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THERMAL GROUND TESTING
OF
CONCORDE AND VERAS
OR
IMPROVEMENT IN FRENCH TEST METHODS AND FACILITIES

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ABSTRACT

The more numerous the requirements are in aerospace vehicle operations, the more the ground test facility have to improve both the nature and the quality of the equipment as well as the volume and the size of the sites, for the importance of ground testing cannot be over emphasized.

As an example, two ground test programs are reviewed in this presentation, namely CONCORDE and VERAS. Special emphasis is given to the facility implementations due respectively to the static and fatigue test of CONCORDE in heat environment and to the dynamic test of VERAS in high level and transient temperature conditions.

TESTING, GROUND TESTING AND AIRFRAME GROUND TESTING

Testing

Testing occurs at almost any time during a development program. Research tests are those which establish basic and fundamental behavior properties, they are upstream of the development testing. The development tests assist the total engineering and design development by evaluation of design concepts and support of manufacturing methods and processes. Verification tests assess the articles to be in compliance with their design and performance requirements. Acceptance tests are performed on flight articles to ensure that the hardware meets design specification requirements.

Ground Testing

"The importance of research, development verification and acceptance ground testing cannot be overemphasized. It is only through exploratory experimentation that many physical processes can totally be understood. Theory and analytical treatment can certainly shed light on possible solutions or further identify difficulties, but only experimentation can provide a technological base for potential problem solutions. The requirement for this technological base becomes even more critical as our aeronautical vehicles gain higher degress of sophistication."

As an example, let us remember that "the most troublesome aerodynamic area in the realm of nearly every flight vehicle has been the nature of the boundary layer. This particular phenomenon must be investigated primarily through experimentation. Although adequate theories exist for the stability of the laminar boundary layer, very little is known from a hypersonic standpoint. The three-dimensional aspect of the turbulent boundary layer is a staggering problem with regard to the flight system, hence wind tunnel investigations of this phenomenon are becoming more common as time goes on. The reliance on high Reynolds numbers to best represent the state of the boundary layer cannot be overstated."

Airframe Ground Testing

"In spite of the tremendous strides in stress analysis capability made possible by the use of computer sciences, the basic tool, and the most powerful tool, for final evaluation of new structural concepts and material systems is still experimental evaluation by means of structural test. The challenge of structural test facility requirements for evaluation of advanced vehicle concepts involves the dual problems of: (a) defining the test plan scope and the size of the test article while, (b) keeping in mind the almost exponential rise in cost of facility development and operation as more and more demanding environmental simulation is provided to represent the structurally significant conditions of the flight environment. Both of the above, mutually interdependent aspects of structural testing, must be satisfied to the degree necessary to provide the structural designer sufficient confidence in his new configuration and material selection that he is willing to commit this design to use on a manned flight vehicle." As an example, "the trend toward greatly increased thrust and power in future aeronautical vehicles will place unique demands on development test facilities in the acoustics area. The variety of acoustic problems will require laboratories with the capability to simulate acoustically induced structural and sound transmission problems, simulation of aerodynamically generated noise, and allow for full scale experimentation in engine noise suppression. Facilities which are presently in operation or are nearing completion will be able to fulfill many requirements of the immediate future. This simulation capability must either be extended or new and larger facilities built to cope with the full scale testing problems for the 1970 to 1980 time period."

Test Facilities - Time/Cost Trade-Offs

"The lead time required to develop facilities is of a crucial nature since it is based upon the trends and predictions of the future. On the other hand the initial impact of the facility expense involved often delays such construction. The philosophy and planning of facilities must relate to future aeronautical vehicles which are in turn thoroughly examined for specific design and performance characteristics. In some cases facility programmers attempt to develop facilities based on specific systems whereas the nature of the facility must relate to a class of technical phenomena such as might be experienced within a certain Mach number range.

The last challenge of these advanced system structural test requirements is not so much a facility design problem but is one of economics.

When the added costs of cold fuel, true atmospheric heat transfer effects, and the associated complex automated facility operation and control requirements are considered, the totals are staggering. We must then first provide a complete test simulation capability for as large a test article as practical and learn by exploratory and advanced development testing how we can meet the future challenge of structural certification of a first flight article of a manned hypersonic flight vehicle."

Two French Examples of Test Facility Improvements

Illustrating the previous general comments made in 1968 at the Fifth AIAA Annual Meeting, the next four chapters will show how two recent French programs, namely CONCORDE and VERAS, have required improvements of the existing test methods and facilities.

THE CONCORDE STATIC AND FATIGUE TESTS IN THERMAL ENVIRONMENT: FIRST IN A SERIES OF NEW DEMANDS FOR IMPROVEMENT OF STRUCTURAL GROUND TEST FACILITY

CONCORDE Program General Characteristics

Figures 1 and 2 evidence that new trends have been originated in the commercial airplane domaine with the joint SNIAS-BAC "CONCORDE" - S.S.T. Program. Due to its wing plan form, level flight speed and expected commercial service-life, CONCORDE aircraft required a structural design adapted to the new problems that heat have initiated. Figure 3 gives an example of the skin temperature distribution during the Mach 2 level flight. Figure 4 shows the general assembly of main sections. Though they are not the main purpose of this presentation, we must mention the tremendous amount of basic research and development tests which had to be performed to assess the static, dynamic, acoustic, fatigue and creep behavior and the protection of basic materials (AU2GN, Ti-Alloy, Steels...), joints (welds, bolts, rivets, glue) and critical structural subsystems. Mainly performed on simple small size articles, these tests nevertheless have required some implementation in the existing laboratory facilities to create the required total stresses within the specimen due to both the mechanical and heat loads.

Test Philosophy Principles

The first general philosophic principle which prevailed was to give the entire aircraft section responsibility for the design, the fabrication and the testing of the assigned articles to both countries. This principle was kept for the establishment of the structural ground test plan, with appropriate arrangements to avoid costly and time consuming overlap and redundancy in test sequences. Figure 5 shows the respective sections of the airplane as they are shared inbetween the two participants.

To integrate the system and to certify its operational specifications to the governmental agencies, one of the last two tests will be performed in France and the other in England, on the completed airframes. The first structure will be devoted to thermo-static certification tests (SNIAS, France), The second airplane will undergo the thermo-fatigue certification tests (BAC, England).

A second major philosophic principle was to generate the thermal stresses inside the test articles, when needed, by heating rather than by applying equivalent computed mechanical loads. This decision was made mainly to satisfy the long service-life fatigue test requirements and because access to the structure for such local mechanical loading devices is rather difficult. The heating approaches are different in the two companies. BAC has chosen a hot air convective heating method (Figure 6). SNIAS utilizes a quartz lamp radiative heating facility with a gentle air convection to homogenize the temperature distribution.

A third philosophic principle was to develop analytical and experimental criteria and methods for test acceleration, thus avoiding simulation of the entire flight time duration (Figure 7). Thermal inertia and fatigue-creep phenomena have to be taken into account for fatigue life prediction with a reduced amount of data scattering. Test acceleration approaches utilized forced overheating/overcooling (locally and timely applied) of internal massive structures to create the major thermal gradients and the stress levels. Accelerated test procedures are developed from the data of initial real-time thermo-static tests, on the article itself and from previous similar test specimens.

Test Plan and Description of Main Tests

The presentation will be limited to the French contribution to the test plan (Figure 8). It will feature the implemented facility through the development tests performed on the four main assigned test articles and the certification thermo-static tests on the completed airframe.

Test Article "2.1"

The test article is a fuselage section 15 feet long including window and emergency exit frames, and the main wing carry-through fuel tankage. Thermo-static tests were performed in real-time to:

- verify stress concentration factors on window and emergency exit frames,
- verify thermal diffusion computation methods and thermal-stress distribution,
- determine adequacy of the thermal and mechanical loading devices for further tests on more elaborate test specimens.

Test Article "2.8.b" (Figure 9)

The test article is a fuselage section (35 feet long) and a main wing torque-box (44 foot span), including the main landing gear backup structure and the corresponding fuel tanks. Two series of tests have been performed:

- thermo-static tests to (a) limit loads under subsonic and supersonic flight regimes, and (b) under ground load conditions. During those tests, two heating rates were chosen to determine both their influence on the stress distribution and the previsional rupture stress level,
- various fail-safe tests, as required by FAA specifications.

Test Article "2.6/2.7"

The specimen consisted of the rear part of the wing torque-box (L/H and R/H, 67 foot span) and the corresponding fuselage section (20 feet long).

The article is fatigue-tested under combined mechanical and thermal loads (Figure 10). The furnace required 40 independent channels delivering 6 MW of electric power. 1,000 strain gages and 800 thermocouples were necessary. The test acceleration is such that in a 40 minute test period the thermal damage of two consecutive flights of more than three hours each is generated. By the end of February 1971 41,000 mechanical flights and 20,000 thermal flights have been performed with no serious damage to the test article. A test cycle costs approximately $300.

