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The Fatigue Safety of Aircraft in Service and its Supervision in the view of F+W Emmen

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Report S - 164

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Summary: The fatigue safety of aircraft in service is ascertained by simulating its service fatigue life in a full scale test on the ground. The key of the problem's solution is a test facility capable of simulating the genuine sequence of the loads occurring in service, such as does the "Fatigue History Simulator" of F+W.
A scheme is detailed for all work which has to be done before, during and after the test, including the evolution of the history loading program. Special inspection methods are mentioned and an example of the displaying method is described. A method to estimate the factor of safety and it's influences is proposed. The aviation authorities are asked to adapt the proposed procedure in the airworthiness requirements.
Finally it is demonstrated that this meets the financial and safety needs of the operators.

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Paper presented at the Second Seminar on Fatigue and Fatigue Design, May 5th, 1964 at the Columbia University, New York, with the permission of the Service Technique Militaire (STM) in Berne, and by the kind invitation of Prof. A.M. Freudenthal, Columbia University, New York.

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A. The philosophy

The conception which ruled the design of the Fatigue History Simulator (report T-197) and the fatigue testing of the P3 (report S-162) and the DH-112 (report S-163) aircraft does not need many proofs. The knowledge of these three events should almost be sufficient to be convinced of its value. Therefore, it may be permitted to put at the beginning of this report in briefness the philosophy which lays behind the whole work:

You dominate the fatigue safety of aircraft in service if you simulate its life in a test on the ground early enough, and as identical as ever possible to their service life, and by supervising the test specimen continuously by the best methods known.

One point needs some explanation as it is not yet commonly recognized, it is:

B. The genuine load sequence

In the year 1956 an international conference on fatigue in aircraft structures was held at the Columbia University. Already at this conference, Prof. A.M. Freudenthal had shown "that the effect of the load sequence appears to be quite pronounced".

At the same meeting Mr. P.J.E. Forsyth said: "If one examines a coarse slip band produced by fatigue, it can be seen that the reversal of stress has produced a set of slip lamellar. No doubt some reverse glide occurs on the original planes, but the important fact seems to be that a second set of glide planes comes into operation. Not every reversal of stress produces new bands, but the number of bands appearing on the surface of the fatigues specimen increases with time".
Also at that meeting Mr. R.F. Hanstock referred on his measurements of the hysteresis caused by the inelastic deformation during each stress cycle. From these observations may be seen, that strain cycling has differing and non reversible effects, which may lead to the explanation of the influence of the load sequence.
At the first symposium of ICAF and AGARD held in Amsterdam 1959 Mr. J. Schyve referred on the tests made in Holland which showed also the great influence of the load sequence.

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Therefore, it is rather astonishing that there are still bodies which try to find the service life of such complex structures as an aircraft by single amplitude cycling or by program loading such as in Fig. 1. If this would be permissible, equations as in Fig. 2 would be right. Certainly that is not the case. The reason for such arbitrary programs is not a scientific one, but the limited capability of the fatigue machines. Obviously, the machines are dictating the methods, instead of the inverse.
Even random tests are not the answer to the problem. Prof. Freudenthal stated 1956: "It is not impossible that the fact that we have used random load sequences may have produced an excessive severity in our load sequence". And Mr. Kuhn of NACA, also 1956, stated: "The most direct attack on this problem would be to conduct laboratory tests duplicating the service loading as exactly as possible".

The most evident solution of the problem is certainly the genuine sequence of the loads, because, if the sequence has any effect, there is simply no room for any other sequence than the genuine sequence. The only explanation for the fact, that it was not simulated earlier, is the lack of corresponding facilities. We think, that this point is definitively overcome by such facilities as our "Fatigue History Simulator" which is capable for "history loading" any aircraft.

With that in mind, let us have a look at the scheme of the "History Loading" Fig. 3, as opposite to all program loadings and random loadings. The terms mean:

Δ = lowest considered step between different magnitudes of loading. It should be chosen not greater than 5% of the ultimate load.

l_q = quasi-cycle, general term for symetric and asymetric cycles.

f_1 = first of a random sequence of flight types, f_q the last one. Each flight type simulates an actual genuine flight.

q = period, all flight types of an unique sequence, which can be repeated so often as you like. We shall see later how to build up a period.

H_q = number of quasi-cycles in a period.

f_q = number of flight types, different our uniform, in a period.

T_q = simulated number of service flight hours represented by a period.

To avoid each misunderstanding, I am mentioning here, that, of course, the size of loads, their number and the number of flights are exactly simulated.

Now we can go on to show how to realize the task.

C. The working scheme

This plan as laid down can be used generally

Phase I

1. Determination of all load cases which may occur. These are first of all the three main load cases, i.e. air case positive and negative as also the groundcase.

   In the air cases included are the lift and inertia forces, engine thrust and drag as well. Superposed to these loads are from time to time the forces from elevator, aileron and rudder as also those from flaps and air brakes. Furthermore, there is the cabin pressure and pressure of the fuel tanks or integral tanks, and these with regard to the dynamic pressure differences. With aircraft to the M 2 classe a temperatur rise due to dynamic pressure must also be considered.

