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Guided Missile Engineering

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PREFACE

The drama of the guided missiles age, the day of push-button warfare, and the anticipated advent of flights into outer space are today matters of intense interest to layman and technical man alike. With this is an atmosphere of mystery and magic, and a general suggestion that there is something new and peculiar about the art of designing guided missiles.

Many of the problems are indeed new—but perhaps more are old problems presented in new form and different combination. To a considerable degree, the art of guided missile engineering requires the simultaneous and compatible solution of problems in aerodynamics, structures, propulsion, electronics, instrumentation, and other related fields. The interaction between these various problems, the search for compromise and balance between the design of components and the design of the whole, is often more complex than the particular problems in the individual technical areas.

Recognition of this has led to the concept of "system engineering"—the emphasis on optimizing the whole rather than the parts. This badly overworked terminology really describes nothing new—such an approach has always been the essence of good engineering. However, the advanced state of the arts involved in guided missiles, and the increasing and probably unavoidable trend towards specialization within these arts, has focused special attention on the need for an integrated "system" approach to design.

Thus we require the ability, on the part of modern guided missile engineers, to understand not only the problems in the field in which they may have specialized, but to some degree the problems in all other areas relating to the over-all performance of the device. We require engineers with the ability to make rational compromises between the conflicting requirements of the elements of a missile system, and to measure these compromises by the effectiveness of the over-all result.

We do not mean to decry the specialist and the expert in the various arts and sciences concerned. It is certainly all the more important to ensure that all the possibilities offered in each area are explored to the fullest, to the limits permitted by current science and knowledge, and often beyond. We must not fall into the trap of depending for design decision only upon a little knowledge of many things, with no penetrating understanding of any one. At the same time we suggest that the contribution of each expert will be increased in proportion to his appreciation and general understanding of problems in neighboring sciences.

It is from such considerations that this book has been generated. The chapters represent a group of review or survey discussions of a number of the sciences that are important in all types of guided missile design today. The attempt has been to present the basic elements of these sciences, with particular emphasis on those aspects which bear on guided missile design. The various chapters are directed at the engineer or scientist who may have considerable skill in some other particular field, and good general technical background, but little familiarity with the subject in question. They are specifically not directed at the specialist or engineer whose principal activity or training has been in the field concerned.

Above all, the chapters are not intended to constitute a handbook of guided missile design. It was not intended to present the type of detailed, ever-changing design information that must be used every day by the practicing engineer. Rather it is hoped that the surveys of the various fields will assist each engineer in appreciating the nature of the problems encountered by his collaborators, and provide him with a better basis for the profitable discussion of mutual or interacting problems.

The expert must continue to rely on the extensive technical literature currently available to support detailed efforts in his own field. It is hoped, however, that the surveys contained in this book will provide him with easier access to the basic elements of arts other than his own. If he is aided in this purpose, we feel that the principal aim of the book will have been accomplished.

Allen E. Puckett
Simon Ramo

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THE GUIDED MISSILE SYSTEM AND ITS COMPONENTS

Ralph P. Johnson

1-1. INTRODUCTION

A guided missile, like any other aerial vehicle, is a thing that leaves a launching point and is expected sometime later to arrive at or passably near a target point. Depending on the location of the launching and target points, four cases are usually distinguished: surface-to-surface, air-to-surface, surface-to-air, and air-to-air.

Guidance is needed when a vehicle has to be brought to its target point with high precision. An unguided projectile such as an arrow or an artillery shell, once aimed and launched, follows a course that may be in error because of imperfect aim, random misbehavior of the vehicle, or unpredicted motion of the target point. With guidance, the error between the actual course and the desired course is observed while the vehicle is in transit, and this error information is used to correct the actual course.

In a manned vehicle the human pilot is the central element of the guidance system. In a guided missile the functions of the pilot are performed by inanimate devices. The missile is therefore free from those limitations as to size, weight, tolerable acceleration, expendability, and the like which the presence of a human pilot would impose. On the other hand, certain characteristics which a human pilot can easily provide, such as versatility, judgment, and acute visual perception, are not easily provided in an inanimate guidance system.

The unique problems of guided missile engineering are chiefly the problems of the guidance system itself. However, a successful guided missile is not made merely by adding guidance devices to an unguided projectile or by replacing the pilot of a manned vehicle with a collection of inanimate parts. A guided missile is not, strictly speaking, either a "guided projectile" or a "pilotless aircraft." The presence of the guidance system allows and requires that other components of the missile be specifically designed. These other components affect the guidance so intimately that the missile system as a whole, and not the components separately, has to be optimized. Although it is convenient for discussion purposes and necessary in organizing for the actual development of a guided missile to divide the missile into its major components and parcel these out for handling by experts in the particular fields, the most difficult part of the engineering is concerned with the interactions among the components.

