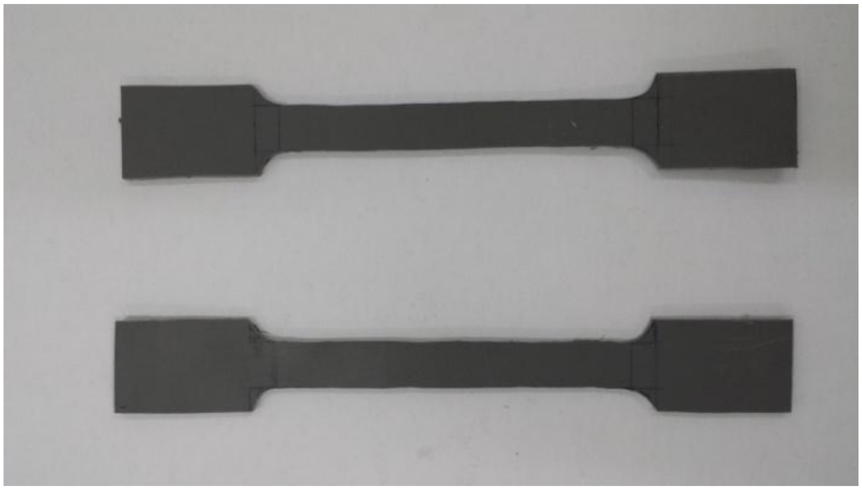


Figure VIII.3. PVC (polyvinyl chloride) spicement.

Figure VIII.4. Tensile experiment on PVC spicement.

From tables back to company **CES Edupack** in **2011** those are the following mechanical proprieties of their polymers products:

Mechanical properties	PE	Acrylic	PVC	MC blue
Minumum value				
Young modulus	0.621	2.240	2.140	2.62
Shear modulus	0.218	0.803	0.766	0.97
Bulk modulus	2.150	4.200	4.700	3.70
Poisson's ratio	0.418	0.384	0.383	0.34
Compressive strength	19.700	72.400	42.500	55.00
Maximum value				
Young modulus	0.896	3.800	4.140	3.20
Shear modulus	0.314	1.370	1.490	1.19
Bulk modulus	2.250	4.400	4.900	3.90
Poisson's ratio	0.434	0.403	0.407	0.36
Compressive strength	31.900	131.000	89.600	104.00

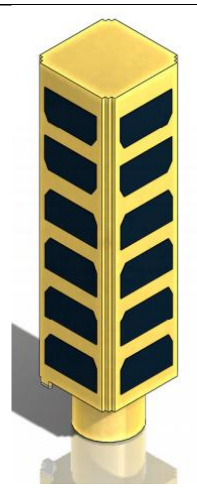
Table VIII.2. Minimum value of mechanical propertiesof polymer according to CES Edupack 2011©.

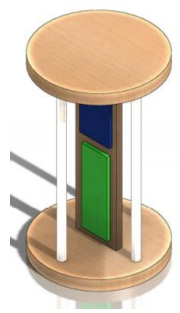
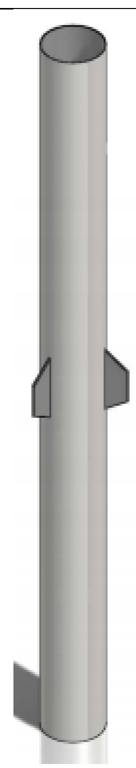
According to Table VIII.2, the minimum values of the Young modulus of the PVC is roughly equal to our value, which means that we can use the other values in our study such as Poisson ratio and Shear modulus.

VIII.4. DESIGNING IN SOLIDWORKS:

We used Solidworks software to design our model because of its simplicity in sketching and creating solids, the resolution is clear and it represent the model in reality.

The need to use solidWorks because we are going to import our model into Ansys software to simulate our model; and Ansys is not CAD software so it will be difficult to make perfect 3D models.

Part name	Part design in SolidWorks
Nose Cone	
Micro-Satellite Compartment	
Micro-Satellite	
Transition	

Parachute	
Electronic Box	
Body tube and Fins	

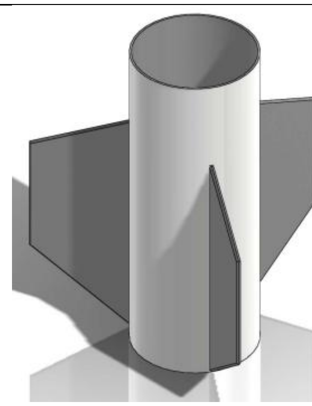
Tail	

Table VIII.3. AMSEC-Rocket parts and content.

VIII.5. THE BOUNDARY EQUATION APPRAOCH:

The Fin of the AMSEC-Rocket has the following Data:

	Value (Unit converting)	
C_r	240 mm	9.6 in
C_t	120 mm	4.8 in
t	4 mm	0.16 in
b	100 mm	4 in
G	766 MPa	111098.87 Psi
$Altitude$	7000 m	22965 ft

Table VIII.4. AMSEC-Rocket Fin geometry data.

After applying the equations (Chapter VI), we found that the flutter speed is:

$$V_f = 525.6\ m/s$$

When we simulate our rocket in OpenRocket program we found that Max speed is $V_{max} = 570\ m/s$ which mean that the AMSEC-Rocket break the prediction velocity.

VIII.6. FSI AND ODE PROGRAM APPRAOCHES:

We made simulation using the third approach which is the FSI to check if our Fin will respond to this speed (570 m/s), here are the results after preparing the coupling system:

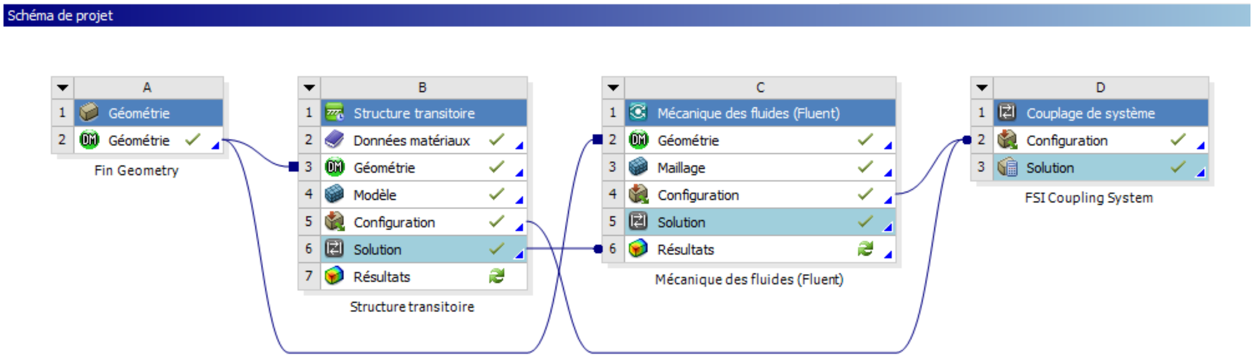


Figure VIII.5. Coupling procedure between Structure transient and Fluid Mechanics.

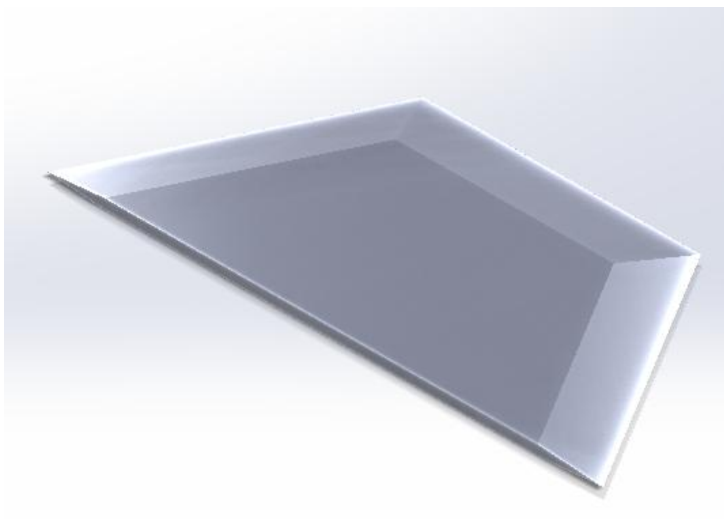


Figure VIII.6. Fin CAD in SolidWorks.

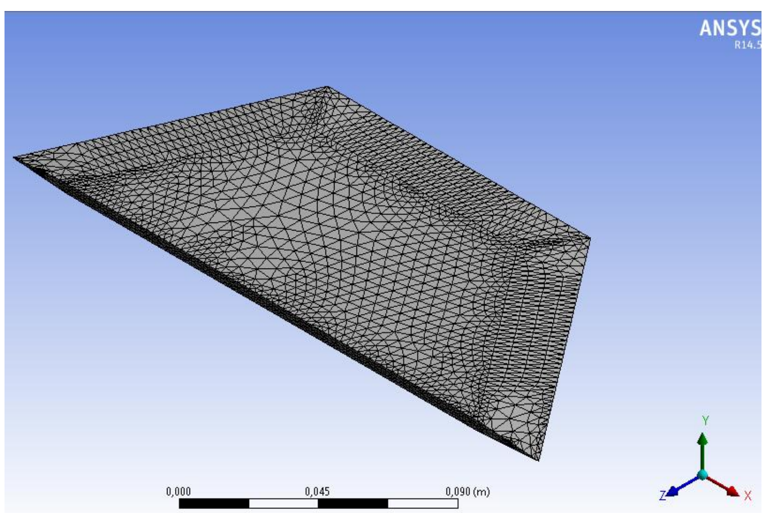


Figure VIII.7. Fin meshing; 18167 nodes, 9046 tetrahedral element.