Test Article "2.3.2"

This specimen consists of the front part of the wing torque-box (L/H and R/H, 35 foot span) with the corresponding fuselage section (25 feet long). Combined mechanical and thermal fatigue tests are performed. The same amount of energy and equipment was required as for 2.6/2.7 test article. The test cycle is 26 minutes long. By the end of February 1971, 48,300 mechanical flights and 13,800 thermal flights have been simulated with minor damage to the test article (Figure 11). A test cycle is expected to cost approximately $150.

Certification Thermo-Static Test on the Complete Airframe

A first series of tests have been performed at room temperature to simulate five flight configurations and ten local loading conditions. Tests have been performed to failure loads. The second series of tests will start in July 1971 and will feature both thermal loading conditions and combined thermal and mechanical loading conditions for final certification. 150 separate heating bays are required, including 20,000 quartz lamps, to heat 12,000 square feet of structure up to 250°F in 20 minutes. 25 MW of electric power is required.

THE "CEAT" THERMAL TEST SITE - IMPLEMENTATION TO MEET "CONCORDE" TYPE REQUIREMENTS

CEAT Origins

CEAT is an agency of the French Defense Ministry created to provide an important and unique ground test site to the French public and private aircraft industries for testing in support of their Government supported civilian or military programs. However, special arrangements may be made by these industries if they want to ground test a private venture vehicle. Therefore, CEAT has become "THE" ground test center for the French civilian and military aircraft programs. Industries are reluctant to invest in large facilities which frequently are troublesome to operate. This position enhances the need for implementing a site such as CEAT.

Requirements of CONCORDE Ground Test Facility

In order to perform the different tests mentioned previously, the capability envelope of the CONCORDE ground test site facility had to be such that:

- mechanical, aerodynamic, and pressure loads could be simultaneously simulated when needed;
- heat loads had to be simulated (heating and cooling) at the same time the above mentioned loads are applied;
- strain, displacement and temperature data must be accurately recorded;
- automation is required to monitor intricate thermo-static/thermo-fatigue test sequences through feed-back of output data;
- overall dimensions and available powers must be able to support tests on the total airframe.

To develop a test facility of that type you must remember that on onehand tests have to be either development/verification tests or certification tests, which imposes a requirement on the equipment for versatility, precision and reproducibility. On the other hand, tests could be either static tests or fatigue tests, which implies for the facilities high reliability and no time-life limitation.

Approaches of CONCORDE Ground Test Facility

Mechanical Loading System

In the area of load application and control, the use of modern hydraulically actuated load devices provide almost unlimited capability to duplicate any required load magnitude and distribution. The control of these load systems with a closed loop electronic servo-control system utilizing load feedback provides a load control capability varying from a simple incremental step input to extremely complex time varying programmed loading.

The facility provides a maximum of 48 separate servo-channels for this mechanical load application. For the certification static test on the complete airframe, 80 hydro-jacks will be used (Figure 12).

Pressure Loading System

In the area of pressure load application and control, depending upon the size of the test article and the nature of the test to be performed (room temperature or elevated temperature test) either hydrostatic or pneumostatic means are envisaged with a closed loop electronic servo-control system utilizing pressure feed-back. For the JP-4 tank, as well as for the cabin pressurization systems, the pneumostatic method had been selected to allow the presence of local heating elements when needed inside the structure. To minimize the air-flow consumption through the compressors and to improve the security for the test personnel, fuselage or fuselage sections were filled to 80 percent of their volumes with low density polyurethane-foam blocs (Figure 13).

Heating and Cooling Systems

In the area of thermal application and control, it has always been difficult to keep up with the aircraft requirements. The following paragraphs will place emphasis upon the automated heating and cooling facility implemented.

Monitoring and Acquisition Systems

To monitor the tests, a central digital computer has been selected. The CDC Pallas - 32K (Figure 14):

- delivers the loading orders to the jacks through a maximum of 48 independent channels;
- delivers the pressurization orders in the same way;
- pilots the heating program of the heating bays by measured temperature feed-back.

A data acquisition system connected to this computer allows 2,000 inputs to be scanned in either 10 seconds, 4 seconds or 0.5 seconds, depending upon the nature of the input data. Real-time output stress data may be obtained through two Cathod Ray Tubes with programming keyboards, and high speed typing machines.

Heating and Cooling Facility Description

Airframe Heating

Convection heat flux reproduction through a radiative heat flux is a main difficulty for radiative heat flux does not drastically depend upon the surface temperature of the heated surface as does the convection heat flux. Radiated heat flux must therefore be locally adapted to the required temperature of the receiving surface. Such an adaptation depends upon the skin thicknesses, the distance to the leading edge, the presence of massive pieces, etc.

To do so, the whole "furnace" has to be constituted of as many adjacent quartz lamp heating bays, each one delivering a unique heat flux at one particular time, as required by the temperature distribution which is to be simulated (Figures 15 and 16).

Computation of surface temperatures can be accurately determined with todays technology. They are of such a precision that heat loads on test articles can be applied by temperature rather than by heat flux simulation. Each bay is designed for a "pilot" temperature and its heating rate is monitored by both a given time-temperature law and by the feed-back of the measured surface temperatures. Parameters affecting the design of a "bay" according to its pilot temperature are a function of the quartz lamps, lamps spacements, distances to the heated surface and various emmissivity factors of the surface obtained by different paintings.

Due to the complex temperature distribution on CONCORDE airframe, the furnace has been divided into 150 heating bays and required a total continuous electric power of 25 MW. Quartz lamps are of three types: 110 volts - 500 W; 220 V - 750 W; 220 V - 1,000 W. Electric power generation system consists in 25/1250 KVA transformers, each one serving six thyristors cells of either 50 KW or 200 KW power each. An over-power of 42 MW can be achieved, if needed, for 8 minutes. The design of these unitary cells is such that they take into account only the integral amount of half-cycles of the a.c. current provided which is ordered by the central digital computer according to the required heating rate. Such a principle drastically reduces noise injection into the data acquisition system. The formula for power generation is given in Figure 17. The feed-back temperature system consists of three identical thermo-couples independently tracked by the control computer which elaborates the temperature to be chosen for feed-back servo-control, according to a checking procedure (Figure 18).

Airframe Cooling

An efficient and relatively simple cooling system uses forced ventilation (45 to 60 ft/sec) with pre-cooled air/liquid nitrogen mixture (-30 to -70°F) (Figure 19). LN_2 consumption rate is computer-monitored with the feed-back of the temperature. Cooling efficiency has been designed such that a small additional heating by the bay is required when cooling. For the static test of the total airframe, each run will necessitate 20,000 gallons of LN_2. For fatigue tests, the cooling system consists of a set of refrigerating machines and heat exchangers, which is much more economical. Even when heating periods occur, a tender air movement is generated on the heated surfaces (25 to 30 ft/sec) to avoid damaging local natural convection effects and to homogenize the temperature distribution (Figure 20). Such a method is in fact a compromise between the two different methods: pure convection and pure radiation heating. Illustration is given by Figure 21.

Fuel Heatsink Simulation

Due to the amount of necessary fuel and electric equipment surrounding the test articles, it was much too dangerous to simulate the fuel mass and inertia effects by JP-4 fuel itself. An equivalent liquid had been selected, namely, gilotherm ALD. Of course, it does not have all the physical characteristics required but realize anyway the better compromise. To accelerate the test cycles, while giving the required temperature to that important mass of fluid, it has been necessary to create an installation which (a) simultaneously provides gilotherm to both required temperatures, 300°F and 60°F, and (b) is able after appropriate temperature mixing to pump the mixture in and out of the tanks according to the desired fuel simulation temperature/time history.

THE VERAS STATIC AND DYNAMIC TESTS IN TRANSIENT HIGH LEVEL THERMAL ENVIRONMENT: SECOND IN A SERIES OF NEW DEMANDS FOR IMPLEMENTATION IN STRUCTURAL TEST FACILITY

At the same time CONCORDE was giving an opportunity to France to setforth a reasonable size and modern thermal ground test facility, a much restricted research program - namely VERAS (Vehicle for Experimental Research in Aerothermodynamics and Structures) was asking for additional capability at this facility. Namely, the study of the dynamic response evolution of a hot structure submitted to mechanical vibration while in permanently transient heated regime. Let us first recall the main characteristics of this program.

VERAS Program Main Characteristics

Vehicle and Trajectory (Figures 22 and 23)

The trajectory and structural shape selected for this investigation are merely illustrations intended to stress the major structural problems associated with hypersonic lifting bodies. Making the vehicle fly was not intended at all. A first approach was to design it as unmanned and non-reusable, but not expendable.

The vehicle considered here consists of a highly swept low delta wing and a cylindro-conical fuselage. The wing is fitted with a ventral fin and is prolonged by two elevons. The total weight is 3,000 pounds, including 2,000 pounds of payload.

The trajectory of this unmanned glider is a 500-second level flight, at Mach 10, at an altitude of 150,000 feet, and with an angle of attack of 8°. This results in a heat flux of 9 BTU/sq.ft.sec. at the current low-surface point.

The level flight is followed by a gliding descent with an angle of attack corresponding to the maximum lift-to-drag ratio, during which occurs a 100-second turn under a 1.65 load factor at a speed equal to 0.85 times the steady level flight speed. The total flight duration is 1,640 seconds.