1-2. PROPULSION

All the standard propulsion devices are available to the guided missile engineer. Depending on the requirements, he may choose propellers, turbojets, ramjets, rockets, or free fall under gravity. The absence of a human pilot allows him to consider higher accelerations than would be tolerable for a manned vehicle. Where air cannot be used as a working substance and a source of oxygen, some sort of rocket is required. Otherwise, the choice is governed by systems considerations, including (usually) the economic consideration that the missile is to be expended in a single flight.

1-3. AERODYNAMICS

To outrun a moving target or to close rapidly with a defended target, the missile needs to travel fast. Supersonic speeds are the rule. For low drag at high speed, a needle-shaped missile with very thin wings is best. The ideal aerodynamic shape has to be compromised, in the practical case, to allow, for example, exit for a propulsive gas jet at the rear. All such compromises have to be skillfully made if the missile is to be kept usefully small and light.

The missile should fly stably through the air. Weathercock stability is achieved by making the center of gravity fall forward of the center of pressure. System stability can, of course, be achieved entirely by the automatic control system, without requiring any particular degree of aerodynamic stability. The stability must not be overdone, however, for the missile must be responsive to the sidewise forces that are generated by the steering signals. All the internal components of the missile must be so distributed, weightwise, as to make the center of gravity come where it is wanted, giving the missile near-neutral stability.

Steering is usually done by control surfaces, as in a manned airplane. These control surfaces act upon an airflow that has been violently disturbed by the passage of the more forward parts of the missile. It is a difficult aerodynamic problem to assure that they will do the desired steering, predictably, in the presence of these interfering flows.

1-4. STRUCTURE

High strength with low weight is the aim of the structures engineer. In supersonic flight the missile heats the adjacent air to a high temperature. It is desirable to keep the heat from soaking into the missile until after the important part of the flight is finished. Insulation being imperfect, the strength of the structural materials at high temperatures is a critical consideration. In any case, the safety factor is to be kept low. It is not economical, from the systems viewpoint, to carry along in every missile enough weight of structural material to be very sure that no missile will ever break up in flight.

1-5. GUIDANCE AND CONTROL

Although the dividing line is somewhat artificial, it is occasionally useful to distinguish between the *guidance system*, which observes the error between the actual course and the desired course and generates the signal calling for course corrections, and the *steering system*, or *control system*, which responds to these signals and generates the lateral forces that turn the missile to a new direction of flight.

The steering is accomplished relatively easily if the desired course between launching point and target point is a course that the missile would naturally take, except for random errors, if it were unguided. The steering system then needs to provide only the small forces that will correct small, random errors in course. On the other hand, some desired course other than the natural course may ease the problem for the guidance system, which has to observe the error between the actual course and the course desired. For example, while the natural course for a short-range missile flying in the earth's gravitational field is curved downward, a straight-line course between the same two points would be easier for a guidance system to use as the norm, although harder for the steering system to follow. As elsewhere in missile engineering, a compromise between the conflicting requirements of simple guidance and easy steering has to be worked out so as to optimize the missile system as a whole.

For the mid-course guidance of a long-range surface-to-surface missile flying at a constant altitude, the guidance system can reasonably be patterned around means that a human navigator and pilot would employ.

Maps, stars, compasses, air logs, and such navigational aids as loran can be used. In a manned vehicle, information needed for guidance can be derived from several such sources, as the circumstances permit, and can be intercompared to yield most reliable estimates of present position and course. In a guided missile, contrastingly, this flexibility and redundancy are usually luxuries; a choice of a single basic guidance system has to be made very early in the design.

For a short-range missile, where target, missile, and launching point are all on the same side of the horizon throughout the flight, the guidance problem is obviously quite different. Several approaches are possible in principle. The errors in course may be observed with equipment remaining at the launching point, the missile needing then to carry only equipment to receive and obey transmitted steering commands. Alternatively, the straight-line path from launching point to target can be marked out by some kind of beam; the missile must then be able to recognize when it is straying from the axis of the beam and return itself to this axis. A more self-sufficient missile will be able to recognize the target in contrast to its background and derive from its own observations of target position the guidance information that it needs for bringing itself to a collision with the target. The target may be distinguishable from the background because it emits energy in a distinctive form to which the missile is sensitive or because it scatters in a distinctive fashion, recognizable by the missile, energy coming to it either from the missile itself or from some other source.