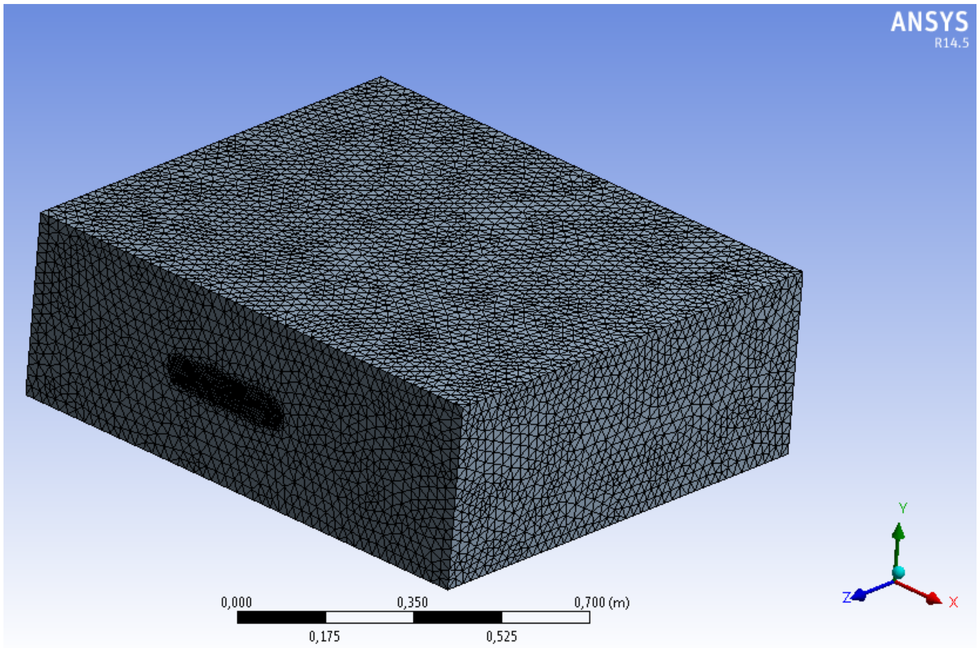


Figure VIII.8. Fluid domain meshing; 40436 nodes, 211436 tetrahedral element.

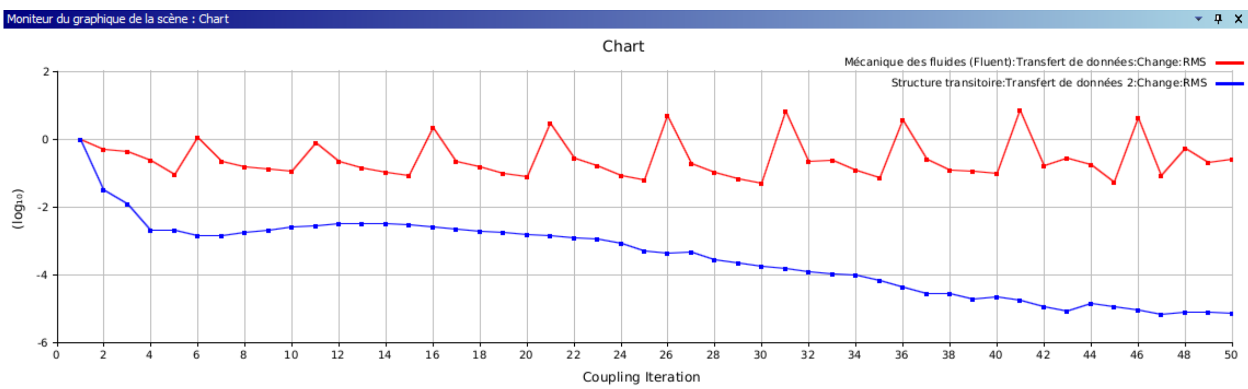


Figure VIII.9. Transformation coupling data chart.

NOTE:

The procedure is the same in when applying all velocities; (1).defining geometry, (2).Meshing, (3).boundary condition then coupling, the only value change is velocities.

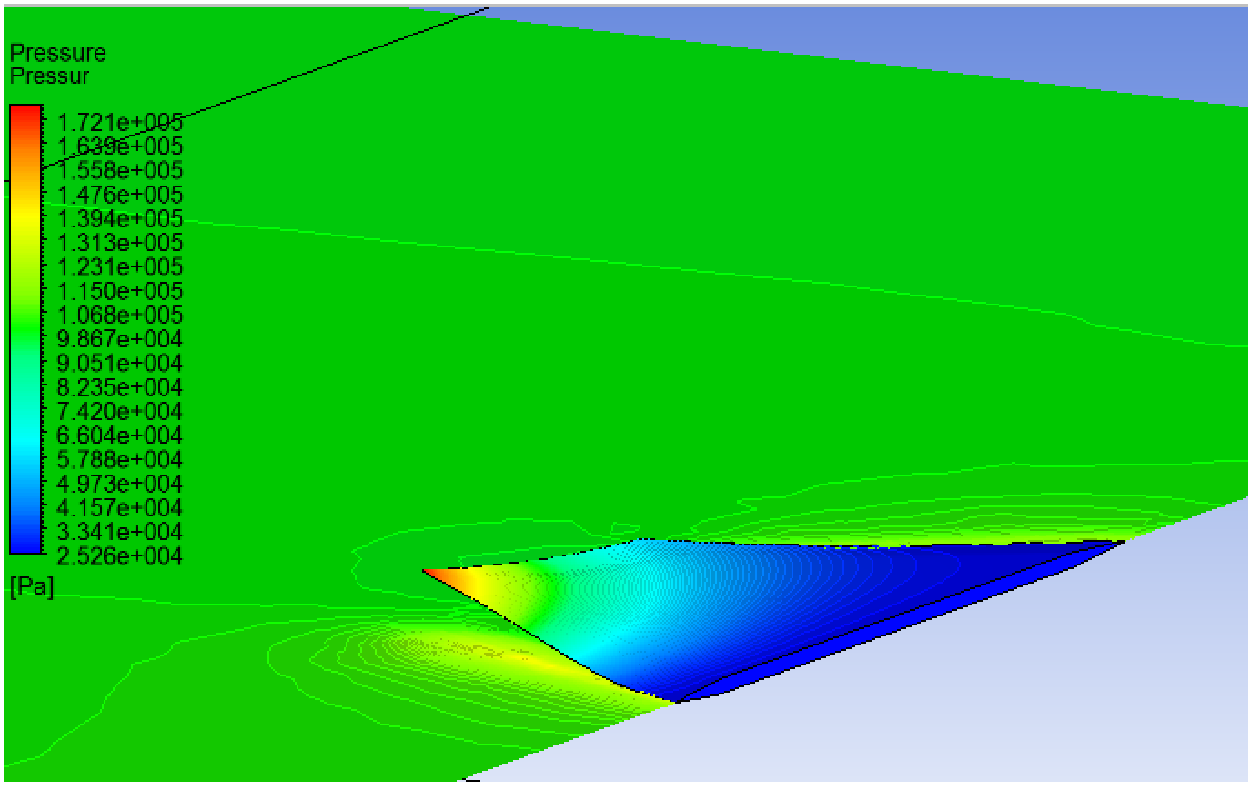


Figure VIII.10. Y axe Displacement vs. pressure at the air speed of 570 m/s.

From the (Figure VIII.6) we note that the Fin had deformed and deviated from the plan (Figure VIII.7) which is pacing through the middle of it with 15.9 mm. this mean that the prediction of the flutter boundary equation is true.

Now we confirmed that in this velocity the flutter phenomena will happen, but it still to find the point where it starts fluttering.

The panel response vs. time was plotted for various velocities [410 440 490 520 570] to study the effect of velocity on flutter and the deflection amplitude. The non-dimensional deflection w/h was plotted against the time in seconds for velocities. And each time we are going to present the simulation of the Fin using FSI analysis.

Five Modes were considered in this analysis and the air density was set to $\boldsymbol{\rho} = \mathbf{1.225}\ \boldsymbol{Kg/m^3}$. The plate deflection was considered at $\boldsymbol{\xi} = \mathbf{0.75}$ for all cases. The value $\frac{\boldsymbol{\mu}}{\boldsymbol{M}}$ was set 0.01.

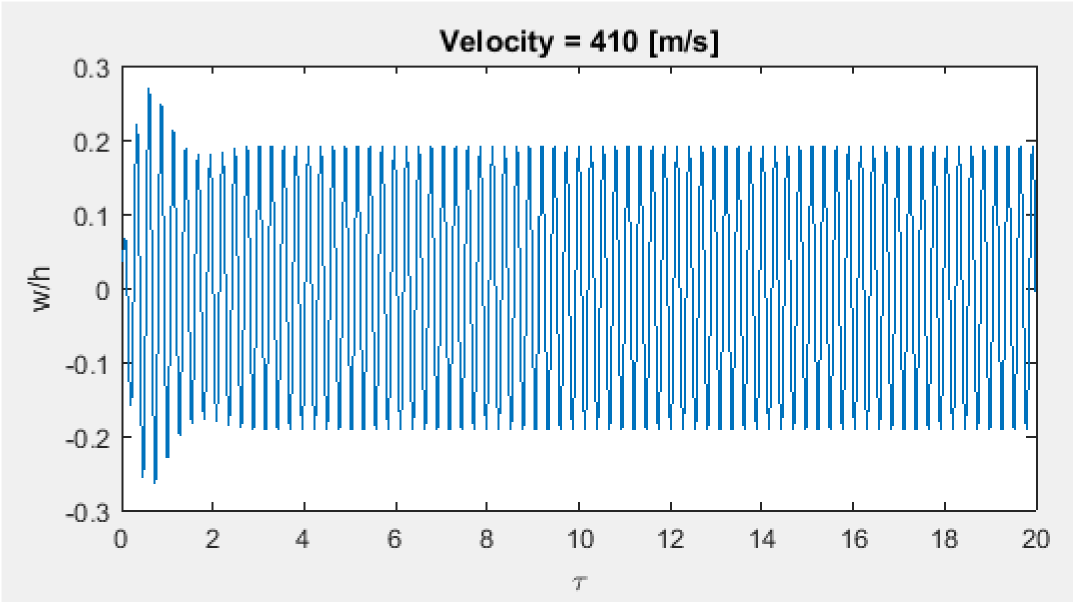


Figure VIII.11. Non Dimensional Deflection vs. Time for V = 410 m/s and μ/M = 0.01.