Loads

The loads are of two types, in the atmosphere at high Mach numbers:

- First, the standard mechanical loads due to the masses and corresponding inertia and to the aerodynamic characteristics of the profile: these loads are moderately high and hardly exceed 80 PSF.
- Second, the loads induced by the high thermal gradients: variations of this type are visualized in wind tunnels by means of heat-sensitive paints. The mean thermal gradient value across the wing section is 1000°F in steady level flight (Figure 24).

Structure and Materials (Figure 25)

The structural design and the necessary engineering materials must therefore be selected on the basis of these two requirements in order to obtain an acceptable internal stress level. An original matrix method has been developed for the computation of the loads, and the flight range concept has been reconsidered, taking into account the structural temperatures and the operating times.

To minimize the thermal stresses and ensure sufficient stiffness, the structure has been designed as a three-level structure. The skin panels, which are divided into "shingles" (Figure 26), are attached by hinges and cover strips to an orthogonally shaped sub-structure which rests freely on the load-carrying structure (Figure 27) by means of sliding attachments. Each member of the primary structure has a corrugated web which is directly welded to the flanges at the corrugation apices (Figure 28).

For the primary structure, the nickel alloy Rene 41 was adopted because it sustains the highest service temperature. For the skin panels, Rene 41, TZM or P333 alloy have been selected according to the surface temperatures.

The sub-assembly selected for the experimental model was that on where most of the technological problems were found, i.e., the aft part of the vehicle, wing and fuselage only (Figure 29).

Tests Program

Thermo-Static Tests

The main testing objective was to assess the validity of the design through limit and failure thermostatic tests. The facility implemented for CONCORDE airplane structural ground test has been choosen. It had to be adapted to:

- much higher heat flux at temperature levels (9 BTU sq.ft/sec. instead of .05 BTU/sq.ft/sec.);
- higher heating rates (2000°F in 140 seconds instead of 150°C in 20 minutes);
- smaller test article sizes (100 sq.ft. instead of 12,000 sq.ft.)

Figures 30, 31 and 32 give an outlook of the rig mount and test site.

In brief, 18 heating channels constituted the two infrared stoves which were developed for simulation of the in-flight changes of the wall temperatures representing 3500 KW of effective heating. The loads were introduced by vertical loadings of four origins. The heating and loading histories were applied simultaneously by means of cam-driven potentiometers, through a computer which delivered the required information to the control and monitoring console.

Prior to the mounting of the model on the rig, 74 thermocouples were connected to the bare wing and fuselage structures. The payload container wall was simulated by an inorganic heat-resistant felt-matting. The test specimen then received its load-introduction and heat-shield elements. The mock-up with its equipment installed was placed upside down into the test rig, under the lower surface stove, and attached to a dynamometric table. The upper surface stove with its supporting frame was positioned underneath the VERAS. Twenty-three displacement pick-ups have been required.

The overall views of the installation (Figures 33 and 34) shows how complicated the problem is and what important means are used to solve it, essentially due to the high temperature level and the small size of the article. No fundamental changes were required to the facility for those tests.

Thermo-Dynamic Tests

According to the high heating rates and the permanent unsteady temperature distribution of this vehicle, the purpose of the scheduled dynamic testing was to determine the behaviour of the model during a simulated flight by characterizing the modes and their variations with time as a function of the static and thermal loadings. In order that the rapid changes in these modes be followed up automatically, the mock-up was set in self-oscillation by injection, into the exciters, of the balanced signals which come from the velocity transducers.

But this process was a new requirement for the test site facility and the next chapter will deal with a more detailed explanation of the method and the design of such equipment.

METHOD AND FACILITY FOR MECHANICAL VIBRATION TESTS IN TRANSIENT THERMAL ENVIRONMENT (ONERA): FACILITY IMPLEMENTATION TO MEET VERAS-TYPE REQUIREMENTS

Dynamic Loads

Dynamic loads interfer quite often in the choice of a geometry for a flying vehicle. Over many years analytical methods have been widely developed which allow us to forsee the behavior of structures and determine their main vibration modes and related frequencies. Experimental work is usually performed on reduced scale models with equivalent mass distribution (Figure 35). But, due to both the high level thermal environment of VERAS-type hypersonic structures and the always changing thermal gradients along the design trajectories, other analytical methods of investigation have to be developed. To set them up, experimental work is needed. An experimental method and instrumentation was created to determine the dynamic characteristics of an aircraft or missile subjected to heavy loads and to a large heat flux. In particular, it permits to follow the evolution of the vibration eigen values on a continuous manner during the phase of kinetic heating. This chapter will emphasize to some detail the main principles and testing devices which had been developed by ONERA for that purpose.

Test Site Description

Figure 36 sketches the main facility feature. The test article is mounted on a test fixture which elastically rests on the building test floor. Excitors and transducers are also tied to this jig-mount and bound to the article by means of quartz rods through the quartz lamps heaters reflectors. Heating elements and procedures are similar to those used for static tests.

Static and Dynamic Loading System Principle

Loads have to be applied in such a way that they do not add any rigidities or masses to the tested article. If there are any, they must be very small when compared to the structural ones and should be rigorously independent of the applied load. Classical hydro-jacks or hanging weights, therefore, must not be utilized.

The proposed solution to add dynamic loads to high level static loads is as follows. Forces are exerted through electromagnetic exciters. The moving part of each excitor is suspended and guided by elastic blades, so that no friction occurs between moving and fixed parts. The exciter body moves up and down between two rigid lateral guides to allow large displacements to the load application point. A jack actuates the exciter body up and down. A relative position detector (fixed to moving parts) monitors the jack position when the inductive electric windings are sollicitated out of their equilibrium position, so that exciter always performs at the best of its working condition. Exciter response has to be linear. The applied load to windings electric current ratio must be constant when current increases or when the winding moves in and out of its magnetic counterpart. If not, parasitic "electric rigidities" are generated.

The device developed here behaves according to these requirements.

Dynamic loads may be applied by means of other independent exciters. But, they also can be induced by the above exciters, by superimposition of sinusoidal current to the continuous one.

Measurements of Velocities and Displacements

Velocity and displacement transducers have to satisfy similar requirements: added rigidities and masses must be small and constant. They must measure with precision small oscillating amplitudes while undergoing the continuous large displacements of the heated test article. The design of the development equipment is almost identical to that of the exciter: an integrated velocity and displacement transducer is mounted to obtain data on the same axis. Its moving parts are elastically suspended to avoid friction. The supporting frame is actuated up and down by an electric motor so that the part fixed to the test article's structure is always set at a same level with respect to the transducer's body. The supporting frame's displacement reflects the continuous and large local displacement of the test article. The vibration amplitude is given by the velocity transducer.

Requirements for the struts which relates the transducers to the article's airframe are:

- high longitudinal rigidity;
- three degree of freedom at both ends for jointing to the structure and to the transducers;
- sustained high temperature levels capabilities, having to cross the quartz lamps reflectors to reach their structure's application joints;
- as low as possible total expansion, to avoid errors on displacement measurements.

The adopted design (Figure 36) consists of a hollow quartz rod filled with asbestos. Two metallic tips end the strut - they are pressed against the quartz rod through a metallic spring joining them together and passing through the asbestos fibers.

Implemented Method for Automatic Measurement

Due to the rapidly evolving surface temperature distribution, the structure never reaches a steady state. Dynamic behavior depending upon thermal gradients distribution, static load distribution and local elastic modules values, the dynamic airframe characterization must be performed while heating on a stressed test article. The automatic measurement method to be developed must therefore allow a rapid scanning of the main instantaneous vibration modes and amplitudes. Another requirement adds to the complexity of the facility, mainly high temperature and overall inaccessibility of the test specimen. Remote control and monitoring systems, and automation are therefore required.

For the design of the system implemented two principles have been setforth:

- proper modes autoexcitation;
- generalized masses measurement through electric stiffnesses displaced frequencies.

Proper Mode Autoexcitation (Figure 37)

Let us take a model on which exciters and transducers are located. The output signals of N transducers are sent to a mixer whose function is to create $\sum_j V_j a_j$ current, V_j being the electric tension out-going of the j - transducer and a_j a real algebric coefficient.

A manual or automatic selector switch (COMMUTATOR) selects one among these functions. The selected sum-signal is amplified and 180° out-of-phase if necessary. Then it goes to a limiting device (LIMITOR) which provides a constant amplified sinusoidal tension of the same phase as the incoming current. The rest of the chain (dynamic exciters) is equivalent to a sinusoidal current generator.

