Closed Loop Thermal Process Control of Airborne Electronic Equipment

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This paper provides the results of analyses and investigations performed at the U. S. Naval Air Development Center on the subject of thermal stability and control of electronic equipments in closed loop forced air cooling systems. Modern types of airborne electronic systems are cooled by a centralized aircraft refrigeration system. The physical connection of the centralized cooling system to the electronic equipments provides a closed loop system that is subject to all the problems of thermal stability and control. Unless the system is properly designed, electronic equipment component parts can undergo excessive heating and temperature cycling, which adversely affects equipment reliability.

Nomenclature

$C(S)$ = quantity or temperature condition of the directly measured controlled system
$G(S)$ = open loop transfer function giving response to change in set point control temperature
j = $(-1.0)^{1/2}$
K = product of all gains of various transfer functions of feedback control system
L = dead time, interval of time between change of input to element and beginning of response to input
M = ratio of closed loop signal size to open loop signal size
ζ = damping ratio
$R(S)$ = set point control temperature
S = complex variable used in LaPlace transformation to permit change from time to frequency domain
T = time required for output of first-order system to change from a given value to within 88% of final value
t = time
$U(S)$ = load change variable
W = pounds of air per unit of time
ω = frequency, rad/min
ω_n = natural frequency, rad/min
σ = real part of complex number
$P.P.B.$ = percent input change divided by 100% output change
ϕ_1 = phase angle for transfer function, $G_1(S) = 1.0/(1 + j\omega T)$
ϕ_2 = phase angle for transfer function, $G_2(S) = -\omega L$

Background

ADIABATIC heating conditions on the surfaces of high speed aircraft as well as heat loads within the interior have necessitated special cooling provisions for airborne electronic equipments. Modern naval aircraft now are cooled by direct connection via ducting from a centralized aircraft air or vapor cycle refrigeration system.

A controller, which can be operated manually or automatically, regulates the amount and temperature of cooling air based upon a measured temperature variable such as surface or air temperature within the electronic equipment.

The physical connection of the electronic and aircraft refrigeration equipments with controllers to regulate quantity or temperature of cooling air provides a closed loop system that is subject to all the problems of thermal stability and control. Although certain of the components of the closed loop system are of a nonelectronic function, their over-all design and arrangement can influence considerably the degree of thermal stability of the electronic equipment. To insure satisfactory performance, it is necessary to analyze the entire closed loop system and all its components installed within the aircraft.

During flight operation, the closed loop system is exposed to various types of thermal load disturbances. Unless the system is designed properly, the hot spot temperatures of the critical components such as tubes, resistors, transistors, etc., undergo excessive heating and temperature cycling. Under these circumstances the electronic equipment can be expected to give unreliable performance. This paper describes certain of the investigations performed at the U.S. Naval Air Development Center on the subject of thermal stability and control of electronic equipments in closed loop cooling systems.

Airborne Electrical Equipment Thermal Process Control Problem

During a flight mission, an aircraft is subjected to transient thermal environments that are transmitted as disturbances to the electronic equipment. These disturbances can take several forms, such as increase in temperature of engine bleed cooling air, reduction in quantity of engine bleed air, increase temperature of aircraft compartment surrounding the equipment, increase in power dissipation as heat by the electronic equipment, and combinations thereof.

There are various types of control actions, such as on-off, proportional reset, and rate. For each type, there are various ranges and conditions of operation. Sources[1,2] provide detailed information on control action characteristics.

There are advantages and disadvantages for each type of control action as well as penalties to the over-all aircraft system. A specific combination of control actions is required to obtain as near as possible to constant temperature control, with minimum penalty to the over-all aircraft system. These have to be determined from analysis of electronic and environmental flight operating conditions.

Figures 1 and 2 illustrate various types of thermal load disturbances that can occur to electronic equipment. Figure 1

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shows a thermal disturbance to engine bleed cooling air prior to entering the electronic equipment.

Figure 2 illustrates a more complicated and realistic condition at which there is a simultaneous thermal disturbance to the engine bleed air and to heat coming into the equipment as a result of a high compartment temperature. The case illustrated (Fig. 2) is considered the more severe and, unfortunately, one of the more realistic situations that can exist in an aircraft during a flight mission.