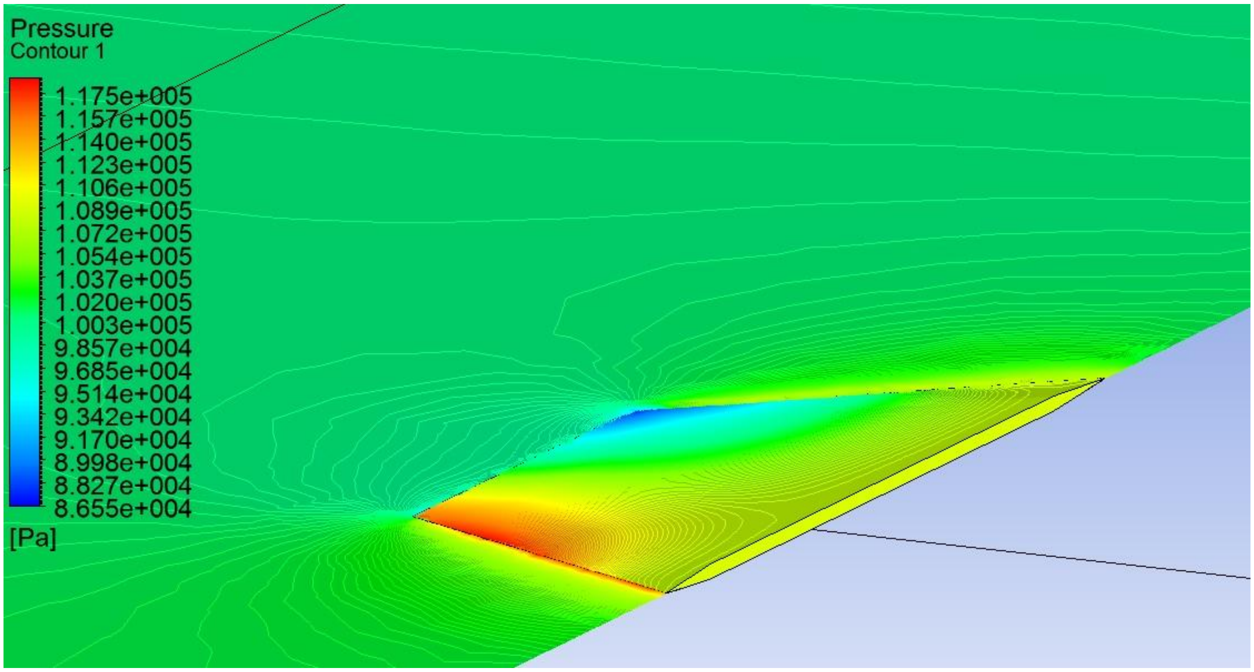


Figure VIII.12. Y axe Displacement vs. pressure at the air speed of 410 m/s.

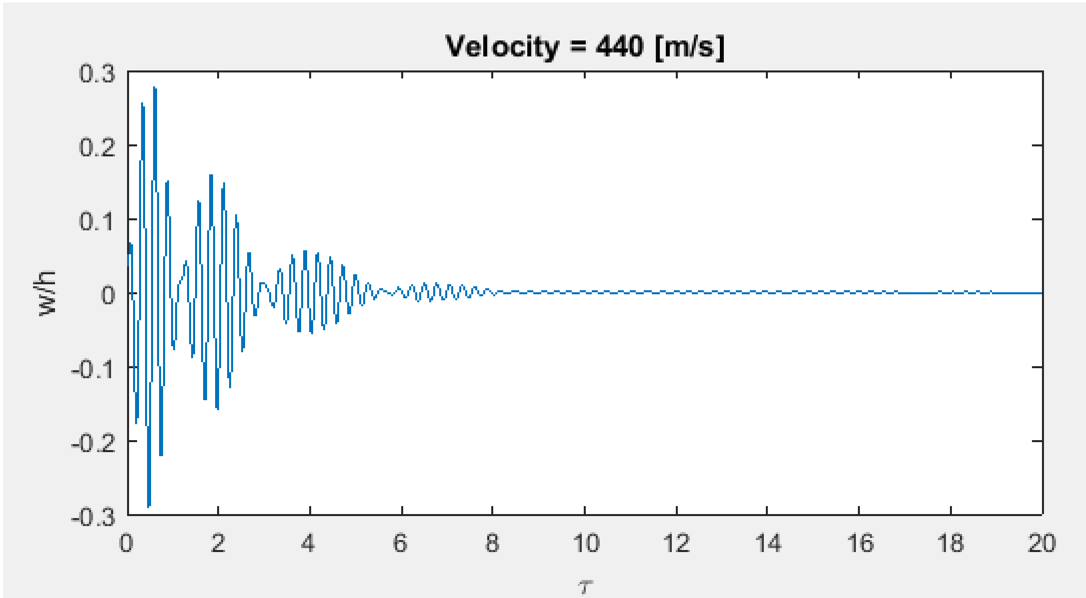


Figure VIII.13. Non Dimensional Deflection vs. Time for V = 440 m/s and μ/M = 0.01.

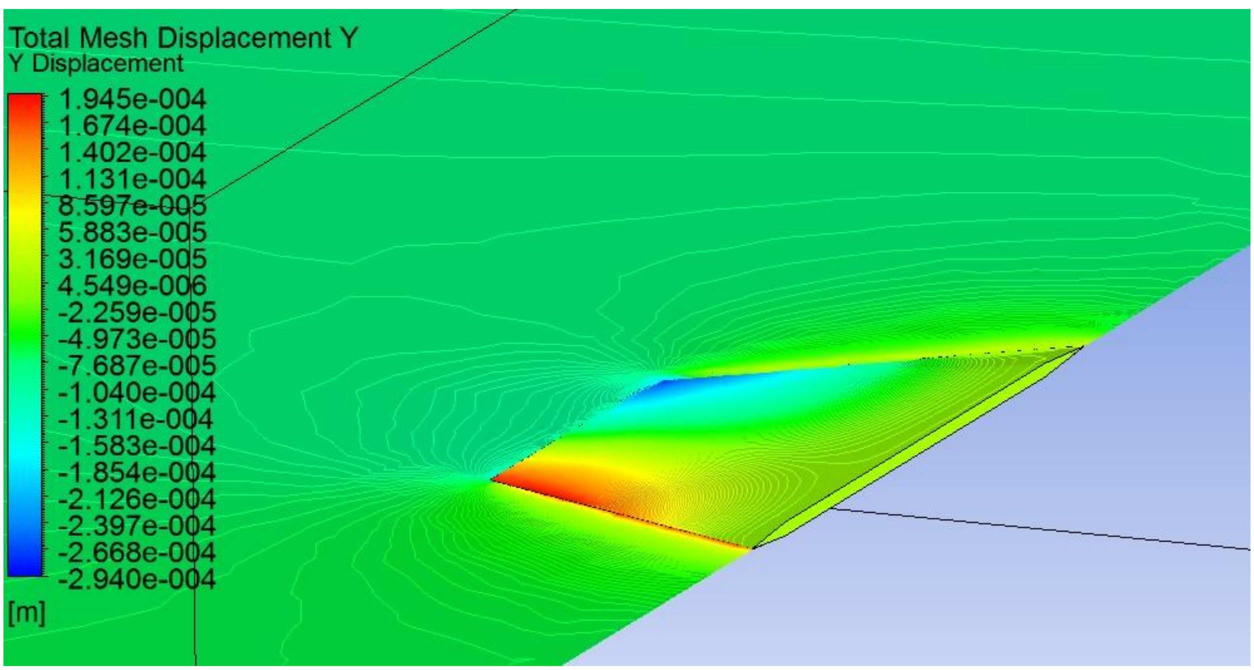


Figure VIII.14. Y axe Displacement vs. pressure at the air speed of 440 m/s.

