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# AGING SYSTEMS IN AERONAUTICS AND SPACE DAMAGE TOLERANCE IN HELICOPTERS

Paolo Santini

A Keynote Lecture

Spring 1999 Meeting on Aging Systems

North Atlantic Treaty Organization

Applied Vehicle Technology Panel

Corfu, Greece, April 1999

## 1 INTRODUCTION

The aim of this keynote lecture should be that of introducing the main (or, at least, the common) features of the papers that will be presented during the Workshops that will take place in Corfu this week: Aging Aeronautical Systems, Life Extension for Helicopters, Propulsion and Gas Generators for aerospace vehicles.

A keynote lecture may be given in several ways. The most obvious form is probably an overview of the subjects that are to be discussed, trying to connect them together, so as to prepare the audience to a more detailed knowledge of them. However, in this way one runs the risk of saying something that will be repeated much better by the specific Authors, (and, often in a much poorer way than the Authors themselves), also because the time is in general very short.

Another way is to address and illustrate forth-

coming needs and future trends in the area of interest: for this kind of presentation it would be necessary to be able to predict the future, because it happens very often that the future is not so smooth as everybody may imagine at the time of the lecture, and so, after a few years, or even a few months, needs and trends are completely different: a good example is the continuous series of war actions in the Balkans and in the Middle East, that may have a strong impact on the policy of the aeronautical production.

I have chosen another approach. When AGARD was established, I had the chance to take part in the first meeting in 1952, and I can well remember the great expectations resting on the new structure. I then followed AGARD throughout the decades, attending many meetings of the Structures and Materials Panel, until I became Panel Member in 1975 and, eventually, Panel Chairman during the period 1986-1988.

I think therefore that it might be of some interest to look to the past, in order to trace back the historical development that led from the early scope of AGARD to the current situation.

## 2 THE HISTORICAL ROLE OF THE TECHNOLOGY

In order to understand clearly the development of AGARD we must before all else try to recall some general circumstances, summarizing them in two axioms.

The first axiom is that HISTORY IS DRIVEN BY TECHNOLOGY. This stems from two historical facts. First of all, political supremacy is retained by the States and by the political entities having a technological superiority with respect to other groups.

There are several examples of this in history. The Hittites of Asia Minor were a very small nation, but they were subjugating and overwhelming some much greater political groups, since they were able to master iron metallurgy, so that their carts were definitely superior to those of other surrounding populations. According to some historians, the military superiority of the Spartans was in part due to the fact that the waters of their rivers were colder than those of other regions of Greece, so that their quenching gave better manufactures. The Romans had a very efficient technology, in particular in civil engineering; they were first-class bridges and roads constructors, so their transportation systems was exceptionally well orga-

nized and allowed them rapid strategic movements of great armies. More recently Germany had a great advantage over the Allied Forces at the beginning of the war, and when the technological supremacy passed on the other side, Germany lost the war. And from this we learn a lesson: technology is not only a matter of scientific advance, but also of capability of mass production and of organization.

However the effect of technology on history is not confined to military superiority only. Its effect upon the quality of life is even more evident. Again here we have several examples. The so-called neolithic revolution, producing a much improved technology of stone artifacts, caused better methods for the stone-age man to acquire food, to cook it, to have better shelters, whose consequence was a lengthening of the average life expectation. Some historians consider the replacement of the double rigid yoke by the single flexible yoke in the Middle Age as a very important technological advance: as a matter of fact, it caused an increase of agricultural efficiency by a factor of 3 to 5.

There is no need to emphasize the scientific and technological discoveries of the Renaissance, or the tremendous progress that created a completely new world in the 19.th century in the wake of the Industrial Revolution. And what about present times where we have a continuous increase not only of technological progress but of its rate of growth. We live today in a way which is completely different from what it was fifty, forty, and even thirty years ago: long trips are possible almost for everybody, every

family has one or two cars, TV and radio keep us informed in real time of the most extraordinary events: ladies at the age of 50-60 years are still charming (due to the much reduced work at home caused by modern appliances), and so on.

The second axiom is : TECHNOLOGY IS NOT CULTURE. By no means do I mean that the level of Technology is lower, but simply that Technology and Culture are two different expressions of the human imagination, and must be treated and considered differently. Culture is a free expression of what the mankind feels, either by reaction to the external world, or through an internal elaboration: the best examples for the latter being music (whatever music) and mathematics. Neither stem from external stimuli.