Let us now consider the n-first modes of vibration. The velocity-amplitudes of the points of measurement for mode - k are:

$$V_{k1}, V_{k2}, V_{k3}\cdots, V_{kj}, \cdots, V_{kn}.$$

For n modes and N transducers, the modal matrix is:

$$\begin{array}{cc} & \xrightarrow{\qquad} \text{N transducers} \\ \text{n modes}\Big\downarrow & \begin{bmatrix} V_{11} & V_{12} & \cdot\cdot & V_{1_j} & \cdot\cdot & V_{1N} \\ V_{12} & V_{22} & \cdot\cdot & V_{2_j} & \cdot\cdot & V_{2N} \\ \hdashline V_{k1} & V_{n2} & \cdot\cdot & V_{kj} & \cdot\cdot & V_{kN} \\ \hdashline V_{n1} & V_{n2} & \cdot\cdot & V_{nj} & \cdot\cdot & V_{nN} \end{bmatrix} = \begin{bmatrix} V_{k_j} \end{bmatrix} \end{array}$$

If we realise $\sum_j V_{kj} a_{jp} \geq 0$ for any k except for $k = p = m$ for which $\sum_j V_{mj} a_{jm} < 0$, then we autoexcite mode m. An infinity of solutions exists corresponding to:

$$\begin{bmatrix} V_{kj} \end{bmatrix} \times \begin{bmatrix} a_{jm} \end{bmatrix} = \begin{bmatrix} \geq 0 \\ \vdots \\ < 0 \\ \vdots \\ \geq 0 \\ \vdots \end{bmatrix}$$

For autoexcitation of the n modes we have:

$$\begin{bmatrix} V_{kj} \end{bmatrix} \times \begin{bmatrix} a_{jp} \end{bmatrix} = M$$

M, being a matrix in which all the terms on the diagonal are negative and the others being either zero or positive. a_{jp} is a n-column matrix. One of the solutions is M diagonal. In such a case, each selected mode's damping is decreasing until it becomes negative and then is autoexcited into oscillation, while other modes' dampings remain unchanged. This is not always the best solution: in cases where two different modes have close proper frequencies, other modes' damping ability would be appreciated.

Determination of $\begin{bmatrix} a_{jp} \end{bmatrix}$ assumes the knowledge of $\begin{bmatrix} V_{kj} \end{bmatrix}$. This could be obtained with classic means through a simple vibration test, without static loads and heat environment. The influence of these two parameters is then determined by mixer's tuning and a continuous checking of the self-excited proper modes' evolutions.

Each different mode could be separately analyzed, but different autoexcitations could also be superimposed. Then to facilitate the analysis, filters automatically operate a first selection of the answer on each of the mixer's output channels.

At least for the five or six first modes, oscillation tuning operations does not require a matrix-inversion computation, provided the N.n elements' signs are known. This is given either by a frequency sweeping/scanning or by the analysis of the geometrical configuration of the test structure. a_{jp} terms are then given opposite signs of the corresponding V_{kj}, correspondance is made from lines to columns.

$$a_{jm} = (-1) \times (\text{sign } V_{mj})$$

So doing, M diagonal terms become negative and much more influent, which is sufficient. Otherwise, some simple tunings of the mixer are required.

Measure of the Generalized Masses by Electric Rigidity Method (Figure 38)

Let us consider proper mode and let us assume it to be completely isolated of the other modes, through an appropriated excitation. So, we can write:

$$(\mu \omega^2 + j\omega B + \phi)\, q = F$$

μ, B, ϕ, F being respectively the generalized masses damping coefficients rigidities and the forces. Mass can be obtained from a known variation $\Delta\phi$ of the generalized mass by

$$\mu = \Delta\phi / \omega^2 - \omega_o^2$$

ω, ω_o: reasoning phase frequency with and without the additional rigidity.

To add pure and well known rigidities, the sinusoidal voltage of a high amplitude point velocity transducer is integrated, amplified in intensity and voltage, then directed towards the dynamic exciters. The created resulting rigidity, or "electric rigidity" is equal to

$$\frac{F}{Y} = Ai/B\, (V/\omega)$$

i: exciter's current intensity
V: exciter's integrated transducer voltage
A and B: parameters related to exciter and transducer

Electric rigidities may be positive or negative. Incremented, they are dispatched to the various locations of excitation.

Methods Proof-Testing on Simple Test Articles

To test the validity of the assumptions made and to adapt the chain of measurement, tests were performed on a long metallic rectangular bar and on a flat rectangular sheet of metal, both built-in at one end. Analytical work has been done to determine theoretical methods of dynamic response evaluation for such type of structure.

VERAS Dynamic Testing

Before sending the whole piece of equipment to CEAT, where the VERAS test article was waiting for testing, tests have been performed at ONERA on a piece of structure identical in design to the CEAT VERAS test article, but smaller in size (Figure 39). It was no longer simple architecture-type test specimens, like the bar on the plate, on which theoretical work could be performed for behavior analysis investigation. The article was a half-wing rear section torque box, constituted of two main longerons with corrugated webs and four spars also with corrugated web. The skins were elementary two-face corrugated sandwich shingles of Rene 41, hinged to both sides of the torque box, and therefore cayying little or no load.

The tests in ONERA were run to define the behavior of such an unusual structure under mechanical vibration and to be able to set the installation for the CEAT test site experimentation with a minimum of tunning time. ONERA tests were performed at the ambient temperature, at a medium temperature (930°F), up to the design operating temperature (1830°F). The evolution of the modes and damping coefficients were observed and were found not to be too much dependent upon the average temperature level, as a general behavior. However, local plastic over-strains might have occured, which changes the stress distribution and do not allow detailed analysis.

In Toulouse (CEAT), the VERAS test article has been excited by four exciters giving 200 pounds maximum static load and 20 pounds sinusoidal load (Figures 40 and 41). Vibration amplitudes and structure distortions due to both static loads and thermal expansion were recorded by 30 fixed velocity displacement transducers. These transducers had access to the structure by means of the previously described quartz rods, traversing the heaters' reflectors. To avoid the article undergoing irreversible damage - local plastic deformation - before being thermo-static tested, dynamic tests had been performed only at room temperature and at an intermediate temperature (970°F). The furnace was monitored through 34 control and monitoring thermocouples.

The above described method and equipment was satisfactory. Results obtained by autoexcitation methods have been compared to results given by classical methods and have been found quite similar. In addition to the wider range of dynamic test experiments this method offers, a drastic saving in time is to be expected, which to itself is a very good point for it.

PRESENT IMPLEMENTATION AND FUTURE NEEDS

Possible Contribution Due to the Present State-of-the-Art

The two programs previously described have given to

SNIAS, CEAT and ONERA a unique opportunity for improvement in static, dynamic and fatigue testing of hot structures. The size and the experience of these three companies could lead them to an individual or joint effort of a valuable contribution to any French, European or International program. The recent proposition of U.S. Government and NASA to make an international concern of the post-Apollo Program, and more specifically of the Space Shuttle System, is a serious temptation for all of us Engineers, who are set into motion as soon as technical curiosity and everlasting search for technology improvement can be achieved. Fortunately, political and economical considerations have to prevail: they might moderate our enthusiasm, but they will establish long-term decisions enabling a valuable and lasting effort, if any.

Heat Simulation Facility Implementation

Anyway, improvements are going on. To the thermal, mechanical ground test facility of CEAT, changes have already been initiated to (a) decrease the turnaround time between different test procedures of a same test article, (b) increase the heating rates delivered by the digital computer to allow simulation on missile and re-entry body type structures, (c) increase the maximum heat-flux levels.

"With new heating developments using graphite heater elements, it appears that surface temperatures of approximately 4000 - 4200°F will soon be possible. The flexibility and quick response of these resistance type heat sources readily lend themselves to sophisticated electronic programming and control, and very precise simulation of the design temperatures can be maintained on a real-time mission profile basis.

On the horizon, is the development of a net radiation thermal fluxmeter which can be used as a control transducer that functions independently of the thermophysical properties of the structures which are not well defined or not available.

The output of the radiation fluxmeter is directly proportional to the structural heating. Thus, test thermal inputs may be controlled without introducing the inaccuracies of thermophysical properties of the test structure."

"Remote reading deflection systems, employing suitable high temperature materials as the mechanical transmission medium thru the "hot zone," are available to measure test article deflection with test article surface temperatures in the 3500°F range. The state-of-the-art of strain measurement systems for this type of testing considerably lags behind the requirements. The limits at high temperatures (above 1000°F) are due to such phenomena as spurious strain outputs caused by metallurgical phase changes within the resistance element, changes caused by variations in coefficient of resistivity, and differences in thermal expansion between the gage and the test specimen involved. Improvement is required and carefully looked at."

New Implementation for Dynamic Test in Rapid Transient Temperature Environment

The test method and facility previously described are undergoing implementation changes to allow tests to be performed in almost any type of vehicle and for any trajectory. Implementation is performed on (a) the size of the exciters, to allow them to deliver static loads of almost any level, the main principle being to superimpose a dynamic vibration on a statically and thermally stressed structure, (b) the volume of the instrumentation and data tracking/recording system to be able to operate on complete airframes.

Analytical implementation is also drastically pursued to provide the design engineers with computation methods allowing a first guess of the dynamic response of such structures all along their flight paths and their life-time local (plastic deformation might bring changes in the stress distribution and dynamic response).

Future Needs: Cryogenics, Acoustics, Automation

The mutual influence of the different nature of loads on a modern airframe is such that to obtain a closer approach of the in-flight behavior, analytical methods do not exist and the ground test facility ought to include most of the simulation requirements together. Two major items must be thought of in this respect, cryogenic and acoustic simulations, along with more automation.