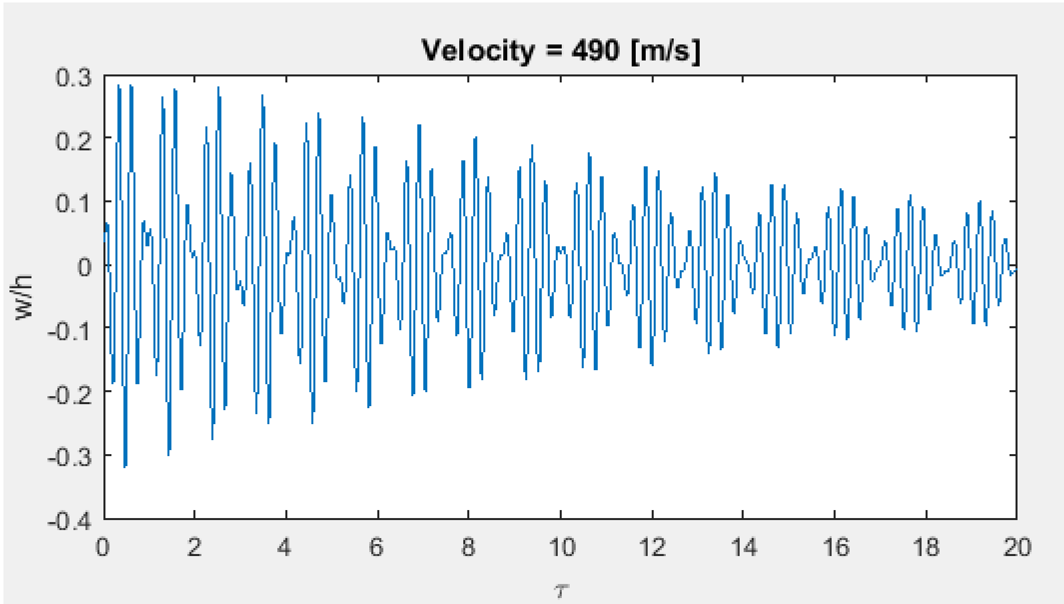


Figure VIII.15. Non Dimensional Deflection vs. Time for V = 490 m/s and μ/M = 0.01.

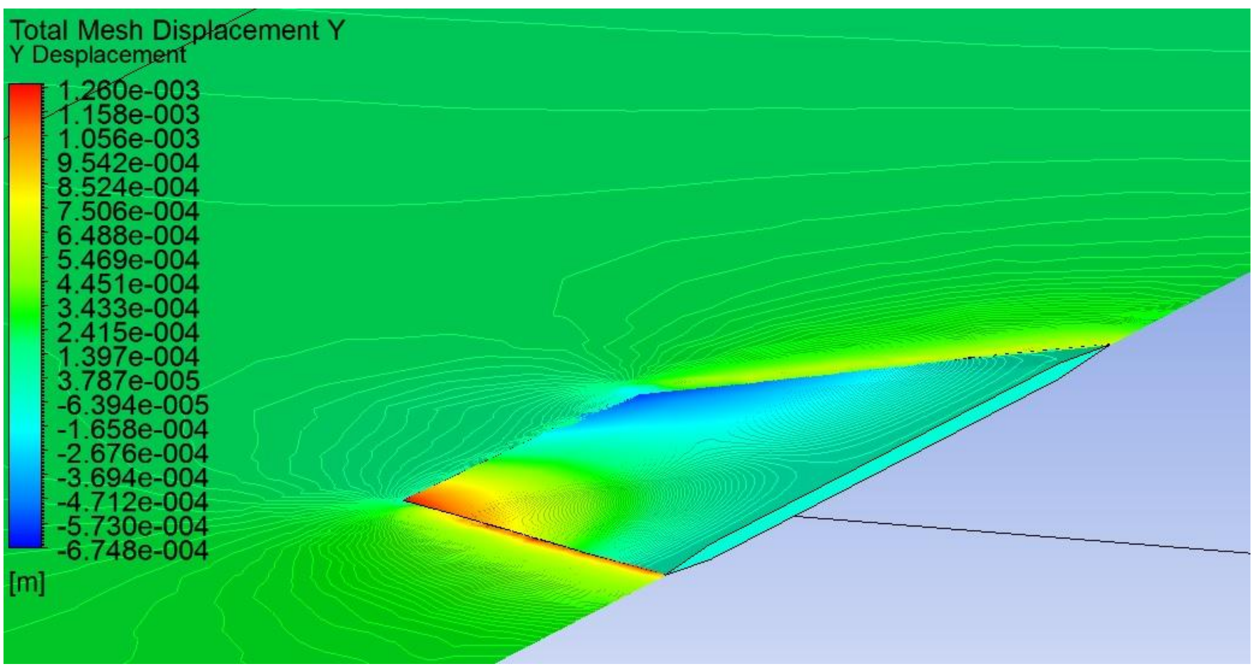


Figure VIII.16. Y axe Displacement vs. pressure at the air speed of 490 m/s.

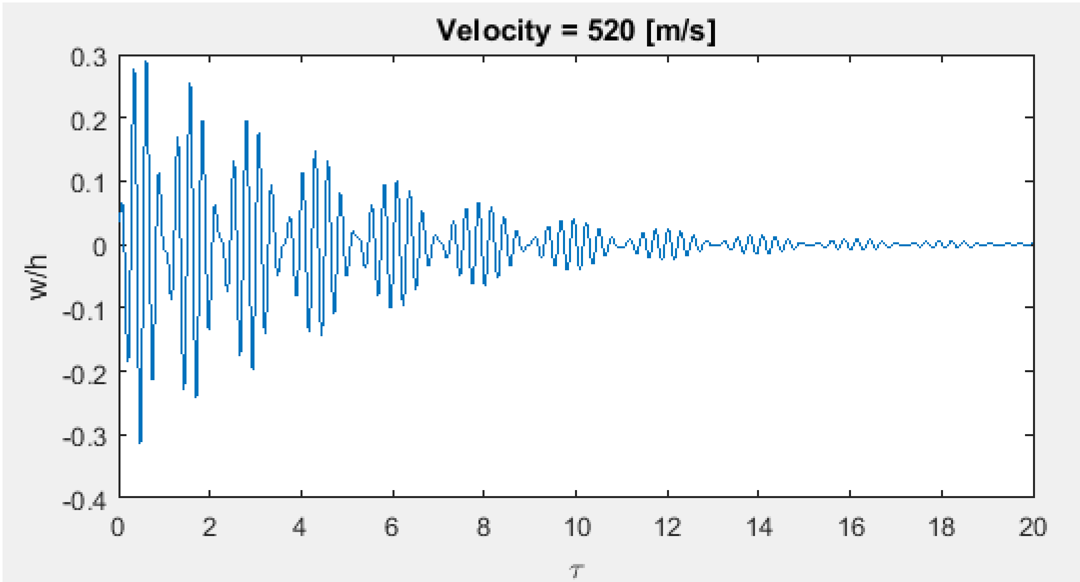


Figure VIII.17. Non Dimensional Deflection vs. Time for V = 520 m/s and μ/M = 0.01.

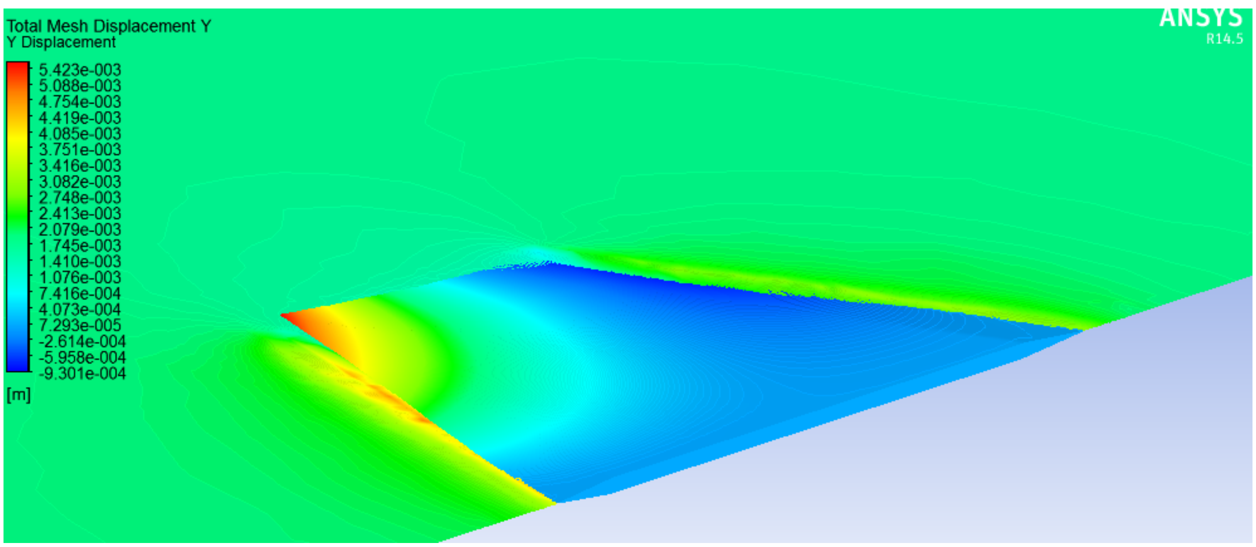


Figure VIII.18. Y axe Displacement vs. pressure at the air speed of 520 m/s.