   Superposed to the vertical inertia forces of the ground cases are the forces from running up the engine, the spin up force of the wheels on touch down, wheel braking and side loads on taxying.

2. Determination of the weight history. For proportional load variations, as by fuel consumption, a few steps have to be chosen, for instance all 20% of the full content.

3. Determination of the load distribution for the invidual load cases, based on the measurements of pressure distribution in the wind tunnel and on detailed weight calculation.

4. Summary of loads of the same kind and distribution to single points, and determination of the resulting forces for the static failure test as also the minimal necessary numbre of jacks (in many cases the air and inertia forces may be combined). In any case the total resultant must be zero.

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5. Determination of the max. bending in the static failure test and accordingly the minimal necessary stroke of the jacks (the deformation to the other side must only be added for the fatigue test).

6. Set up of the first hydraulic scheme, i.e. determination of those jacks which are working for the different load cases simultaneously and also for those jacks which are giving a superposed load.

7. Design and build of the rest rig.

8. Fix up of the specimen for the static measurement tests and for the failure test. This means the arrangement of the load introduction points (which must not weaken or strengthen the structure, and on the other hand should obscure the structure not more than necessary) and of all gages. Furthermore, the displacement bodies must be fitted which enable the use of air instead of water for pressure differences.

9. Installation of jacks, the whiffletree and the test specimen, and the connection of the hydraulic load maintainer. Of the electronic only the defect supervision and the manual control of the control pressure is necessary but not yet the program control.

10. Static tests.

With them Phase I is terminated, and whereas the results are being worked out, and respected for the other prototyps

<u>Phase II</u> is running parallel. This takes perhaps one year time.

11. Multi-flight-measurements on a prototype with a special instrumentation to get information about the dynamic behaviour of the aircraft, and the relations gust/acceleration and acceleration/local stress as far as they are not yet known from wind tunnel tests. With this information we are getting a connection to the existing gust statistics.

12. Continuous records of some criterion, as v - g (c.g.) - h - T - G (fuel) - stress at certain points (if possible statical determined) - longitudinal and lateral acceleration (for ground loads) in the following kind of flights:

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a) Test flight by test pilots.

b) All of flights for which the aircraft is intended (in peace). Al these flights by service pilots. At least one flight for the following combinations:

Some different
   Characters of the pilot (say A, B, C)
   Distances and routes flown
   Weather,
   The season and
   the different parts on the globe (which may be flown in peace).

The flights a) and b) are not special flights but can be made in combination with the test flights which are anyway necessary with a new type of aircraft. If for the fatigue test an aircraft is used which was already in service the flights "a" may be remitted, and the flights "b" may be flown with aircraft in service of the same type.

The evaluation of these records is a most important task and a very fatiguing also, It needs a person who's knowledge in fatigue is good since he has always to interpret (e.g. the friction in the jacks) and also to pay regard to the commentary of the pilot. We use for the evaluation a device which was made by ourselves, consisting of glass-lamp - 2 cranks - calibrated sheet - as shown in Fig. 4, on which the record is fixed.

By this manner we get the flight types f_1 to f_q

13. Statistics, i.e. compiling of all happenings:

   a) Service flights, separated according to the combinations of 12 b with registration of the appropriate weight historys, and their relativ happenings

   b) Gust spectra as known and compiled under similar conditions as the service flights

   c) Exceedings of the permitted limits (all aircraft have to be fitted with trailing pointer on the accelerometer or similar means).

14. Build up of the program for one period

   a) The length must be such, that the most rare happening appears at least 1 time as far as it has to be simulated in the automatic program. This results in the determination of T_q and hence it follows f_q.

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b) From 13 b, reduced to this T_q, a rough skeleton results, which is for checking of the product from 12 b and 13 a. If necessary some modification are made until conformity with the mentioned spectrum-skeleton is reached.

c) From each flight-type is now known, how many times it exists in a period. The whole number f_q (of the different and of the uniform) flight-types are numbered continuqusly and mixed according the Monte-Carlo method. This only is random. But not always, as it may be, that season groups, etc. are grouped together, and only within them a random sequence is made. The whole sequence of flight types yields to the period q which is transferred by a computer to the tape.

15. For new test specimen a special program from 12 a is made which is run at first and only this time.

16. Adaption of the test facility:
After all the program orders are known, the facility is adapted to the special requirements. This means alteration or completion of the wiring for the electronic control and supervision, fitting of electro-hydraulic valves (for simultaneousness in the load cases).

17. Preparation of the test specimen, i.e. fitting of gages on critical points (statical determined, see 12), of instruments for supervision (television camera, sigmatest - transmitters) and of the load attachment points.

    Furthermore, if and where pressure-differences have to be simulated, displacement bodies must be fitted which enable the use of air instead of water.

18. Fitting of test specimen and connection to the hydraulics and electrics of the rig.

And now to

<u>Phase III,</u> which is the most important.

19. Run of the fatigue testing. First, simulation of the test flights, and then running the periods "q" which are repeated continuously, only interrupted by the regular inspections.