For every type of electronic equipment and its associated control system installed in an aircraft, there is a penalty[3] that must be charged against its performance. This penalty can be reflected in several forms: fuel consumed in overcoming momentum drag of the aircraft, range of flight, period of time on flight deck of aircraft, reliability, and other factors.

In the design of the aircraft electronic system, the weighing of advantages and disadvantages of alternatives always exists. The service that the electronic equipment performs has to be weighed against the penalty it causes to performance of the aircraft. Consequently, engineering activities involved in the development of avionic electronic equipment in closed loop engine bleed air cooling (or other refrigeration types) systems constantly are being directed to optimize performance by techniques of controlled cooling that will minimize penalties and still maintain highly efficient electronic performance.

In certain cases, as in the installation of the electronic equipment in the aircraft, there is conflicting interest of scientific disciplines. The transfer function of an electronic equipment on a frequency domain contains at least one dead time and time constant. When a Nyquist stability plot is made of this function with proportional control, the dead time can cause unlimited phase lag as a result of the locus spiraling counterclockwise and outward as frequency increases. From a servo and fluid dynamics point of view, it would be desirable to minimize dead time and loss of pressure head. However, these design conditions could be found to be in conflict with the electronic function. The nature of this function may well require that, to obtain optimum electronic performance, the equipment be located within an area of the aircraft which is a relatively long distance from the centralized aircraft refrigeration system, thus requiring a considerable length of ducting.

Even when an electronics equipment in a closed loop control system is designed to give minimum penalty for a specific

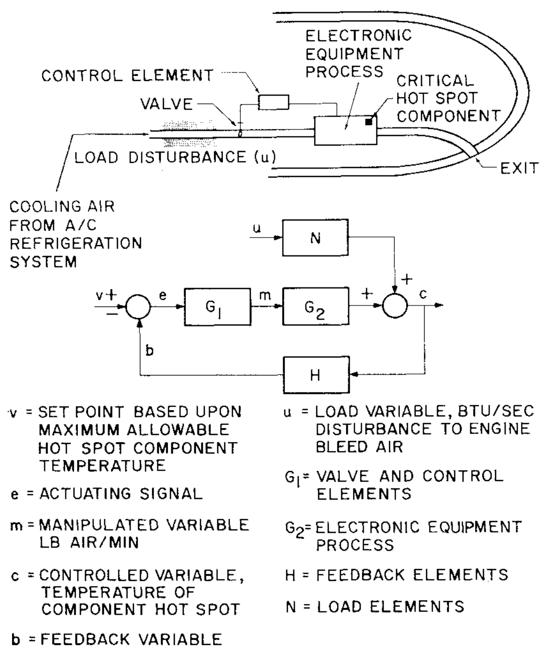

Fig. 1 Thermal load disturbance to air cooling airborne electronic equipment.

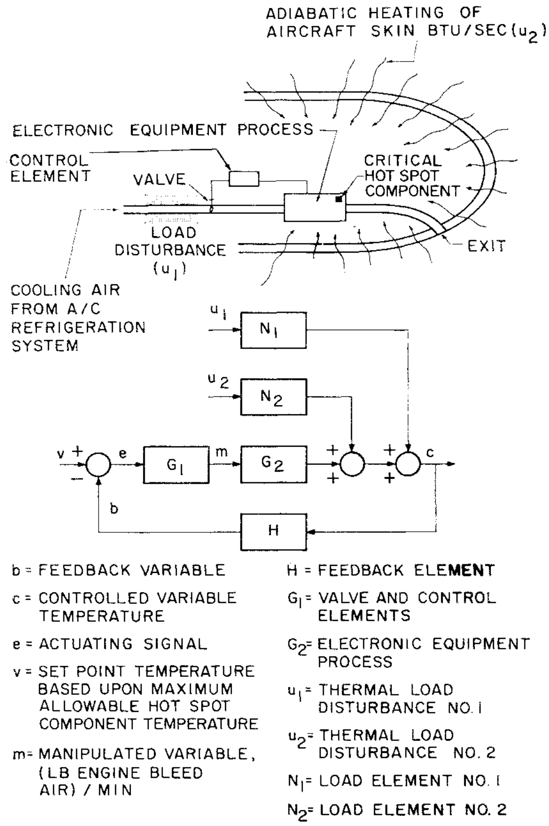

Fig. 2 A combined thermal load disturbance to an airborne electronic equipment.

type of aircraft and its mission, it does not follow necessarily that the same equipment and control system will give the same minimum penalty for another type of aircraft that has different kinds of mission environments and disturbance conditions. Each type of aircraft requires a complete unit operation of flight control analysis. The degree to which optimization is achieved depends on how well all the scientific disciplines entering into the closed loop design are recognized, coordinated, and integrated.