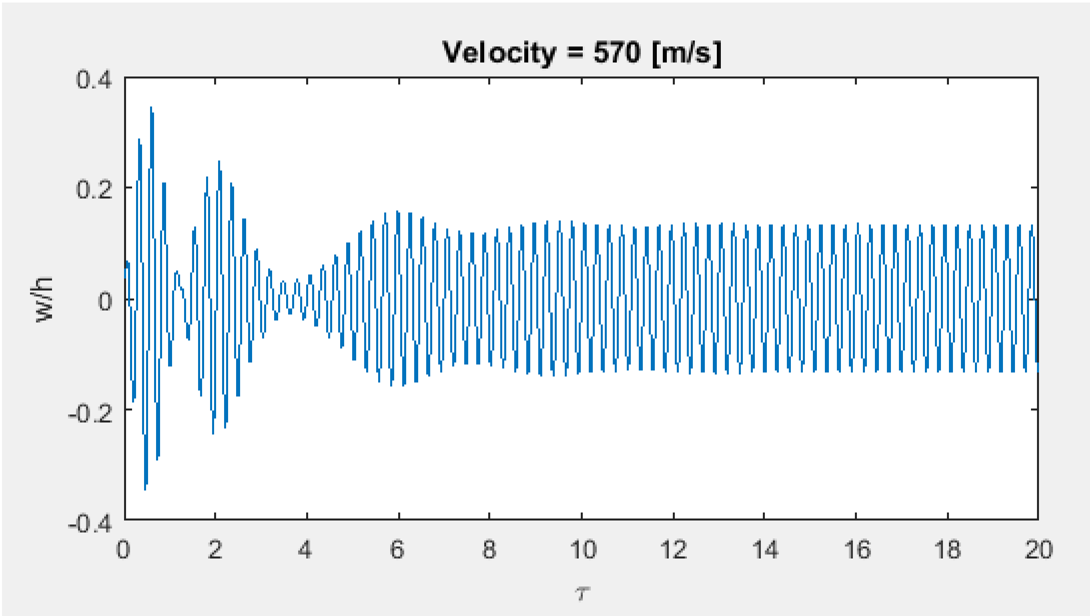


Figure VIII.19. Non Dimensional Deflection vs. Time for V = 570 m/s and μ/M = 0.01.

As indicated in Figures VIII.9.11.13, the plate's response with respect to time is damped for air velocities 440, 490 and 520 m/s, however at 410 and 570 m/s the response oscillates between (0.2 to -0.2) and (0.18 to -0.18) showing over time strong indication of flutter as shown in Figure VIII.7 and Figure VIII.15 respectively. Two velocities were the flutter can occur should be avoided.

GENERAL CONCLUSION

Since flutter can be a dangerous phenomenon with disastrous effects, flutter is considered as an essential design parameter. The aircrafts and missiles are those days subjected to flutter test after its manufacture in order to ensure the safety. During these tests, they are purposely subjected to oscillation in order to verify that the aircraft does not flutter in the normal operation conditions as well as dampens the effect of flutter in the presence of oscillation. The aircrafts or missiles are recommended not to exceed critical air speed in order to avoid flutter.

This study treated the performance characteristics of a fluttering Fin for preliminary rocket model using the Galerkin method to convert the partial differential equation of motion of the plate into an ordinary differential equation. Runge-Kutta, numerical integration method was used to solve the set of ordinary differential equations by program in Matlab. Five (5) modes were sufficient to produce a reasonable accuracy.

The panel response against time was plotted for various velocities to study the effect of velocity on flutter and the deflection amplitude. It had been shown that, the plate's response with respect to time is damped for air velocities 440, 490 and 520 m/s, however at 410 and 570 m/s the response oscillates over time demonstrating sustained flutter.

Fluid Solid Interaction was made for all cases of velocities and it gives good results about the displacement of the Fin.

The plate's flexural rigidity demonstrated in (Appendix B), the derivation of the Plate's Equation of Motion in (Appendix C) and the coupled set of non-linear ODE's after Galerkin's application treated in (Appendix D).

APPENDIX

APPENDIX A

ADDITIONAL PICTURS

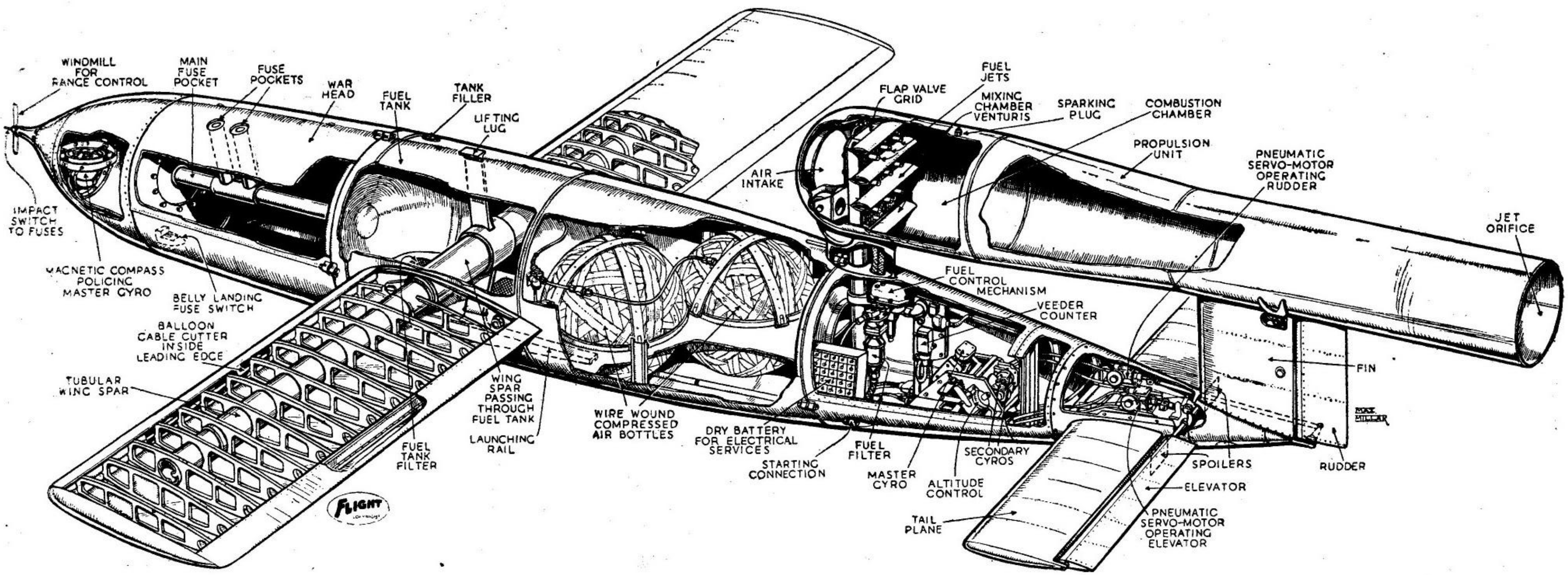


Figure A.1. V-1 bomb nomenclature.

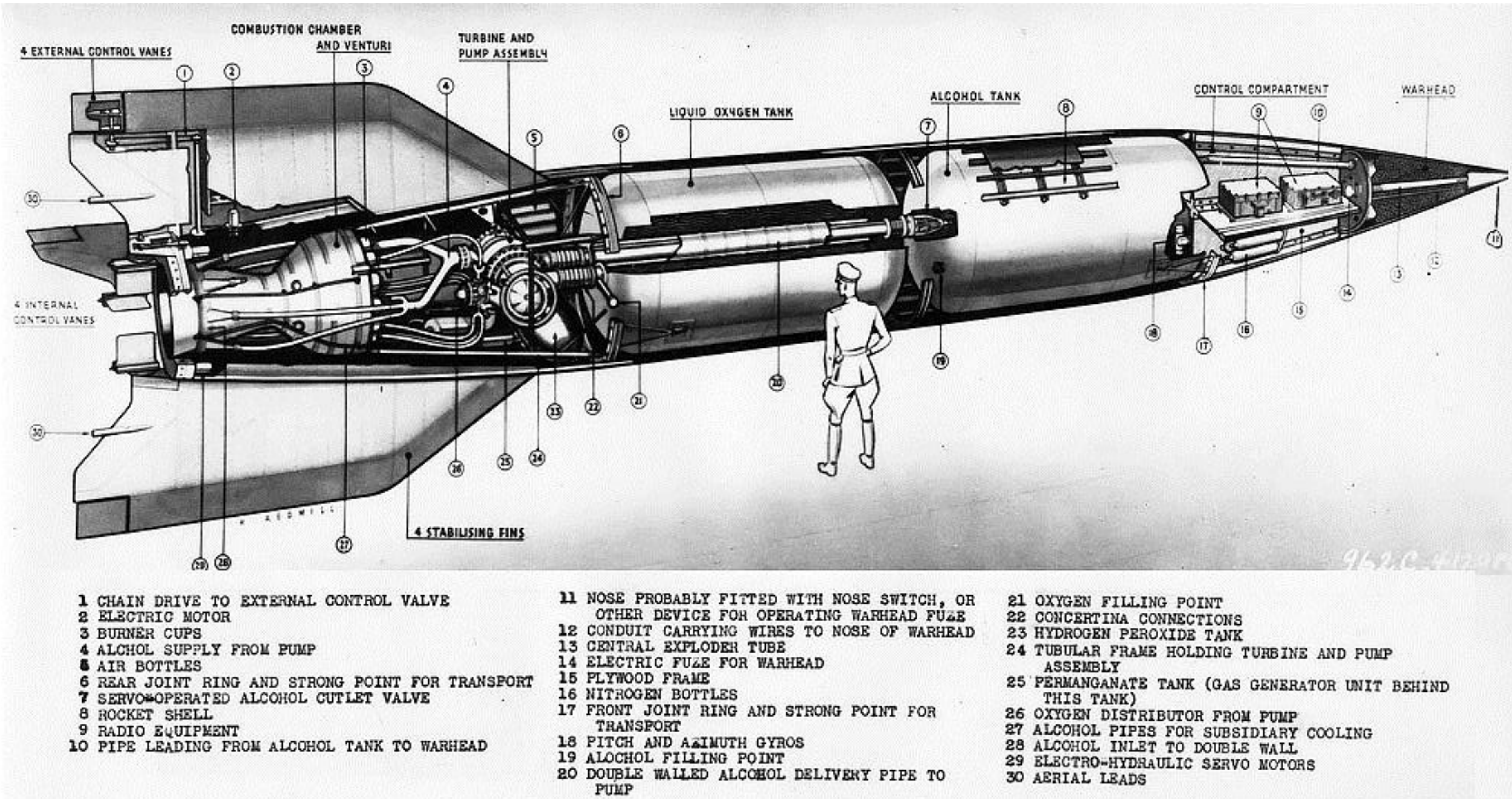


Figure A.2. V-2 Rocket nomenclature.