"The problem of acoustically induced fatigue has plagued the reliability of structural components of many jet aircraft. Numerous ground simulation facilities dealing with this problem have been built in industry and government. Many problems particular to a specific aircraft have been solved by these facilities and limited design criteria were established for sonic fatigue resistant structural components. Today a high percentage of fatigue failures occur in substructure components such as stringers, ribs, beads, and webs. One shortcoming of component testing in the laboratory is the fact that the specimen is disconnected from the total structural assembly, that is, the boundary conditions in the laboratory are not duplicated. This results in differences of the structural responses and associated frequencies. In addition, the laboratory sound field does not reproduce the service environment entirely. Also the simulation of additional combined loads causing thermal, static, and other dynamic stresses is required. Recently performed experiments on large scale structures showed that the small component development effort is only part of the total requirement and that large component testing is mandatory to assess the effects of interaction between the components of a structure. Since the vibration analysis of this type of structure is too complex, laboratory experiments seem to be the only way to assure integrity from a fatigue viewpoint. Therefore, with aeronautical vehicles becoming larger and larger it becomes necessary to have acoustic test chambers available which can accommodate large sections of these vehicles for the development testing phase. Full scale sonic fatigue test of the complete or large sections of the structure is still required to fulfill structural requirements and reliability specifications. Initially this was accomplished by exposing the structure to its own noise environment during an engine ground run up. This procedure is very expensive and has the disadvantage that accelerated testing by exposing the structure to higher noise levels than experienced in service is not possible."

"The other end of the thermal spectra - low temperature - presents the area of greatest facility weakness for cryogenically fueled hypersonic vehicles. In conducting structural tests on these vehicles it will be necessary to simulate the extreme cold of the fuel along with its relative heat sink effects. It appears that for hydrogen fueled vehicles the LH_2 itself must be used as the test simulant. This obviously poses very difficult facility design problems; particularily that of safety of operation."

"The overall operation of the test facility considering the simulation of these extreme environments, each controlled by a sophisticated electronically programmed system, has developed into a serious problem of combined facility operation. The complexities of the individual systems (loading, thermal simulation, data acquisition, etc.), are tending to produce combined operations problems requiring very careful operational procedures to insure successful test operation and to protect the extremely costly test article from detrimental effects of inadvertant test system malfunctions. Since testing of this nature requires a 'countdown' procedure, and once the test is started, all subsequent actions are preprogrammed, some means of real time test monitoring with built-in periodic fault checks and 'over test' abort capability must be developed."

CONCLUSION

"The structures test engineer's problem of the future can be summed up very briefly. The selection of material and the design of a structure for vehicles which fly at hypersonic speeds is a very complex problem. Each vehicle and each part must be designed and analyzed to provide the most structurally efficient configuration for the specific application. There is very little actual experience, flight or otherwise, to provide a basis for analysis, and what experience does is mostly on vehicles totally unlike the ones being considered for this flight regime. The aerospace industry is now deeply involved in the renaissance of flight within the continuum. Designs for the development of aerospace vehicles of unprecendented size, weight, sophistication and performance are being conceived for vehicle development in the 1970 - 1985 time period. However, their development may be delayed or even precluded unless a broad technological base is established to cope with the nature and magnitude of foreseeable technical problems associated with these aerospace vehicles."

ACKNOWLEDGMENTS

The first and last chapters of this presentation reviews and summarizes the main statements and conclusions of AIAA Paper No. 68-1084, by Zonars, Lowndes and Kolb, entitled "Ground Testing" which was presented at the Fifth AIAA Annual Meeting in Philadelphia, Penn., on October 21, 1968.

The innocent contribution of these authors to my paper has enabled me in focusing my presentation of two specific examples to their assessments in the field of hot airframe ground test methods and facilities. Thanks be to them. I also want to thank the Space Shuttle Team of McDonnell Douglas Astronautics Company of which my Company, SNIAS, is an associate in the Phase B study, for their advice and material help in preparing this paper.

ILLUSTRATIONS

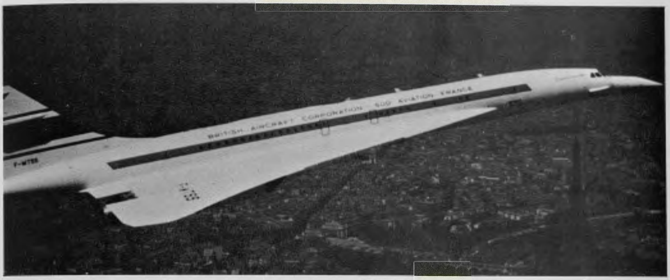


FIGURE 1

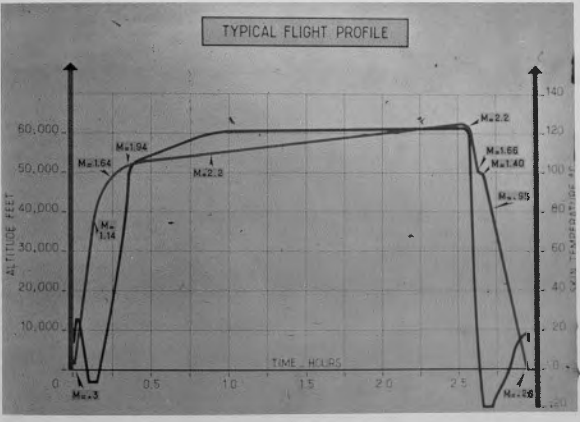


FIGURE 2

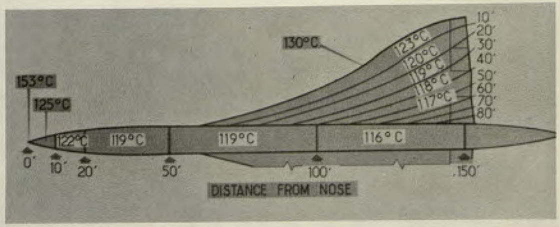


FIGURE 3

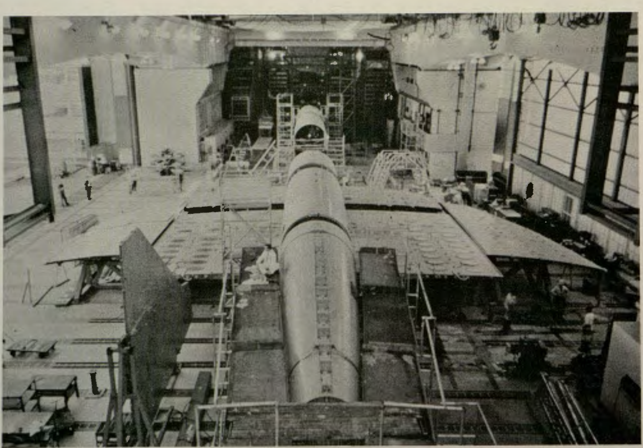


FIGURE 4

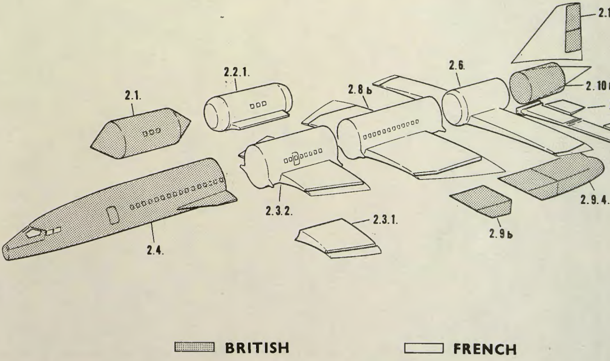


FIGURE 5

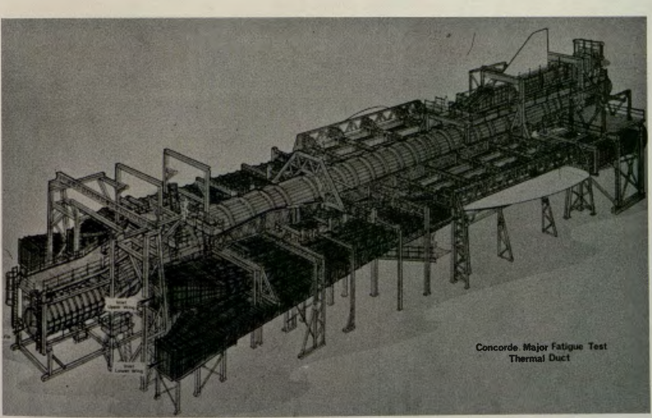
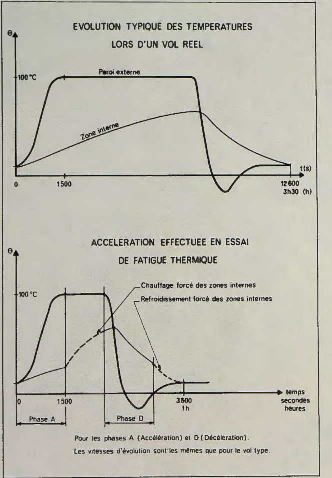


FIGURE 6



EVOLUTION TYPIQUE DES TEMPERATURES LORS D'UN VOL REEL

ACCELERATION EFFECTUEE EN ESSAI DE FATIGUE THERMIQUE

Pour les phases A (Accélération) et D (Décélération).
Les vitesses d'évolution sont les mêmes que pour le vol type.