Experimental and Analytical Basis of Analysis

Introduction

Experiments were performed in environmental chambers with the electronic cooled system operating as an open loop. The amount of cooling air, temperature of air, temperature of hot spots of electronic components, and other necessary measurements were made on the open loop system prior to, during, and after being subjected to a thermal load disturbance. The time constant and dead time data obtained from the open loop process reaction curve[4] subsequently were utilized for evaluating the performance of the closed loop system with various values of gain corresponding to three regions, namely; 1) overdamped, 2) critically damped, and 3) underdamped (unstable).

The frequency response of an electronic equipment in a closed loop system can be represented by a second-order equation. The magnitude $c(S)/R(S)$ is the ratio of component hot spot temperature variable to maximum allowable value of hot spot temperature.

$$C(S)/R(S) = \frac{1.0}{(S^2/\omega_n^2) + (2\zeta S/\omega_n) + 1} \tag{1}$$

The maximum value of the hot spot compoent can be considered to be the set point control temperatures $R(S)$.

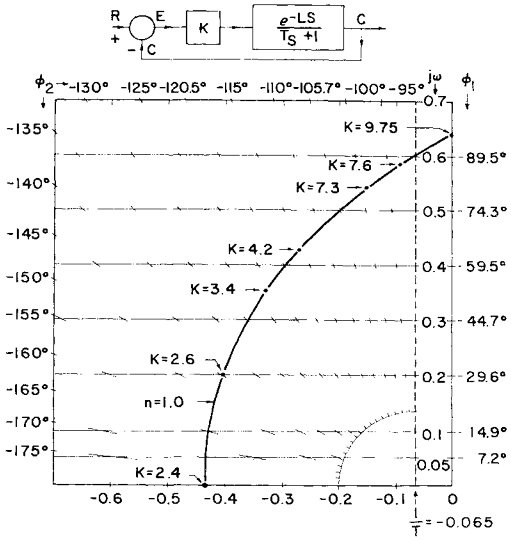

Fig. 3 Phase angle loci for $G(S)$.

As the gain of the system is increased, the damping factor ζ decreases and reaches a value at which $\zeta < 1.0$. At this condition, roots of the equation become complex and there is the start of temperature cycling of critical electronic components. With further increases in gain, the value of ζ continues to decrease with consequent relative increases of temperature cycling and instability. Ultimately, a value of ζ is obtained at which there is not attenuation at all and the temperature cycles continuously. This condition is known as "critically stable." Further increases in gain and reductions of damping factor cause the electronic closed loop system to become completely unstable with amplification rather than attenuation of temperature cycling of electronic components.

The amount of air required to cool the electronic equipment in a closed loop system was determined as a function of time for each value of gain. Correlations were made of the gain of the sytem and amount of cooling air vs degree of stability for the three regions specified above.

Frequency Domain Methods

The methods[5–7] used for analytical studies of electronic equipment in closed loop cooling systems were those of Bode, Nyquist, and Evans. The root-locus method originated by Evans[7] to handle transfer functions with dead time lag was later modified by Chu.[8] The curves shown in Fig. 3 were prepared utilizing Chu's method.

Thermal Stability and Control Characteristics of an Electronic Equipment

Electronic equipment, closed loop, cooling systems with a high gain have an advantage in that they can reduce considerably the amount of cooling air required to control around a certain set point control temperature. However, high gain systems can have a disadvantage in that there may be extensive cycling of hot spots of critical components.

With increases in amount of cooling air, there is a reduction in the amount of temperature cycling until, finally, with a low gain system, the closed loop critically is damped or overdamped. At this point, the hot spot temperature of the critical component of the electronic equipment lines out at or below the maximum value of the set point control temperature.