1-6. SYSTEMS PROBLEMS

In the development of a missile system, experts must be working on each component, trying to make that component do its assigned task with just as little weight, space, power, and cost as possible and yet with enough reliability for the purpose. The success of this effort, with a particular component, cannot be predicted with certainty. On the other hand, the specifications for each component are determined, not by any absolute requirement, but by the requirement that it be compatible finally with all the other components as they emerge from their own development efforts. It is necessary at the outset to estimate what advances over present art can be made by each component, with the time and the talents that are available, and to design the system to contain these components that have not yet been realized and, in fact, may never be realized. It is equally necessary, as the development proceeds, to keep modifying the design of the over-all system and keep changing the detailed specifications for each component so as to get along with components that have not progressed as well as had been hoped and so as to exploit favorable findings that had not been foreseen.

This kind of development activity needs high competence in the engineering of the particular components. It needs also imagination, engineering judgment, and a willingness to take risks in predicting how untried ideas will actually turn out. Most important, the development team has to be so organized and so led that all parts of the team are working, at any one time, on the same missile system.

2
AERODYNAMICS OF GUIDED MISSILES

Allen E. Puckett

2-1. SURVEY OF THE FIELD

Perhaps the only distinguishing characteristic possessed in common by the class of vehicles which we call missiles is that they fly through the air—or at least above the surface of the earth and therefore in part through the air. To some extent, then, an important part of the force system acting on the missile is created by the flow of air over it. The basic business of aerodynamics is the calculation or prediction of the forces caused by a specified motion of a body through the air. These forces are required to predict the motion or trajectory of the missile; they are also required to predict the details of the motion and to devise means for controlling it. They are further required to design the structure of the missile.

As a matter of practical fact, the aerodynamicist is also often concerned with the calculation of the motion of the missile, which determines the air forces as well as being in part determined by them. He may become concerned with stability problems and responses to control forces. He may be concerned with the deflections of an elastic airframe under air loads, which in turn affect the air loads. He may be required to calculate the interaction between the performance of a propulsion system and the airflow over and into a missile.

In other words, although the aerodynamicist is in principle concerned only with the calculation of aerodynamic forces, he is often required to make considerable excursions into related areas because of the interaction between the production of these forces and other elastic or dynamic aspects of the system, and the boundaries of the problems included in practical aerodynamics become quite fuzzy. This fuzziness has always existed to a certain extent in conventional aircraft aerodynamics. It becomes even more evident in guided missile problems because of the wide variation in the characteristics of missile control systems and the strong dependence of aerodynamic requirements upon these characteristics.

Guided missiles can be divided into types and classes in many ways. For convenience here we shall use a breakdown according to the types of performance problems which tend to be critical and which therefore determine the principal aerodynamic problems.

First are the "short-range" antiaircraft missiles, both surface-to-air and air-to-air. It will be shown later that the short range can be defined in terms of a dimensionless variable, but for practical purposes here we mean generally 1 or 2 to 20 or 30 miles' range. For these missiles both speed and maneuverability must evidently be in the same range as or greater than that of the target aircraft. At present, generally speaking, this means supersonic speeds of the order of 1,000 to 3,000 or 4,000 fps and maneuverability of 3 to 15 g. Clearly the primary aerodynamic problems are very rapid and accurate control and ability to achieve high maneuver load factors. Low drag and power-plant efficiency are generally of secondary importance.

A related class is the short-range ground-target missile, which usually differs primarily only in that its speed and maneuverability need not be so high. In both these cases, however, the energy required for propulsion is relatively low while the energy required for control is relatively high, so that design of a very efficient control system becomes extremely important. Structural design criteria are likely to be associated primarily with maneuvering loads.

Next are the medium-range cruising missiles, either ground or air target. By "cruising" we mean that an appreciable portion of the flight is at nearly constant altitude in the atmosphere. For these, essentially by definition, low drag and high ratio of aerodynamic lift to drag become important. In this range category, which may cover one hundred to several hundred miles, small miss at the target may also be required, in which case maneuverability and control response are also important. Structural design criteria may arise from either air loads due to gusts or maneuvering loads or both.