Figure A.3. Members of Russian amateur rocket group GIRD work on the first Soviet liquid propellant rocket (left to right): Sergei Korolev, Nikolai Yefremov and Yuriy Pobedonostsev. The rocket reached an altitude of 400 m on 17 August 1933 [NASA/Asif Siddiqi].

Figure A.4. V-2 on launch pad. The German V-2 was a key element of early U.S. and Soviet ballistic missile development. This V-2, at White Sands in New Mexico, served as a test bed for the U.S. Army and allowed engineers to experiment with several new technologies. (Courtesy, U.S. Army).

Figure A.5. Atlas launch of Surveyor 1 [NASA].

APPENDIX B

DERIVATION OF THE PLATE'S

FLEXURAL RIGIDITY

Flexural Rigidity of the plate:

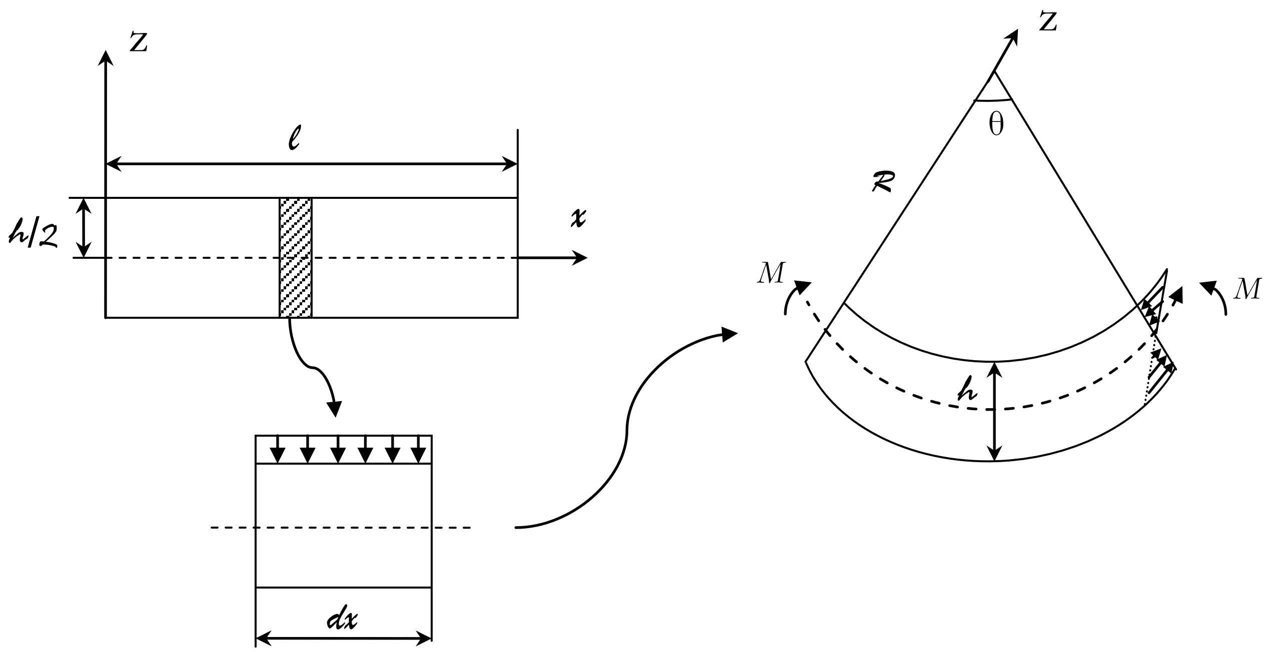


Figure B.1. Plate under momentum forces.

$$M = \int_{-h/2}^{+h/2} \sigma_{xx}\, z dx \qquad (1)$$

$Hooke's\ law$:

$$\cdot\ \varepsilon_{xx} = \frac{1}{E}\left(\sigma_{xx} - \nu\sigma_{yy}\right)$$
$$\cdot\ \varepsilon_{yy} = \frac{1}{E}\left(\sigma_{yy} - \nu\sigma_{xx}\right) \qquad (2)$$

$\varepsilon_{yy=0}$ (No out of plane strain)

$$\varepsilon_{yy=0} \Longrightarrow \frac{1}{E}\left(\sigma_{yy} - \nu\sigma_{xx}\right) = 0 \Longrightarrow \sigma_{yy} = \nu\sigma_{xx} \qquad (3)$$

$(3) into (2)$:

$$\Longrightarrow \varepsilon_{xx} = \frac{1}{E}(\sigma_{xx} - \nu\nu\sigma_{xx}) = \frac{\sigma_{xx}}{E}(1-\nu^2)$$

$$\Longrightarrow \sigma_{xx} = \frac{E}{(1-\nu^2)}\varepsilon_{xx} \qquad (4)$$

$(4) into (1)$:

$$M = \int_{-h/2}^{+h/2} \frac{E}{(1-\nu^2)}\varepsilon_{xx}\, z.dz \qquad (5)$$

From figure above:

$$\varepsilon_{xx} = \frac{-\Delta l}{l} = \frac{z}{R} \qquad (6) \Longrightarrow \frac{1}{R} = \frac{\varepsilon_{xx}}{z}$$

$$l = R.d\theta = R.\frac{d\theta}{dx}dx = R\frac{d}{dx}\left(-\frac{d\omega}{dx}\right)dx = -R\frac{d^2\omega}{dx^2}dx$$

$$\Longrightarrow d\theta = \frac{l}{R} = -\frac{d^2\omega}{dx^2}dx$$

$$\Longrightarrow \frac{d\theta}{l} = \frac{d\theta}{x} = \frac{1}{R} = -\frac{d^2\omega}{dx^2} = \frac{\varepsilon_{xx}}{z} \qquad \big(from\ (6)\big)$$

$$\Longrightarrow \varepsilon_{xx} = -z\frac{d^2\omega}{dx^2} \qquad (7)$$

$(7) into (5)$:

$$\Longrightarrow M = \int_{-h/2}^{+h/2} \frac{E}{(1-\nu^2)}(-z)\frac{d^2\omega}{dx^2}z.dz$$

$$= \frac{-E}{(1-\nu^2)}\int_{-h/2}^{+h/2} z^2\frac{d^2\omega}{dx^2}dz = \frac{-E}{(1-\nu^2)}\frac{d^2\omega}{dx^2}\int_{-h/2}^{+h/2} z^2\,dz$$

$$= \frac{-Eh^3}{12(1-\nu^2)}\frac{d^2\omega}{dx^2} \equiv D\left(-\frac{d^2\omega}{dx^2}\right)$$

$$\Longrightarrow D = \frac{Eh^3}{12(1-\nu^2)}$$

APPENDIX C

DERIVATION OF THE NONLINEAR ODE SET OF EQUATIONS AFTER APPLYING GALERKIN'S METHOD

SOLUTION METHODOLOGY OF THE EQUATION OF MOTION:

The two dimensional simply supported plate is assumed to be undergoing cylindrical bending with no spanwise bending. The plate is infinitely long in the direction parallel to the flow velocity. The plate is subject to pressure loading given by quasisteady supersonic piston theory.

$$W'''' - 6\alpha(1-\nu^2)\left[\int_0^1 (W')^2 d\xi\right] W'' - R_x W'' + \frac{\partial^2 W}{\partial \tau^2}$$

$$+\lambda\left\{W' + \left(\frac{\mu}{M\lambda}\right)^{1/2}\frac{\partial W}{\partial \tau}\right\} = P \qquad (1)$$

$$W(\xi,\tau) = \sum_{m=1}^{\infty} a_m(\tau)\, sin(m\pi\xi) \qquad (2)$$

$$W'(\xi,\tau) = \sum_{m=1}^{\infty} a_m(\tau)\cos(m\pi\xi)(m\pi) \qquad (3)$$

$$W''(\xi,\tau) = -\sum_{m=1}^{\infty} a_m(\tau)\sin(m\pi\xi)(m\pi)^2 \qquad (4)$$

$$W'''(\xi,\tau) = -\sum_{m=1}^{\infty} a_m(\tau)\cos(m\pi\xi)(m\pi)^3 \qquad (5)$$

$$W''''(\xi,\tau) = \sum_{m=1}^{\infty} a_m(\tau)\sin(m\pi\xi)(m\pi)^4 \qquad (6)$$

Substituting(3), (4) and (6) into(1):

$$\sum_{m=1}^{\infty} a_m(\tau)(m\pi)^4\, sin(m\pi\xi) + 6\alpha(1-\nu^2)$$

$$\times\left[\int_0^1\left(\sum_{m=1}^{\infty} a_m(\tau)\cos(m\pi\xi)(m\pi)\right)^2 d\xi\right]\sum_{m=1}^{\infty} a_m(\tau)\, sin(m\pi\xi)\,(m\pi)^2$$

$$+R_x \sum_{m=1}^{\infty} a_m(\tau)\, sin(m\pi\xi)\, (m\pi)^2 + \sum_{m=1}^{\infty} \frac{d^2 a_m(\tau)}{d\tau^2} sin(m\pi\xi) \qquad (7)$$

$$+ \lambda \left[\sum_{m=1}^{\infty} a_m(\tau)\, cos(m\pi\xi)(m\pi) + \left(\frac{\mu}{M\lambda}\right)^{1/2} \sum_{m=1}^{\infty} \frac{da_m(\tau)}{d\tau} sin(m\pi\xi) \right] = P$$