An analysis was made of proportional controller actions covering a range of cycling conditions from excessively underdamped (unstable) to overdamped, in which the temperature of the critical component of the electronic equipment never reaches the maximum value of the set point control temperature.[5, 6] Figure 4 shows the effect of gain on the open loop thermal response of the electronic equipment. It will be shown that curve 1 of Fig. 4 corresponds to a high gain (narrow proportional band) having excessive critical component temperature cycling but requires a minimum amount of cooling air.

The open loop curves 1–5 cover proportional bands of 13.1, 17.8, 21.2, 28.2, and 31.6%. These were plotted on a Nichols chart from which the curves of the closed loop were obtained. The closed loop data plotted in Fig. 4 are systems that may be defined by second-order linear differential equations with constant coefficients. Curves 4 and 5 represent an overdamped system. Curve 1 represents an underdamped system corresponding to a situation of excessive component temperature cycling. Curves 2 and 3 represent various intermediate stages of damping and temperature cycling.

Figure 5 presents the temperature cycling characteristics of the electronic equipment critical component for the range of proportional bands specified previously. Each curve represents the response of a critical electronic equipment hot spot transistor component temperature as a function of time. During the transient period of time, the value of the critical component temperature is changing and, consequently, the amount of cooling air required at any given instant will be a function of the critical component temperature.

Using conventional thermal methods of analysis, the amount of cooling air per minute per kilowatt of power dissipated as heat was calculated for the closed loop system during the transient period of time following the application of a thermal load disturbance. The cooling data for all values of proportional band are plotted in Fig. 6 and the three basic regions of relative stability previously referred to are defined. The data shown in Fig. 6 need to be considered in conjunction with the data presented in Fig. 5 for critical component temperature cycling.

Curves 4 and 5 of Fig. 5 correspond to low controller gain system, 28.2 and 31.6% proportional band. Curve 5 of Fig. 5 illustrates there would be no temperature cycling or overshooting. For an electronic equipment reliability point of view this would be a desirable situation to achieve, providing the centralized aircraft refrigeration system could provide the large amounts of cooling air shown in region 1 of Fig. 6. Region 2 of Fig. 6 is an area of temperature cycling of critical components varying in degree and bordering on the brink of instability as shown for 13.1% proportional band ($K = 7.6$). Region 3 requires special consideration as it covers the case of thermal instability of electronic equipment.

In the past, for older type of aircraft, the amount of cooling air allocated to an electronic equipment could be based mainly upon electronic power dissipated as heat. In general, little consideration had to be given to peculiar temperature sensitive characteristics of the equipment, its location in the aircraft, electronic function, type of transient thermal disturbances that the equipment would see during mission operations, and whether the equipment would be stable or relatively

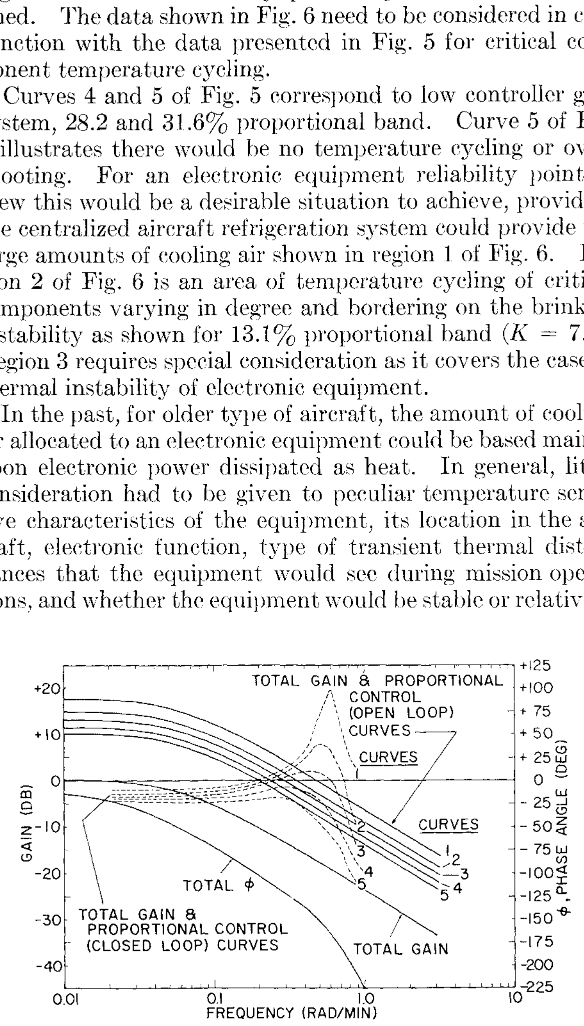

Fig. 4 Frequency and phase angle response curves for open and closed loop systems.

stable when connected in a closed loop to the centralized aircraft refrigeration system. Only recently was consideration given to the development of a thermal control specification requiring coordination of design activities of all disciplines involved in the closed loop system.