In another category are the long-range cruising missiles, covering several hundred to several thousand miles. Minimum drag and maximum lift-to-drag ratio now become the primary aerodynamic design criteria. Careful integration of the aerodynamic design with the power-plant design and installation becomes an essential requirement. The long range means that the ratio of fuel weight to structural weight will be large, which places extreme emphasis on very light structure and therefore increases the importance of the interaction of elastic deflections and air forces, or aeroelastic effects.

In another category are the ballistic missiles: short, medium, and long range. To a first approximation they follow trajectories determined primarily by initial velocity and gravity. Generally speaking, then, both low drag and aerodynamic control are of less importance—the longer the range, the less important. It will be seen later that the longer ranges require extremely high velocities, and because range is approximately proportional to velocity squared, even the medium ranges require very high velocity. A primary aerodynamic problem then enters in the heating due to friction with the atmosphere. Again, because of the low required structure to gross weight ratio, aeroelastic effects may dominate the structural picture.

All the design problems occurring in the above categories may be subdivided to some extent according to speed ranges. As we shall see later, the speed of sound in air, approximately 1,000 to 1,100 fps, is a crucial parameter. At near-sonic speeds, say from 0.8 to 1.2 times the speed of sound, which roughly speaking is often called the transonic range, the effect of the compressibility of the air first becomes important. This region is characterized by the very rapid appearance of compressibility effects, by high rates of change of aerodynamic parameters with speed, and therefore by difficulties with control. Because of these high rates of change, often associated with nonsteady phenomena, this region is particularly characterized by the difficulties in analytical prediction and experimental measurement of many aerodynamic parameters.

At low supersonic speeds the large drag associated with the formation of waves in the air has become important. At the higher supersonic speeds, say greater than three or four times the speed of sound, the effects of aerodynamic heating are likely to receive major attention.

A further crude subdivision of problems can be made in terms of altitude. At low altitudes, in relatively dense air, the molecular mean free path is generally so short compared with other dimensions in the problem that the air can be treated as a continuum. Although this characteristic can be defined more analytically in terms of appropriate dimensionless parameters, this will turn out to be generally true at altitudes less than 200,000 to 250,000 ft. At very high altitudes, say above 250,000 ft, the mean free path is so large that the air begins to behave more like a collection of independent molecules with certain distributions of velocities. It will turn out that the aerodynamic forces and heating effects in this region are essentially negligible except for a missile that will operate for a very long time in that range, such as a missile orbiting about the earth. Usually, however, aerodynamic effects are unimportant at altitudes greater than 150,000 ft; at this point the air density is down to approximately 0.13 per cent of its sea-level value.

2-2. METHODS OF APPROACH

The physical laws which determine the motion of air are fairly well understood in most important problems, and the differential equations describing the motion can be written with some exactness. Unfortunately, exact solutions to these equations are almost never practical in engineering problems. Approximate theoretical treatment of a problem is still of enormous value, however, in engineering aerodynamics and forms the basis for most design work.

The use of large, rapid automatic computing machines has recently encouraged further exploitation of more exact versions of the equations of motion, but the complexities in setting up a problem make this approach of value primarily where many calculations are to be made through a range of parameters.

In a few areas even the underlying physical laws governing the flow are not too well understood. One important example is turbulent flow, in which the motion can be described in terms of a mean velocity with small, apparently random fluctuations about it. In this area much theoretical work exists to correlate experimental results, but at the present time the real mechanism of the flow cannot be described on a purely theoretical basis.

Experimental observation is clearly necessary to the engineer to supplement or confirm his approximate calculations. Perhaps his most basic tool is the wind tunnel. In this device, he holds a model stationary and blows air past it. Measurements can then be made at some leisure of forces and pressures acting on the model and its components. The wind tunnel introduces its own approximations and errors—in the method of supporting the model, in the character of the airflow over it, in the finite size of the tunnel, and in the "scale" of the experiment—i.e., the reproduction of the dimensionless parameters describing the problem. It has the enormous advantage of permitting rapid and accurate control of some parameters over a wide range and the rapid obtaining of a large amount of data.

Flight testing—observations on vehicles in free flight—is most important in those cases where the approximations or limitations in the theoretical approach or in wind-tunnel techniques render these attacks of doubtful accuracy. The difficulties lie primarily in the problems of accurate observation, accurate control of parameters, and the relatively small amount of data which can be obtained in one test.

It is clear that these methods of investigation complement each other in general and that a certain amount of overlapping is usually necessary because of the uncertainties associated in particular problems with any