Simplifying the term:

$$\int_0^1 \left(\sum_{m=1}^{\infty} a_m(\tau) \cos(m\pi\xi)(m\pi)^2 \right)^2 d\xi$$

$$= \left[\sum_{m=1}^{\infty} \sum_{n=1}^{\infty} (m\pi)^2 (m\pi)^2\, a_m(\tau) a_m(\tau) \int_0^1 \cos(m\pi\xi)\cos(m\pi\xi) \right] d\xi$$

Orthogonality Conditions:

$$\int_0^L \sin\left(\frac{n\pi x}{L}\right) \sin\left(\frac{m\pi x}{L}\right) dx = \begin{cases} 0 & m \neq n \\ \frac{L}{2} & m = n \end{cases}$$

$$\int_0^L \cos\left(\frac{n\pi x}{L}\right) \cos\left(\frac{m\pi x}{L}\right) dx = \begin{cases} 0 & m \neq n \\ \frac{L}{2} & m = n \end{cases}$$

As the above term reduces to:

$$= \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} (m\pi)^2 (n\pi)^2 a_m(\tau) a_n(\tau) \frac{1}{2} = \left[\sum_{n=1}^{\infty} \frac{(n\pi)^2}{2} a_n(\tau) \right]^2$$

Applying Galerkin's:

Following the Galerkin method we multiply (7) by $sin(s\pi\xi)$ and integrate over the panel length.

$$\int_0^1 \sum_{m=1}^{\infty} a_m(\tau)(m\pi)^4 \, sin(m\pi\xi)\, sin(s\pi\xi)$$
$$+ \int_0^1 6\alpha(1-\nu^2)\left[\sum_{n=1}^{\infty} a_n^2(\tau)\frac{(n\pi)^2}{2}\right]^2$$
$$\times \sum_{m=1}^{\infty} a_m(\tau)(m\pi)^2 \, sin(m\pi\xi)\, sin(s\pi\xi)$$
$$+ \int_0^1 R_x \sum_{m=1}^{\infty} a_m(\tau)(m\pi)^2 \, sin(m\pi\xi)\, sin(s\pi\xi)$$
$$+ \int_0^1 \sum_{m=1}^{\infty} \frac{d^2 a_m(\tau)}{d\tau^2} sin(m\pi\xi)\, sin(s\pi\xi)$$
$$+ \int_0^1 \lambda \left[\sum_{m=1}^{\infty} a_m(\tau)(m\pi)\, cos(m\pi\xi)\, sin(s\pi\xi)\right.$$
$$\left. + \left(\frac{\mu}{M\lambda}\right)^{1/2} \sum_{m=1}^{\infty} \frac{da_m(\tau)}{d\tau} sin(m\pi\xi)\, sin(s\pi\xi)\right] d\xi = \int_0^1 P\, sin(s\pi\xi)\, d\xi$$

$$\Rightarrow a_s(\tau)\frac{(s\pi)^4}{2} + 6\alpha(1-\nu^2)\left[\sum_{n=1}^{\infty} a_n^2(\tau)\frac{(n\pi)^2}{2}\right] a_s(\tau)\frac{(s\pi)^2}{2} + R_x a_s(\tau)\frac{(s\pi)^2}{2}$$
$$+ \frac{d^2 a_s(\tau)}{d\tau^2}\frac{1}{2} + \lambda\left\{\eta + \left(\frac{\mu}{M\lambda}\right)^{1/2}\frac{da_s(\tau)}{d\tau}\frac{1}{2}\right\} = P\left[\frac{-\cos(s\pi\xi)}{s\pi}\right]_0^1 \qquad (8)$$

The term:

$$\left[\frac{-\cos(s\pi\xi)}{s\pi}\right]_0^1 = \left[\frac{-\cos(s\pi\xi)}{s\pi}\right]_1^0 = \frac{\cos 0}{s\pi} - \frac{\cos s\pi}{s\pi} = \frac{1-(-1)^s}{s\pi}$$

The term η :

$$\eta = \int_0^1 \sum_{m=1}^{\infty} a_m(\tau)(m\pi)\, cos(m\pi\xi)\, sin(s\pi\xi)\, d\xi$$

We know that:

$$\sin A \cos B = \frac{1}{2}[\sin(A-B) + \sin(A+B)]$$

$$cos(m\pi\xi)\, sin(s\pi\xi) = \frac{1}{2}[\sin(s\pi\xi - m\pi\xi) + \sin(s\pi\xi + m\pi\xi)]$$
$$= \frac{1}{2}\big[\sin\big((s-m)\pi\xi\big) + \sin\big((s+m)\pi\xi\big)\big]$$

$$\Rightarrow \eta = \sum_{m=1}^{\infty} a_m(\tau)\frac{m\pi}{2}\int_0^1 \{\sin[(s-m)\pi\xi] + \sin[(s+m)\pi\xi]\}\, d\xi$$
$$= \sum_{m=1}^{\infty} a_m(\tau)\frac{m\pi}{2}\left[\frac{-\cos[(s-m)\pi\xi]}{(s-m)\pi} - \frac{\cos[(s+m)\pi\xi]}{(s+m)\pi}\right|_0^1$$
$$= \sum_{m=1}^{\infty} a_m(\tau)\frac{m\pi}{2}\left[\frac{\cos(0)}{(s-m)\pi} + \frac{\cos(0)}{(s+m)\pi}\right.$$
$$\left. - \frac{\cos[(s-m)\pi]}{(s-m)\pi} - \frac{\cos[(s+m)\pi]}{(s+m)\pi}\right]$$
$$= \sum_{m=1}^{\infty} a_m(\tau)\frac{m}{2}\left[\frac{(s+m)+(s-m)}{(s^2-m^2)} - \frac{2s}{(s^2-m^2)}(-1)^{s+m}\right]$$

$$\eta = \sum_{m=1}^{\infty} a_m(\tau)\frac{sm}{s^2-m^2}[1-(-1)^{s+m}]$$

The term:

$$\left[\frac{\cos[(s-m)\pi]}{(s-m)\pi} - \frac{\cos[(s+m)\pi]}{(s+m)\pi}\right]$$

Using the trigonometric identities:

$$\cos(\alpha+\beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$$
$$\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$

The term becomes:

$$= -\left[\frac{\cos(\pi s)\cos(\pi m) + \sin(\pi s)\sin(\pi m)}{s - m} + \frac{\cos(\pi s)\cos(\pi m) - 0}{s + m}\right]$$

$$= -\left[\frac{(s + m)[\cos(\pi s)\cos(\pi m)] + (s - m)[\cos(\pi s)\cos(\pi m)]}{s^2 - m^2}\right]$$

$$= \frac{\cos(\pi s)\cos(\pi m)\,[s + m + s - m]}{s^2 - m^2} = -\frac{2s}{s^2 - m^2}(-1)^s(-1)^m$$

$$\left[\frac{\cos[(s - m)\pi]}{(s - m)\pi} - \frac{\cos[(s + m)\pi]}{(s + m)\pi}\right] = -\frac{2s}{s^2 - m^2}(-1)^{s+m}$$

By substituting the terms in the equation(8):

$$a_s(\tau)\frac{(s\pi)^4}{2} + 6\alpha(1 - \nu^2)\left[\sum_{n=1}^{\infty} a_n^2(\tau)\frac{(n\pi)^2}{2}\right]a_s(\tau)\frac{(s\pi)^2}{2} +$$

$$R_x a_s(\tau)\frac{(s\pi)^2}{2} + \frac{d^2 a_s(\tau)}{d\tau^2}\frac{1}{2} + \qquad (9)$$

$$\lambda\left\{\sum_{m=1}^{\infty} a_m(\tau)\frac{sm}{s^2 - m^2}[1 - (-1)^{s+m}] + \left(\frac{\mu}{M\lambda}\right)^{1/2}\frac{da_s(\tau)}{d\tau}\frac{1}{2}\right\} = P\frac{1 - (-1)^s}{s\pi}$$

APPENDIX D

DERIVATION OF THE EQUATION

OF MOTION

THE EQUATION OF MOTION FOR A TWO-DIMENSIONAL PLATE:

$$D\nabla^2\nabla^2\omega - \left[N_x\frac{\partial^2\omega}{\partial x^2} + N_y\frac{\partial^2\omega}{\partial x^2}\right] + \rho_m h\frac{\partial^2\omega}{\partial t^2} + \rho_m h\epsilon\frac{\partial\omega}{\partial t} + \overline{P}(x,y,t) = 0 \quad (1)$$

Where:

- $\omega(x,y,t)$ The plate deflection.
- N_x, N_y The plane tensile forces.
- ρ_m The material density.
- ϵ The damping coefficient.
- $\overline{P}(x,y,t)$ The component of the aerodynamic pressure caused by the deviation of the plate form its undisturbed state.