Since it is the electronic function that necessitates the closed loop engine bleed air cooling system, the electronic equipment can be thought of as the critical component of all the components making up the closed loop system. It follows that the determination of the transfer function of the electronic equipment is a most important requirement.

Electronic equipments in closed loop systems contain an integral heat exchanger or cold plate. One familiar with this type of equipment would, therefore, suspect that the passage of a slug of cooling air involves a time delay or transportation lag. Likewise, the response of a critical hot spot of an electronic component would involve a thermal time constant. Therefore, just by qualitative-type reasoning, the open loop transfer function could be considered as some combination of a transportation lag and a time constant. The stability of a closed loop system may be determined by plotting the open loop frequency response on polar graph paper. The polar plot also shows how close a system is to being unstable, and may be used as a guide in evaluating possible changes in closed loop electronic equipment cooling system design.

The Nyquist diagram (Fig. 7) is a polar plot of the frequency response for the open loop transfer function. The gain is plotted as the radius vector, and the phase shift is plotted in degrees clockwise from the right hand abscissa.

The open loop thermal transfer function of the electronic equipment can be expressed by the relationship

$$G(\omega) = (Ke^{-Lj\omega})/(1 + Tj\omega) \qquad (2)$$

For the particular electronic equipment under test having the specified time constant and dead time, the absolute value of gain and phase angle are

$$G(\omega) = K/(1 + 240\omega^2)^{1/2} \qquad \text{(gain)} \qquad (3)$$

$$\angle G(\omega) = 57.3\omega L + \tan^{-1}15.5\omega \quad \text{(phase angle degrees)} \qquad (4)$$

Equation 2 was tested and found valid for other types of electronic equipment in which the basic thermal design involves a transportation lag and a time constant. For this type of open loop equation, instability of the closed loop occurs if the Nyquist plot shown on Fig. 7 encircles the (-1) point. If the plot for positive frequencies passes to the left of the (-1) point, the over-all gain is greater than 1° and 180° phase lag. Figure 7 shows that the equipment is unstable when the proportional band ($K = 15.0$) is reduced to 6.7%. The amount of cooling air 3.2 lb of air/min kw (Fig. 6) for this value of gain would not be sufficient and the equipment could be expected to fail because of excessive temperature cycling.

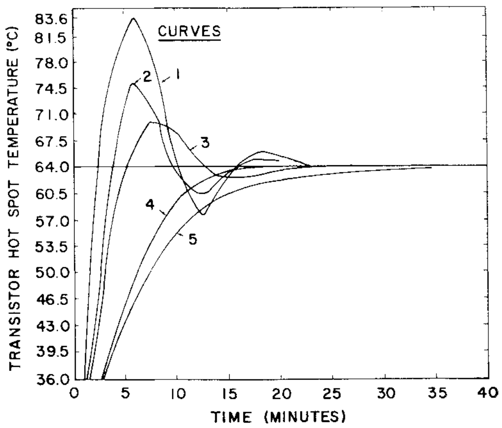

Fig. 5 Electronic equipment hot spot transistor temperature vs time.

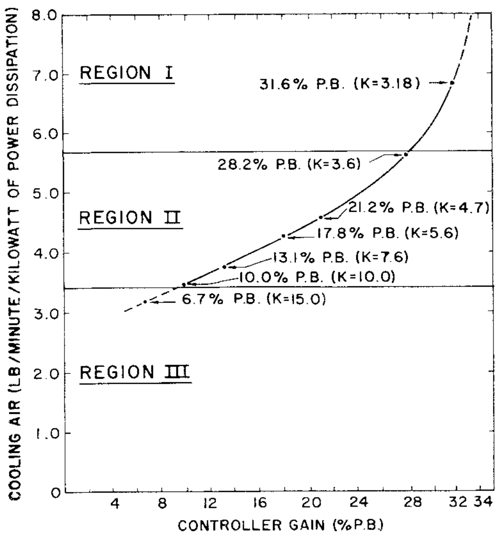

Fig. 6 Effect of controller gain on cooling air flow rate.