By contrast, technology cannot be free; it stems from human needs although in many cases industry creates those needs and imposes them: fifty years ago, nobody missed TV broadcasting, today nobody could live without it.

Technology is not applied science, but an application of science, which is culture. That is the difference and there is a continuous transformation moving from science to technology: a vivid example is provided by the history of space-flight, synthetized by this sequel: Tsiolkowsky, Oberth, Goddard, von Braun.

### 3 THE DEVELOPMENT OF AGARD

AGARD seems to have been well aware of, and to have applied, the two axioms above.

In 1949, in connection with the 'warmest' period of the 'cold' war, NATO was founded (called at that time the Atlantic Pact) with a declared feature of military deterrent as a reaction to the increasing armament of the Eastern Block. The first axiom was immediately clear to the top men of the Western World; and, of course, one of the main concerns was relevant to Aeronautics (Space at that time was almost unknown). For this reason, some of the top scientists of the NATO countries were asked to meet and to propose which kind of organization would have been most adequate to improve the level of research and of technology in the aeronautical field in western country.

There was a large meeting in Rome at the end of 1952, attended by a great number of scientists; among them probably the most outstanding one was Theodore von Karman, a man of great scientific prestige and great cultural level. A typical mitteleuropean gentleman, he was the Chairman of the Meeting. I am proud to say: I was there, and I took part, although unofficially, in the foundation of AGARD. During those days, I had the opportunity to talk several times with Karman; especially at lunchtime we often sat together with Professor Broglio, my mentor, and Karman illustrated us his ideas on what the new organization should have been like. In industry at that time there was very lit-

the research, also because the requirements were not so stringent as today: and he thought that a field such as aeronautics, in order to be competitive, should have been fed by science, by culture. In thinking so, he applied the second Axiom.

Theodor von Karman was a volcano: every time we met he came out with new ideas. I saw him personally drawing on a blackboard the word AGARDograph: he drew up a first draft of the future organization; he also chose the men who should have been the leaders of AGARD, and most of them were scientists or University Professors. Let me remember just some of them: Frank Malina, Frank Wattendorff, Luigi Broglio. Antonio Ferri. Karman transferred the same imagination to the other bodies he created in subsequent years and which are still in existence and flourishing: ICAS (International Council for Aeronautical Sciences), IAF (International Astronautical Federation), IAA (International Academy for Astronautics).

The following year AGARD was formally established and the first Panels were formed. I remember the early steps of SMP, in 1955 with Broglio as Chairman, and four members only; among them was Thurston, recently dead. A great number of Members of the Panels came from the Universities, and brought their University mental attitude into the activities which were being proposed.

Thus the birth of AGARD was, in agreement with Karman's ideas, almost an academic institution, where basic research had a very important role. The 50's and the 60's saw a terrific de-

velopment of the basic sciences of Aeronautics, and the beginning of the attention for Space. I will give just some examples. In 1957 there was a famous Meeting of SMP in Copenhagen where the foundations of modern structural dynamics were laid down. In 1960 a Meeting of the same SMP in Rome was one of the first Meetings dealing with the effect of kinetic heating upon structures, with special attention to reentry: and it should be remembered that we were in the very era of space challenge between USA and URSS, with the latter well ahead of the former. And, again, a basic step in Fluidodynamics was the famous meeting of FDP in Scheveningen, Netherlands, with the first results and methodologies in hypersonics, again with an eye to Space; of particular interest were the discussions and the forecast for future high speed experimental facilities. And let me also remember the wonderful results in the field of Aeroelasticity, an activity that lasted for decades, and that became a kind of permanent institution in SMP: and the great cooperative effort in this area, with the contribution of all the Nations under the leadership of giants such as Ashley, Kussner, Mazet; the discussions among them became a kind of social event!

I was appointed an official Member of SMP in 1975, and since then I took an active role in proposing activities: I must say that AGARD was for me an invaluable vehicle of contacting outstanding personalities in the aeronautical world. Also, my Department and my University took advantage, at a large extent, from the exchange of ideas and of personnel through

the Support Program which I believe was very beneficial not only to the supported nations but to the supporting nations as well.

However I noticed that the twenty years elapsed since the establishment of AGARD had basically changed the objectives and the general frame. Most of the Panel Members came from industry or from Air Force, and the subjects of investigations had gradually shifted towards applications: or, if you wish, towards Technology or Engineering. I consider that a very positive circumstance, since people like me were put directly in contact with the realities of the world of production. At every Meeting I learned a lesson; and I hope that some of my colleagues of the Panel also learned something from me.