FIGURE 8

MAJOR STRUCTURAL TESTS

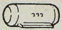
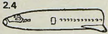
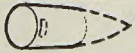
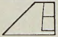
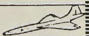
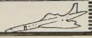
SPECIMEN AND NUMBER		TEST LOCATION	DESCRIPTION	TYPE OF TESTS
2.1		BAC FILTON	15' Fuselage section	Pressure, Static hot and cold. Hot fatigue,fail safe
2.2.1		CEAT TOULOUSE	Fuselage section to original design	Pressure, temperature and torsion
2.3.1		CEAT TOULOUSE	Forward wing	Static hot and cold Fatigue hot and cold
2.3.2		CEAT TOULOUSE	Fuselage and forward wing	Static hot and cold Fatigue hot
2.4		RAE FARNBOROUGH	Forward fuselage	Pressure, bending, Static hot and cold. Fatigue hot and cold
2.6/2.7		CEAT TOULOUSE	Fuselage and rear wing	Fatigue hot and cold
2.8b		CEAT TOULOUSE	Fuselage and centre wing	Static hot and cold Photostress and fail safe
2.9b		BAC FILTON	Prototype intake	Static cold Thermal soak
2.9.4.1		BAC FILTON	Pre-prod intake	Static hot Fatigue hot
2.9.4.2		BAC FILTON	Pre-prod rear engine bay	Static hot and cold
2.10b		BAC WEYBRIDGE	Pre-prod rear fuselage	Static hot and cold
2.11.1		CEAT TOULOUSE	Elevons - stainless steel honeycomb	Influence coefficients, vibration, static hot and cold
2.11.2b		CEAT TOULOUSE	Elevons Aluminium alloy honeycomb	Static, fatigue hot and cold acoustic
2.12		CEAT TOULOUSE	Rudders - transferred as part of static airframe	
3		CEAT TOULOUSE	Major static airframe	Static hot and cold
4		RAE FARNBOROUGH	Major fatigue airframe	Fatigue hot and cold

FIGURE 7

FIGURE 9

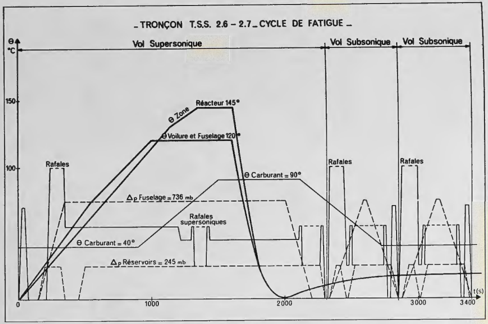


FIGURE 10

FIGURE 11

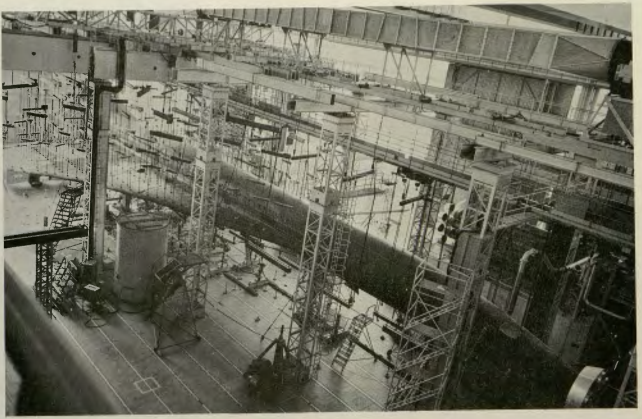


FIGURE 12

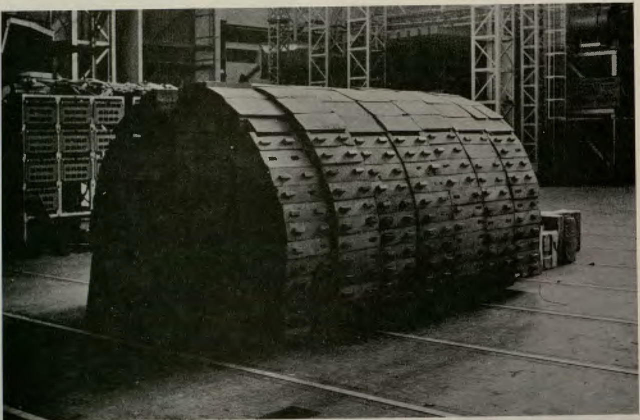


FIGURE 13

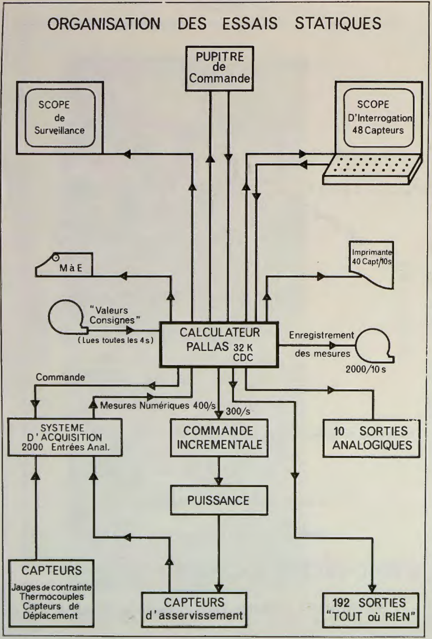


FIGURE 14

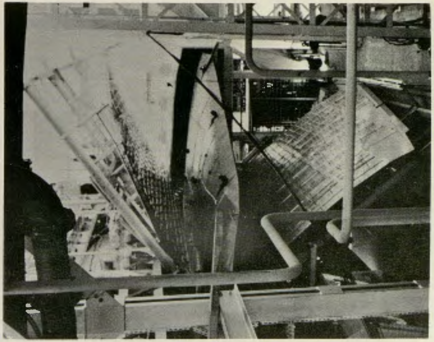


FIGURE 15

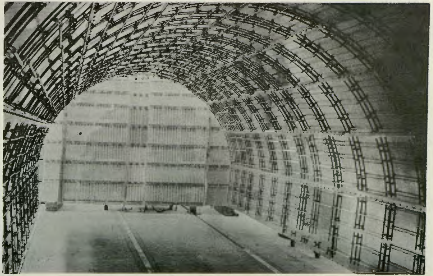


FIGURE 16

FORMULE GÉNÉRALE D'ASSERVISSEMENT DE CHAUFFAGE

$$u(t) = \Theta_p(t) - \Theta_m(t) + K(t)\,\frac{[\Theta_p(t) - \Theta_m(t)] - [\Theta_p(t-T) - \Theta_m(t-T)]}{T}$$

$\Theta_p(t)$	température de consigne à l'instant t
$\Theta_m(t)$	température mesurée à l'instant t
T	période d'échantillonnage
Δn	nombre d'ordres à envoyer (incréments ou décréments)
β	gain en incréments /degré

CARACTÉRISTIQUE n (u)

La caractéristique n (u) est représentée ci-contre pour $\beta = 0{,}66$ incrément /°C
Δn est écrêté de façon à avoir $|\Delta n| \leq 6$

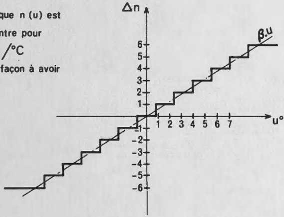
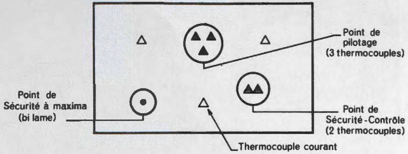