A Nyquist diagram made for a 10% proportional band ($K = 10.0$) clearly demonstrated that the critical point of stability had been reached and there would be continuous temperature cycling of electronic components. Obviously, it would not be proper to allow (as shown by Fig. 6) only 3.45 lb air/min kw for cooling.

Although the information provided by Fig. 6 from 13.1% proportional band ($K = 7.6$) indicates a stable region, curve 1 of Fig. 5 indicates relative instability because of high amplitude temperature cycling. Even values of proportional band ranging up to 21% should cause considerable concern since temperature cycling conditions occur and reliability of electronic equipment performance could be questionable. The recognition that the transfer function of an electronic equipment is composed of time constant and transportation lag and that high proportional bands above 21% (low gain, $K = 4.7$) are required for stable operation is cause for caution from several points of view.

Aircraft air cycle or refrigeration systems during certain types of unfavorable mission environments have a limited amount of air available for cooling. Electronic equipments generally are expected to operate with relatively small quantities of cooling air corresponding to values of proportional band at about 21%. In this region, there is considerable temperature cycling and relative thermal instability.

The very nature of the open loop transfer function [Eq. (2)] also is cause for concern since it readily lends itself to instability. As shown by the Nyquist diagram (Fig. 7), the locus spirals counterclockwise and outward as frequency decreases. Any indiscretion or lack of knowledge on the part of the electronic equipment manufacturer in the design and selection of components, or aircraft manufacturer in method

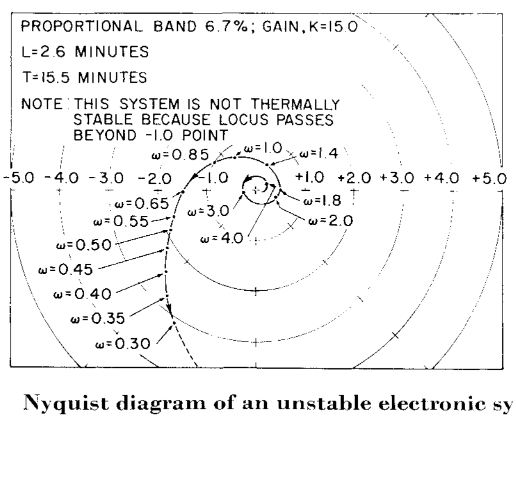

Fig. 7 Nyquist diagram of an unstable electronic system.

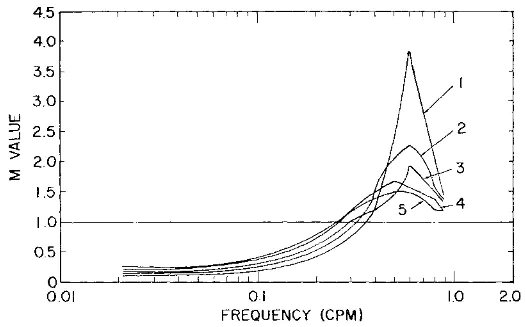

Fig. 8 Deviation ratio curves.

of installing the equipment in the aircraft closed loop system, could lead to difficulty. An overall open loop dead time would be provided which causes unlimited phase lag with the locus spiraling far to the left of the −1.0 stability point.

In the discussion presented previously, Eq. (2) was considered the complete open loop. In actual practice, the situation described before could be aggravated further by the fact that there may be several dead times and time constants of other nonelectronic hardware in the closed loop with which to cope. Thus, it may be necessary to further widen the proportional band of the over-all closed loop system and require a further increase in the amount of cooling air for the electronic equipments.

Nyquist diagrams utilized to obtain relationships of gain and stability are a time consuming method. The root-locus technique is a graphical way in which to inspect the effect on the roots of the closed loop transfer function for changes in one of the quantities of the open loop transfer function such the open loop gain K. With K being varied, the root-locus is a graphical means of inspecting the effect of the roots of the closed loop transfer function, as K is given all values from zero to infinity. Thus, with one plot (Fig. 3), the characteristic response of the closed loop system is determined for any value of gain K. A similar process is to let other quantities in the transfer function vary, one at a time (e.g., the time constants).