I proposed several activities in SMP, also gradually shifted from science to Technology. Not everything, of course, was quite satisfactory: one of my criticisms concerned the fact that an Aero-Space Panel had very minor Space Activities. This was true also of other Panels. I was invited once to chair a session in a meeting of FMP centered on Space Flight and I was surprised to discover that the subjects were not as up-to-date as I would have thought.

As a Panel Deputy Chairman I was for two years the Chairman of the Program Committee, and thus I had the opportunity to have a clearcut idea on what the general trend was, with an increasing shift towards more and more applied technology. F.i., I was rather surprised when a subject like 'Painting Removal' was proposed. Now I am well convinced that Painting Removal is of prime importance in every-

day aviation practice. This is an example of what I believe was the invaluable contribution of AGARD.

In today's world much progress has been made in the past to improve our products. Now we also have another need: preserve what we have acquired, avoiding wast. AGARD and, subsequently, RTA have followed such requirement; this is the reason for the present Meeting on aging aircraft.

#### 4 AGING AIRCRAFT

The age of the current aeronautical fleet can best be appreciated by referring to statistical value. Most of them refer to US data, which are probably the most updated and complete. In 1997, 46% of the commercial aircraft were over 17 years of age, 28% over 20 years: the average age for the major companies is reported in Tab.I (from Ref.1).

TAB:I

Airline	Average Aircraft Age (years)
Alaska	7.6
American	10.0
American West	11.0
Continental	14.4
Delta	12.2
Northwest	19.9
Southwest	8.8
TWA	17.0

United	10.8
US Airways	12.8

The expectations for the near future are of an increase of 70% in the next ten years, with a total of 12,000 new airliners to meet the demand in 2015, for a typical design life of 60,000 cycles. Probably already in 2001 2,500 US commercial airliners will be flying beyond the original life span.

The definition of 'aged' or 'aging' structure and/or system would need a clear definition, which, on the contrary, is rather vague. We report, (from Ref.2) two definitions as provided by ESA: Aged Structure - A structure which may have structural degradation or damage as the result of being exposed to the combined effects of the environment.

Aging - The process of the effect t on materials of exposure to an environment (elevated temperature, ultraviolet radiation, moisture or other hostile environment) for a period of time. The problem of aging aircraft has attracted the attention of civil and military authorities since more than a decade. In general, the attention and the need for new studies are prompted by some spectacular accidents, which have a strong impact on the public opinion.

In 1988 a Boeing 737 of the Aloha Airlines, 19 ys.old, suffered from an accident caused by a fatigue failure in a panel of the fuselage: a flight attendant was killed, and 171 passengers were injured. This accident was almost immediately followed by an action from FAA who established the NAAR (National Aging Aircraft Research).

In 1996 another most famous accident occurred with the flight 800 TWA: the airplane was a Boeing 747, 25 years old, 90000 flight hours, 18000 cycles, vs.the original design life of 60,000 hours, and 20,000 cycles (Ref.(1)). In this case the cause was attributed to an electrical malfunction followed by a spark in the fuel compartment. This was followed by a five year project to investigate and check nonstructural parts of the airplanes, such as wiring, hydraulics, avionics, etc. Especially wiring seems to need careful maintenance and inspections (almost zero until few years ago). Now in a commercial airplane there are miles and miles of wires and careful and systematic inspections may cost several million dollars to a Company. Yet they are necessary.

On the other hand, it must be recognized that maintaining old aircraft in service is a definitely positive factor from an economic viewpoint; f.i., the current cost of an Airbus 300 would be of the order of 100 million dollars, while refurbishing an old airplane of a comparable capacity could only cost 4 to 5 million dollars.

Very similar problems apply to military fleets also. F.i., the United States Air Force has many old (20 to 35 years) aircraft that are the backbone of the total operational force, some of which will be retired and replaced with new aircraft. However, for the most part, replacements are a number of years away: for many aircraft, no replacements are planned and many are expected to remain in service for another 25 years or more. Such aircraft have encountered or are considered likely to encounter aging problems,

such as fatigue cracking, stress corrosion cracking, corrosion and wear.

For these reasons, Committees and Working Groups were formed within the Air Force scientific framework, with the following objectives: (i) Identify and correct structural deterioration that could threaten aircraft safety; (ii) prevent and minimize structural deterioration that could become an excessive economic burden or could adversely affect force readiness, in terms of performances; (iii) predict, for the purpose of future force planning, when the maintenance burden will become so high or the aircraft availability so poor that it will no longer be viable to retain the aircraft in the inventory.