Since the plate is undergoing cylindrical bending the above equation reduces to:

$$D\nabla^2\nabla^2\omega - N_x\frac{\partial^2\omega}{\partial x^2} + \rho_m h\frac{\partial^2\omega}{\partial t^2} + \rho_m h\epsilon\frac{\partial\omega}{\partial t} + \overline{P}(x,t) = 0 \qquad (2)$$

From the result the Piston theory in paragraph **VI.3.1**, $\overline{P}$ is equal to the aerodynamic pressure loading only since it is assumed that is no pressure differential across the plate $(\Delta P = 0)$.

$$\therefore \overline{P} = p - p_\infty = \frac{P_\infty U}{a_s}\left[\frac{\gamma}{U}\frac{\partial\omega}{\partial t} + \frac{\partial\omega}{\partial x}\right] \qquad (3)$$

Where a_s here is the speed of sound.

$(3)\ in\ (2)$:

$$D\frac{\partial^4\omega}{\partial x^4} - N_x\frac{\partial^2\omega}{\partial x^2} + \rho_m h\frac{\partial^2\omega}{\partial t^2} + \rho_m h\epsilon\frac{\partial\omega}{\partial t} + \frac{P_\infty U}{a_s}\left[\frac{\gamma}{U}\frac{\partial\omega}{\partial t} + \frac{\partial\omega}{\partial x}\right] = 0$$

Where:

- D Plate flexural rigidity stiffness; $D = \frac{Eh^3}{12(1-\nu^2)}$

APPENDIX E

WORKSHOP

The competition was started in the summer of 2016 in the name "Algerian Competition in Aeronautic between Universities in Mechanical Engineering" with collaboration of Mr. Abdelkader KHERRAT, Senior Engineer at Bombardier Aeronautic Company Montreal, Canada. The University of Mohamed Khider Biskra is one of the eleventh Universities which are participated in this competition, our university represented by Al Jazzari Mechanical Science and Engineering Club (AMSEC) and the mechanical engineering department. The edition 2016/2017 of competition titled as "Study and Design of a Competition Rocket with Deployment system", organized in Blida University in 25 September 2017.

Figure E.1. I was working on the nose cone in milt machine.

Figure E.2. I Abdelhakim AISSAOUI and S. KHERRICH working rocket prototype fins.

Figure E.3. I'm and A. AISSAOUI holding aluminum rocket cone.

Figure E.4. Rocket prototype complete, from left to right: I'm, A. AISSAOUI and S. KHERRICH.

Figure E.5. The AMSEC-Rocket v.01 prototype.

الخلاصـــــة

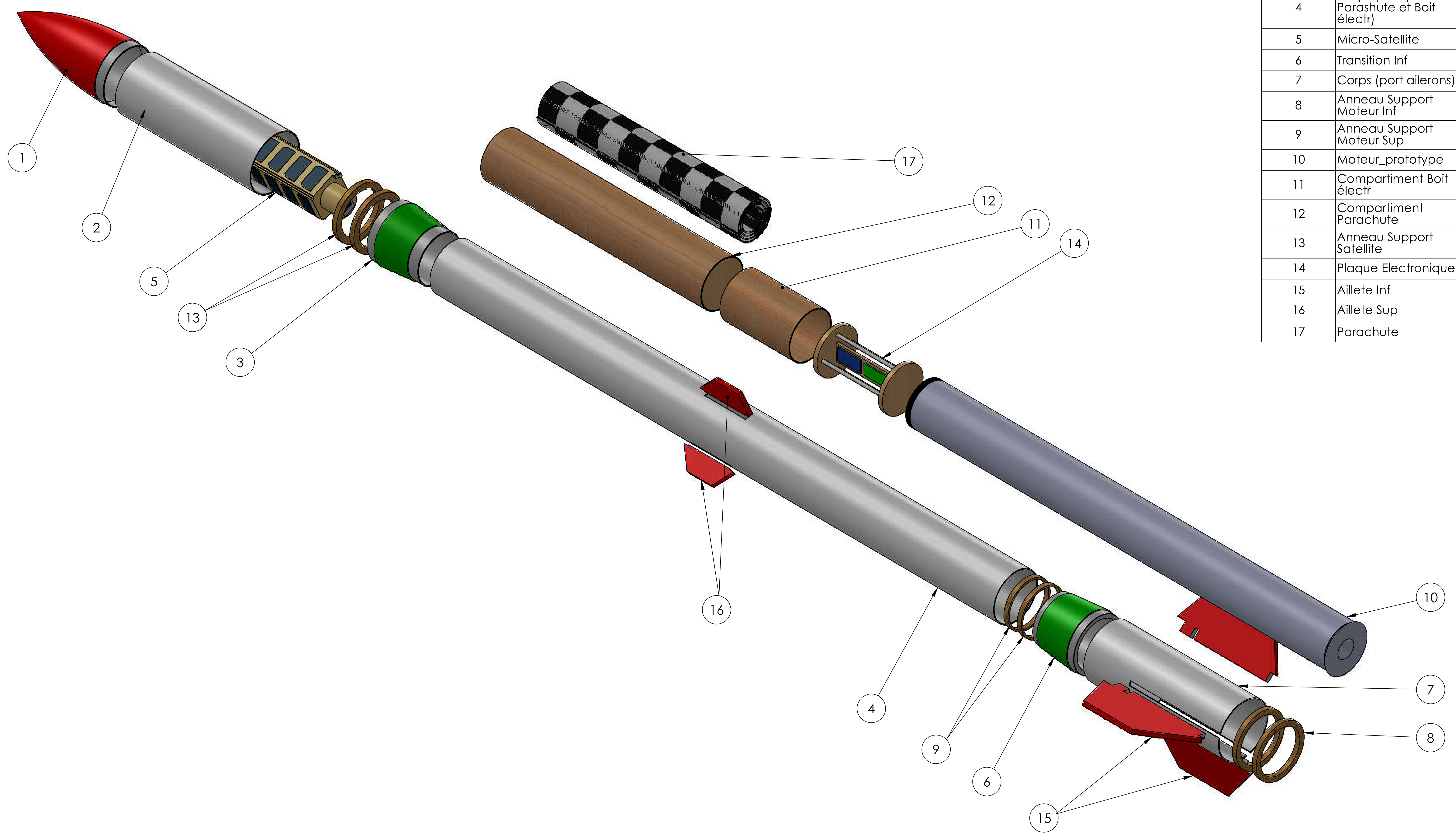
إن دراسة سلوك الصفاح موضوع ذو أهمية كبيرة في مجال الهندسة وعلوم الطيران كما أن دراسة هذا النوع من البنيات يشغل حيزا واسعا في حقل البحث العلمي. نتناول في هذا العمل دراسة للخصائص المرونية - الديناموهوائية للبنية الهيكلية لصاروخ للنموذج المعتمد **AMSEC-R v.01**، هذه الدراسة في أساسها تعتمد على التفاعل بين الوسطين المائع والصلب ومدى تأثيرها على البنية الهيكلية. تم نمذجة هذا التفاعل وتحليل السلوك الناتج بواسطة البرنامج **Ansys 14.5**، كما تم إستعمال برنامج في المحيط **Matlab** يمكننا من حل المعادلة الحاكمة وإستخراج الأنماط والإستجابات الممكنة لزعانف الصاروخ عند تفاعلها مع الهواء المحيط وذلك في مجال السرعات **[410, 440, 490, 520, 570] = *V*** وتمت مقارنتها مع تلك المتحصل عليها باستعمال البرنامج **Ansys**.

ABSTRACT

The study of the behavior of the plates is a subject of great importance in the field of engineering and aeronautical sciences, and the study of this type of structures occupies a large space in the field of scientific research. In this study we deal with the Aeroelastic properties of a rocket structure of the AMSEC-R v.01 model. This study is based on the interaction between fluid and solid mediums and their effect on the structure. This interaction and behavior analysis was modeled by Ansys v.14.5, and a Matlab program was used to solve the ruling equation and extract patterns and possible responses to the rocket's fins when interacting with ambient air in the velocity range V = [410, 410, 490, 520, 570], compared with those obtained using the Ansys software.

RESUME

L'étude du comportement des plaques est un sujet d'un grande importance dans le domaine de l'ingénieur et sciences aeronautique, l'étude de ce type de structures est bien placées dans le domaine de la recherche scientifique. Cette mémoire traite les propriétés aéroélastiques d'une structure de fusée d'un modèle AMSEC-R v.01, cette étude dépend essentiellement de l'interaction entre les deux milieux fluide et solide et son impact sur la structure. La modélisation de cette interaction et l'analyse du comportement fait avec le logiciel ANSYS v.14.5, comme cela a été l'utilisation des programmes dans l'environnement Matlab, nous pouvons résoudre l'équation régissant et l'extraction des modes et les réponses possibles à ailettes de la fusée quand ils interagissent avec l'air ambiant dans le domaine des vitesses V = [410 440 490 520 570] et comparés avec les résultats obtenue par ANSYS.



No. ARTICLE	NUMERO DE PIECE	QTE
1	Ogive	1
2	Corps (compartiment Satellite)	1
3	Transition Sup	1
4	Corps (compartiment Parashute et Boit électr)	1
5	Micro-Satellite	1
6	Transition Inf	1
7	Corps (port ailerons)	1
8	Anneau Support Moteur Inf	2
9	Anneau Support Moteur Sup	2
10	Moteur_prototype	1
11	Compartiment Boit électr	1
12	Compartiment Parachute	1
13	Anneau Support Satellite	2
14	Plaque Electronique	1
15	Aillete Inf	3
16	Aillete Sup	3
17	Parachute	1

NOM SIGNATURE DATE
AUTEUR AMSEC 06/01/2017
VERIF.
APPR.
FAB.
QUAL.
MATERIAU:
MASSE:
TITRE:
AMSEC-R v.01
No. DE PLAN
A2
ECHELLE: 1:5
FEUILLE 1 SUR 1