Thought also needs to be given to the controller deviation ratios and the effect of gain on deviation ratio. It should be noted that in the region of (Fig. 8) 0.3 to 1.0 cycles/min, the controller will do considerable harm particularly as the gain is increased. With deviation ratios above 1.0 cycles/min, the controller does neither harm nor good, and there is no protective control action for the closed loop system.

Formulation of an Aircraft: Electronic Thermal Control Specification

Environmental specifications play an important role in the development of new aircraft systems. The U. S. Navy, realizing the importance of these specifications, constantly is updating them so that environmental design and test conditions will represent the dynamic conditions of environmental operation of the aircraft and its associated electronic system on the ground and in the air.

Regarding thermal environments, there are overlapping disciplines. The effectiveness of the thermal design of the electronic equipment is dependent, to a large extent, on the type of flight conditions. Because of this interrelationship and dependency for reliable over-all system performance, it is necessary that there be close coordination between the prime contractor and all other contractors involved in the contractual process long before any hardware is developed. To achieve this type of cooperation, an analytical thermal cooling specification[9] has been developed to delineate the technical requirements, procedures, and time schedule for coordinating intercontractual activities.

The objective of an analytical cooling specification for airborne electronic equipments is to achieve reliable electronic equipment thermal performance with minimum penalty, such as fuel consumed in overcoming momentum drag of the aircraft to the over-all aircraft system. The analytical specification requires four timely reports covering the four basic steps making up the technical development process.

The general objectives of the specification are such as to require the coordination and cooperation of the various activities involved in the over-all aircraft system. This is evident particularly in the development stage prior to performing any analytical calculations, and when the cooling problem must be defined and agreed upon by the various activities involved. The first paper entitled, "The Cooling Problem Definition Report," is issued for this purpose. The second of the four reports, "The Analytical Solution," presents the analytical unit operations of the cooling problem requirements. The results of the analysis bring forth a complete definition of all the unit operations of cooling design parameter value and over-all electronic cooling equipment characteristics which provide an optimum solution to the problem of cooling the electronic equipment throughout the various operations performed by the aircraft system during its mission. The "Mechanization Cooling Report" is the third report and shows how the results of the analytical solution, the various unit operations of cooling system parameters, and other characteristics are translated into hardware.

The three reports previously discussed, which are part of the analytical specification, contain engineering decisions the correctness of which depends upon the theoretical known-how of the vendors and contracting agencies. To check these decisions leading to and including the mechanization report there is a need for a verification environmental specification and environmental report.

The environmental specification[10] calls out requirements for simulating the different temperature conditions and determining electronic equipment thermal performance as well as penalties of the electronic equipment to the aircraft under various flight simulated conditions.

The thermal process control specification, at the time of writing this paper, is being developed along the same general lines as indicated earlier for the analytical thermal cooling specification. Its objective is to provide a reliable, stable temperature of electronic equipment operation throughout all types of aircraft flight missions, including operation on the ground prior to takeoff; the design of the over-all closed loop system provide this condition with minimum penalty to the over-all aircraft system.

As in the first stage of the analytical cooling specification, "The Thermal Process Control Problem Definition" would be issued to accomplish the same objective. However, "The Analytical Cooling Problem Definition" is being defined to cover mainly conditions of steady operation, whereas "The Thermal Process Control Problem Definition" evaluates the closed loop system during a transient thermal disturbance period. Likewise, the other reports consider the transient temperature effects of thermal load disturbances seen by the over-all closed loop system. In this way, both transient and steady state temperature conditions seen during operations of a flight mission are covered.

To assist contractors who are responsible for the design of electronic equipment and those other components which must meet the requirements of the analytical cooling specification, a comprehensive design manual[11] has been made available by the U. S. Navy. This manual provides design equations and performance characteristics of various types of aircraft components. The interrelationship of these components is spelled out in an orderly manner which allows values of performance and penalty factors to be calculated for cooling the entire avionic system for a specific type of aircraft and mission.