The Committee arrived at Near Term and Long - Term Research Recommendations, and produced a rather lengthy list of items to address the attention to. This list can be found in Ref.(3) (it would be too long to reproduce it here): looking at it, we can see that there is room not only for technology, but also for basic research, and for items that are prone to be completely re-invented.

It is very instructive to have a look at the items of the list. First of all we have the confirmation of the prime role of corrosion in defining the lifetime of an airplane. This well known to everybody, except perhaps for the 'size' of this role. As a matter of fact, corrosion is a social problem : it costs about 100 billions USD per year to United States, almost 300 dollars per citizen. And USAF is responsible for about 10% of this figure. Furthermore we see other fields to which, in my opinion, insufficient attention

has hitherto been given by fatigue people, such as structural dynamics and dynamic response.

But it must be a completely new structural dynamics, not based on the conventional analytical methods, eigenfrequencies and modes, but rather on the need of predicting stress concentrations arising from dynamic effects and following cracks under dynamic conditions. I am sorry for not being able to illustrate other important suggestions that can be derived from the list for lack of space.

But the subject of aging aircraft is so important that there is a sure need in the future of specialized technical staff in this area. Appropriate courses of formation have been designed, with the aim of providing the attendees with the necessary knowledge: an example is given in Ref.(4-5). Specialists in aging airplanes will become in the future a new professional profile.

## 5 DAMAGE TOLERANCE ISSUES

The life of a structural component is limited by the effects of its usage history, which may consist of cyclic loads, fluctuations in temperature, etc. In the past, and also today, several design philosophies have been introduced into current practice, and among them damage tolerance has probably become one of the most prominent in aircraft industry (Ref.(6)).

I shall not dare to give a general overview on what damage tolerance concept is. I just will confine myself to recall - or try to imagine- why

there is a special need to treat damage tolerance as applied to helicopters in a very special way. As said, the life of a structural component depends on its usage, which varies from one type of flying machine to another. There is however a general agreement that critically loaded components such as engine rotors or landing gears can have shorter replacement intervals. In any case, the usage profile must describe the various flight conditions, and the amount of time spent at each gross weight, speed, and altitude, which define the load factor spectrum, and subsequently dictate the inspection intervals.

There is no need to illustrate how much the environmental spectra for an helicopter is different from that of an airplane. Considerable effort is needed on loads generation, and determination of material data. Also, this is a field where theoretical investigation must also be accompanied by experimental data.

Let me clarify this concept in some detail. In the past there has always been a dichotomy: theory vs. experiments, the former being looked at rather suspiciously. The two activities were almost independent of each other, and the optimum was reached when there was a satisfactory (not always well-defined) agreement between the two results. With the advent of computers, 'theory' has been replaced by 'mathematical model' and everybody is happy, but the dichotomy has not yet been fully overcome. It is my opinion that the two activities must be viewed not from the point of 'mutual check' but from that of 'mutual integration'. Experimental data for a specific problem or design must

supplement mathematical models, providing information that no theory whatever can provide : theory must provide detailed information that no experiment can provide. Although the last statement is more difficult to accept, there are several examples validating it (e.g., in Fluid Dynamics).

And again, I must say, damage tolerance in helicopters is a good example on how increasing industrial needs stimulate basic research.

## 6 PROPULSION

I am not an expert in Propulsion: I am simply an admirer of it. I have already mentioned the names of the pioneers of Spaceflight, which is one of the top conquests of man : for all of them Spaceflight was identical with Propulsion. And, as a matter of fact, space activities only became possible when sufficient thrust was made available to scientists. This is very often, not to say too often, forgotten today.

Most recently, because of economic problems, as happens more and more frequently today, the subject of small rocket motors has become increasingly popular. In this Symposium attention is focused on the specific goals of NATO and on the relevant applications. All the main features of the problems are examined with respect to weapon systems. And here a further remark is appropriate: in the history of technological development, military applications have very often led the way to a more general use of the progress achieved. My hope and my message is that this will be the case also for this

Conference.

## 7 CONCLUSION

We have two main conclusions to draw. The first that we are at an era in which we rediscover a new feature of Technology: the Technology of restoring, refurbishing, reusing the system created by the human imagination in the recent past. Second, that such operations of re-whatever we must use Science and Culture again, although in a different (and probably more advanced) way than in the past.

Paolo Santini

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