FIGURE 17

ORGANISATION DES MESURES DE PILOTAGE ET DE SÉCURITÉS D'UNE VOIE DE CHAUFFAGE



TRAITEMENT EFFECTUÉ PAR L'ORDINATEUR

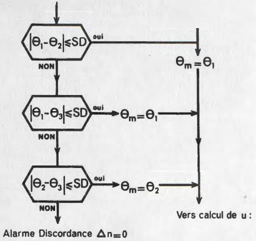


FIGURE 18

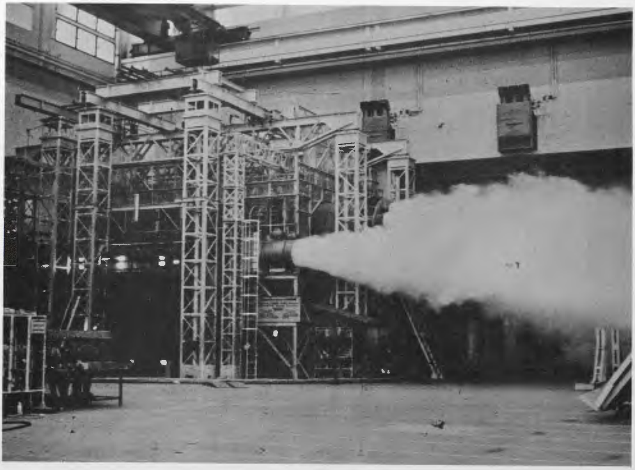


FIGURE 19

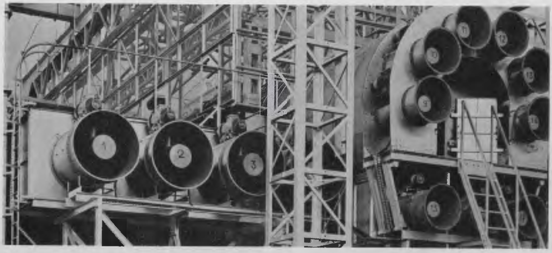


FIGURE 20

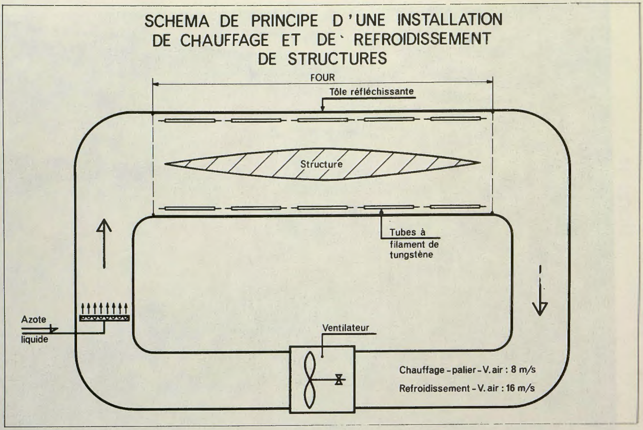

SCHEMA DE PRINCIPE D'UNE INSTALLATION DE CHAUFFAGE ET DE REFROIDISSEMENT DE STRUCTURES

FIGURE 21

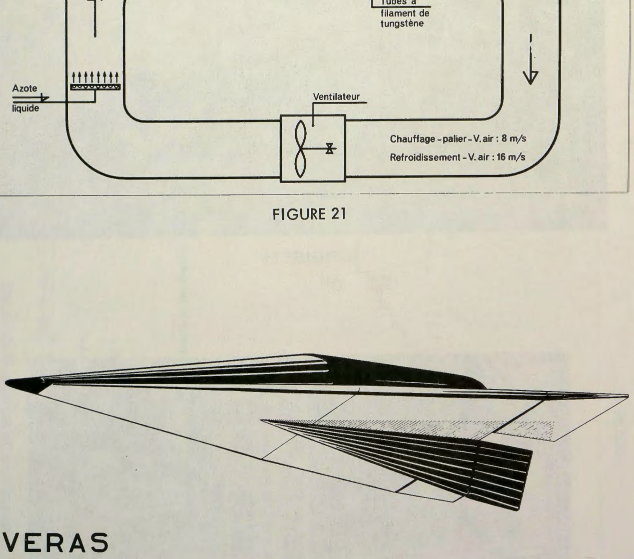


FIGURE 22

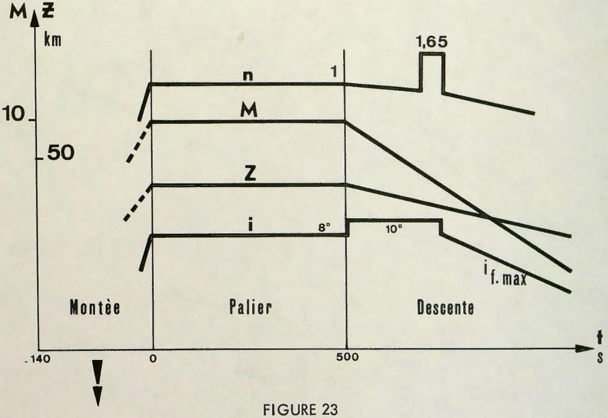


FIGURE 23

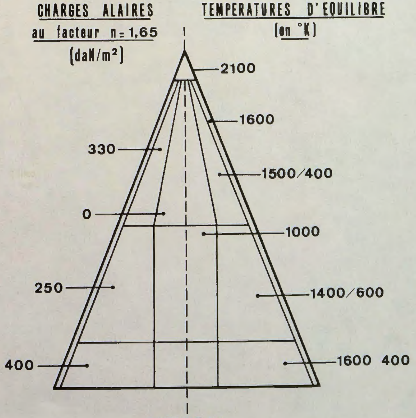


FIGURE 24

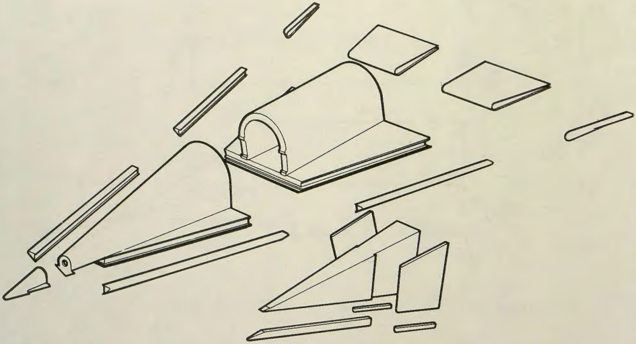


FIGURE 25

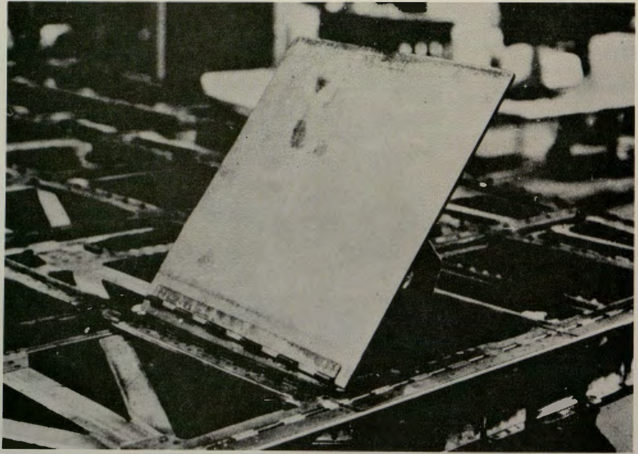


FIGURE 26

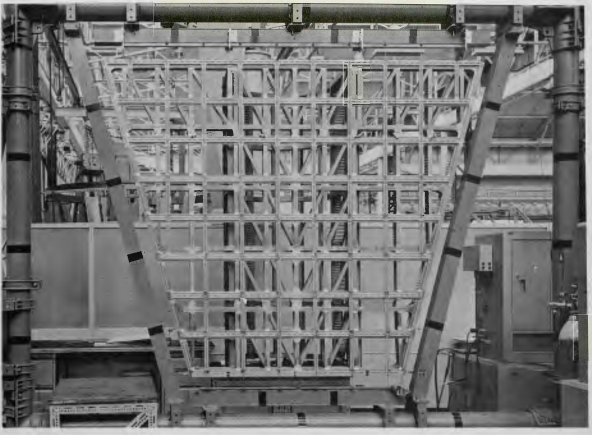