The objective of analytical and environmental cooling specifications for airborne equipments is to achieve reliable thermal performance with minimum penalty to the aircraft system. The objective of the thermal process control specification for closed loop cooling systems follows the same basic pattern. However, methods of calculation presented are on a frequency as well as a time domain basis. The basic purpose of the thermal process, controlled closed loop system is to protect the electronic equipment and its associated components from overheating or over temperature cycling to the extent that the equipment will give reliable performance.

The over-all factors defined in an avionic control system specification are listed below.

1) General requirements for avionic equipment cooling control system: These requirements taken as a whole define certain limits for the system such as weight, volume, permissible power consumption, electro-magnetic interference limitations, etc. Typical operating conditions of environment are items such as heat dissipated by the electronic equipment, ambient temperature and pressure conditions surrounding the avionic equipment, thermal load disturbances seen by the engine bleed cooling air or the avionic equipment throughout all mission operations, applied mechanical disturbances of vibration and shock, driving functions, and sources. These general specifications are of interest to electronic and environmental test engineers because they specify the different conditions under which operating tests must be performed.

2) Dynamic performance specifications: Terms that may be used in specifying dynamic performance in both the frequency and time domain are a) damped natural frequency, b) period of electronic hot spot component overshoot, c) electronic component hot spot temperature rise time, d) component temperature settling time and offset temperature differential, e) amplitude of temperature overshoot above maximum value of the set point control temperature, f) critical component time constant, g) component temperature dead time, h) controller deviation ratio, i) damping ratio, and j) relative stability of the open loop electronic equipment cooling system.

Summary

If early consideration is given to the thermal stability and control problem, electronic equipment installed in airborne centralized cooling systems can be designed to function reliably with minimum penalty to the over-all aircraft system. The establishment of an analytical control specification is recognition that there is a thermal stability and control problem that needs to be evaluated in the early stages of the design or development process.

Several scientific disciplines are involved in the design of various components of the closed loop system. Before reaching even a hardware stage, a complete thermal stability and control analysis must be performed covering all transfer functions of the closed loop system and disturbance conditions.

It is conceivable that an electronic equipment inherently could have a good thermal design and yet be unstable in the loop system. A high degree of temperature cycling of critical electronic components could occur in the equipment, through no fault of its own, because of poor arrangement in the closed loop system. This result could be brought about by an excessive dead time that, in turn, causes ulimited phase lag with the locus spiraling far to the left of the -1.0 stability point.

The converse of the situation described previously also could exist if the electronic equipment is designed improperly for the closed loop system. The very nature of an avionic electronic equipment cold plate or heat exchanger design is such that a time delay is involved. If the equipment is designed improperly for the closed loop system and the associated thermal disturbance conditions, an excessive phase lag may occur causing instability, regardless of the efficiency of the aircraft centralized refrigeration system or other components of the closed loop system.

The effectiveness of an electronic equipment thermal design should not only be evaluated environmentally as a separate entity but also as a component part of the closed loop system. Temperatures used to define thermal dead time and time constant should be representative of, or capable of, being correlated with the critical hot spot temperatures of the electronic equipment.

The amount of air required for cooling an electronic equipment should not be determined only on a steady-state environmental temperature and electronic power dissipation of heat basis. Consideration must be given to the periods of transients which occur during exposure to a thermal load disturbance.

Reliability figures for components of electronic equipment are based mainly upon steady-state environmental temperatures. Little data are available showing reliability performance under cyclic temperature conditions. Results of investigations show temperature cycling of critical components cannot be eliminated entirely until the closed loop gain action is reduced to a low value and critical damping or overdamping is obtained. To achieve this condition, the amount of cooling air required per kilowatt of heat must be increased to the point that limitations on aircraft refrigeration capacity may prohibit this situation from becoming a practical reality.

Temperature cycling of electronic components will probably not be entirely eliminated. Therefore, reliability data will be required on the performance of electronic components under temperature cycling conditions.

Under certain types of disturbance conditions, the controller in the closed loop may not only be unable to provide effective control but may do considerable harm. The deviation ratio is a measure of the controllers ability to correct for disturbances. When this ratio is more than 1.0, the controller makes the peak height of deviations greater than it otherwise would be. Above the value of 1.0, its corrections are so mistimed with respect to the fluctuations that they are in the wrong direction. It is therefore important in the selection of a controller to make certain there will not be any frequencies of operation in the closed loop system where they will give ineffectual performances.

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