FIGURE 27

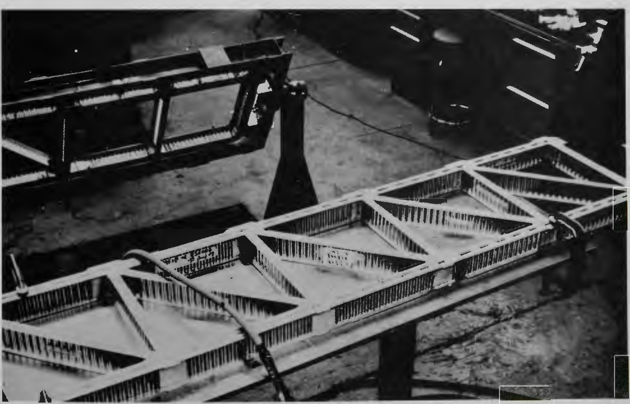


FIGURE 28

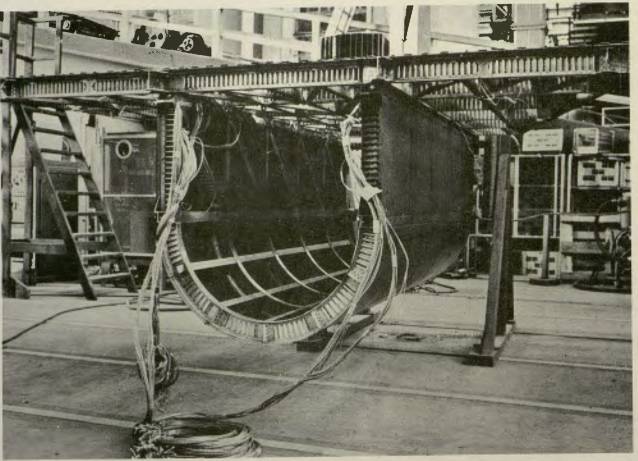


FIGURE 29

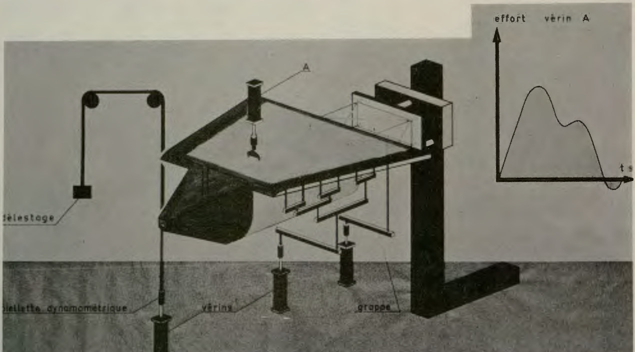


FIGURE 30

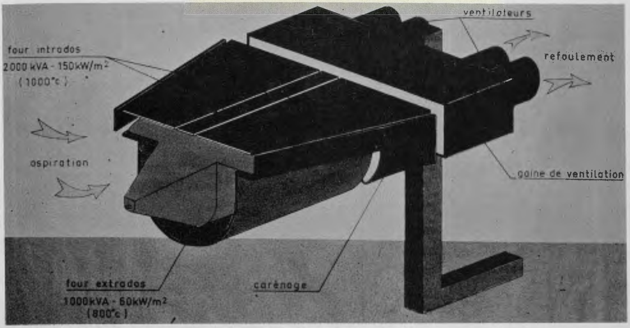


FIGURE 31

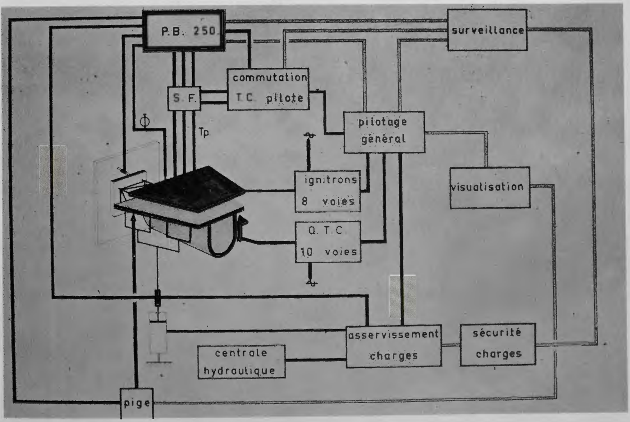


FIGURE 32

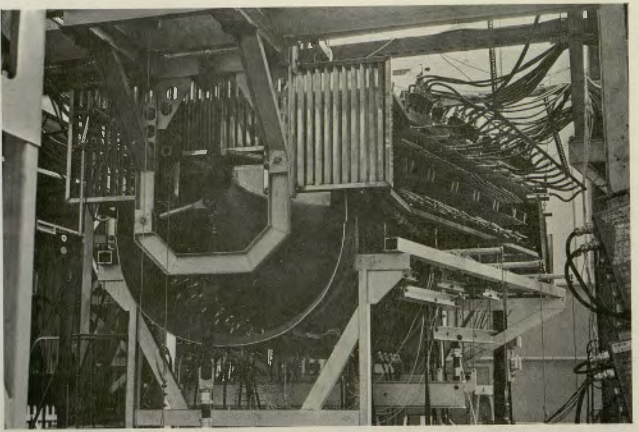


FIGURE 33

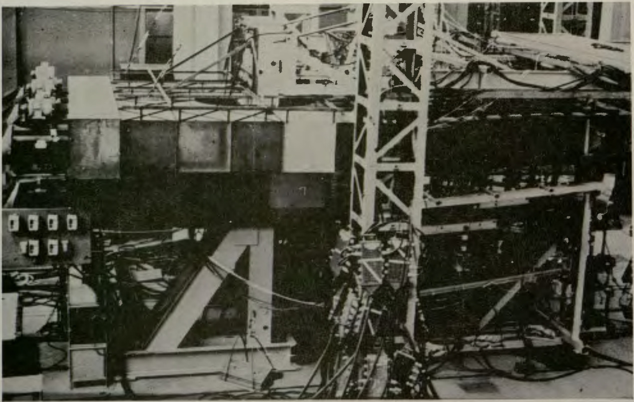


FIGURE 34

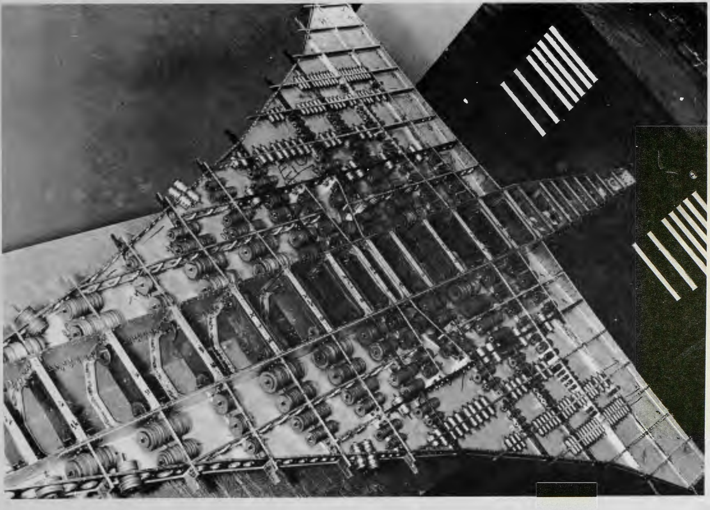
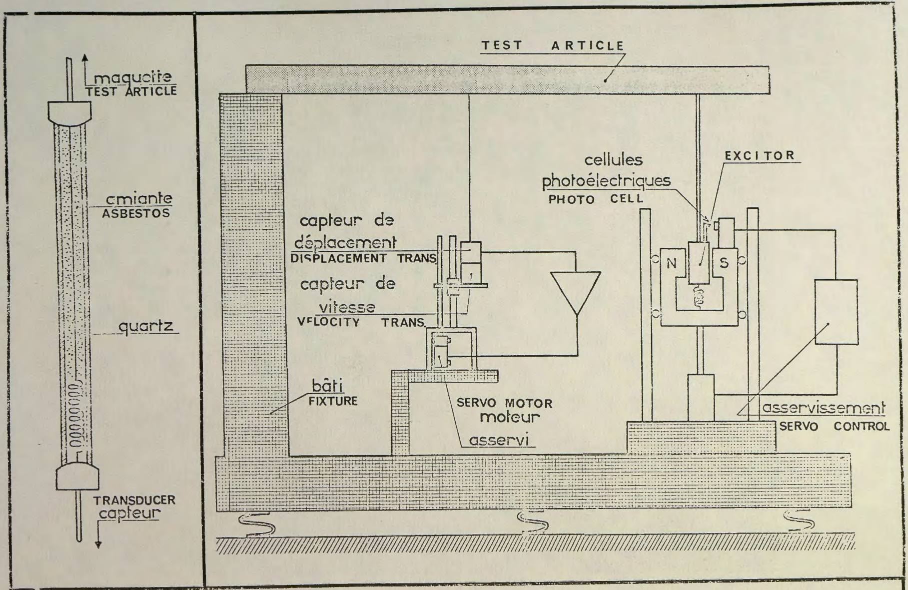


FIGURE 35



MECHANICAL VIBRATION TEST SET-UP

FIGURE 36

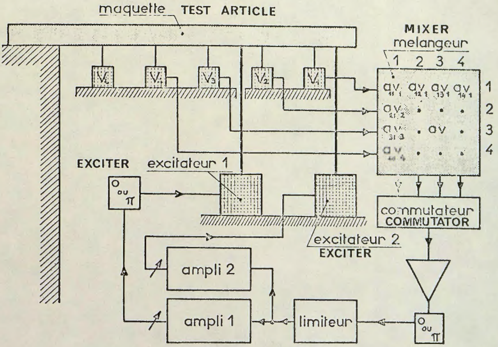


FIGURE 37

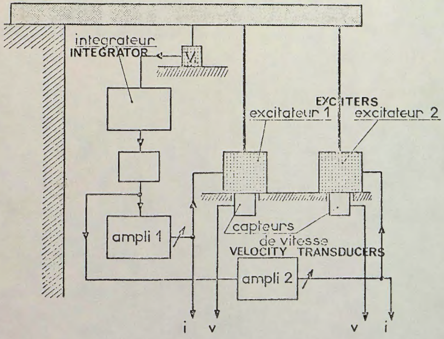


FIGURE 38

FIGURE 39

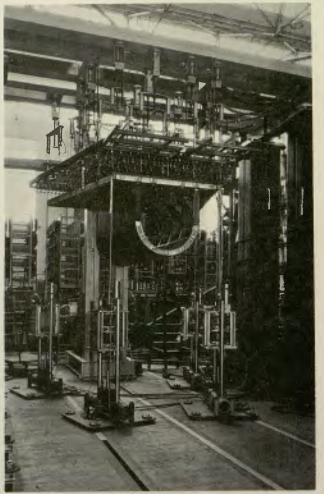


FIGURE 40

FIGURE 41