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20. Determination of the virtual advance factor

$$\varphi_v = \frac{T_q}{T_v} \text{ , where}$$

T_q = simulated service hours per period,

T_v = number of test hours for the lapse of one period.

21. Control of the use of the service aircraft in such a manner that at the beginning their operation remains about equal to each other. Determination of the highest service factor η (effective flying hours per year to 8760).

22. Determination of the effective advance factor

$$\varphi_w = \frac{T_q}{\eta \cdot T_v}$$

23. Fatigue defects which are detected on the test specimen are repaired or reinforced in the same manner as this would be made on operational aircraft. The latter are perhaps only supervised at the position in question and a repair or reinforcing made after the test specimen has proved the usefulness of it. Should the defect however be at a critical position with possible fatal consequences, no time is wasted and all aircraft are repaired and reinforced. Nevertheless, the repaired and reinforced test specimen should prove its correctness or fault before any failure on operational aircraft can occur since the test is always in advance. On the other hand all modifications made on operationel aircraft have also to be made on the test specimen.

24. Determination of inspection periods for the operational aircraft, i.e. lapse of time and extend of inspections. After a sufficient advance is reached the extend of inspection and lapse of time are revised, holding the inspections as small as possible with the greatest possible space of time between them.

25. After a non reparable failure has occurred the service life time Z is fixed, and perhaps a new safety factor ζ against fatigue failures laid down to get the admissible life time

$$Z_{adm} = \frac{Z}{\zeta}$$

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Though the fatigue test is terminated, we have to look at

Phase IV:

26. On all service aircraft the v - g - h - records and fatigue meter counts are continued as long as the aircraft is used. These readings are continoúsly evaluated. It is thus possible to fix eventually a new admissible life Z_{adm} or a new safety factor, should any change in the spectrum occur. It is furthermore possible to pay regard to any change in operation (when this is not too big), and other observations on the aircraft can also be evaluated.

D. Special Inspection Methods

As it may go rather a long time until a fatigue defect appears, it is of utmost importance to develop and use inspection methods which allow the detection of defects as early as possible. By such methods it may be possible to save valuable test time.
These inspection methods should allow as far as possible an inspection without interruption of the test to save time, since the inspection time is e.g. 40% of the overall time.
By means of a few examples I like to show some possibilities and also incite the development of further methods since our next aim is the introduction of automatic inspections.

1. Optical methods

Inaccessible places may be watched by television cameras. For that the surfaces are treated with soot with which cracks are better visible. Several cameras may be switched one after the other to only one screen. This method is not automatic but nevertheless rather simple, and since the television-material may be re-used the method is not to expensive neither.
In certan cases a suitable method would be by introducing endoscops. This too enables the detection of cracks of a certain size optically at otherwise inaccessible parts.

2. Displaying Methods

In any aircraft exist parts which can be watched by no method when fitted in the structure. If a failure of such parts would lead to a fatal accident, it should be tried with all possibilities to get knowledge of the

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begin of cracks. This is approximately possible, when you imagine this part without the surrounding structure. When you take one or more samples of such a part, and make with them the same program it is possible to get the necessary observation. It is, however, of importance that the displayed parts in their critical zones get the same stresses as the parts in the aircraft.

For certain cases it may be necessary that not only the single part but the whole groupe to which this part belongs must be built and tested parallel to the main-test-specimen. Such a sub-assembly must, however, allow the observation without restriction what means that all unnecessary parts are omitted.

This method is explained on an example which is running parallel to our VENOM full-scale test and which is of interest also as a comparative test. In report S-163 is mentioned that the area of the kink at the lower wing spar boom of the DH-112 aircraft must be considered as very critical, and that it is impossible to examine this area for cracks. All tests to identify cracks by x-ray which have been produced at this area artifically, have failed.

We have thus decided to design a special test rod Fig. 5, which we formed so that it has in the two main axis the same stress situation as the critical spar boom area, and to submit it to the same program as the aircraft.

The manufacturing history of the spar booms made in Switzerland for the DH-112 series has shown that they must be classified into 6 groups which differ by provenance, treatment and machining methods. We have of all spar booms test specimens which were cut from the booms after final treatment, and which have the series No. of the belonging boom stamped on. Of each group 6 such special test rods were machined. Thus we had a total of 36 rods to which the history loading has to be applied, parallel to the aircraft test specimen.

To this end we designed and built a rig which allows the testing of 36 test rods with the same program (Fig. 6). The rig consists of 2 chains with 18 identical test specimens each. Obviously, of a similar arrangement in Australia was spoken 1961 in Paris by Mr. Mann. The test specimens are attached by universal suspension to mounting blocks which slide in ball bearings.

Max. load = ± 11,7 tons, friction (total) max. 2 %o. The test rod Fig. 5 is made eccentric to produce a bending stress similar to that on the original boom at

the kink. The hole in the test rod corresponds to the bolt hole near the spar boom kink, and has also a bolt fitted. To double the number of critical test areas we have made 2 holes. The stress concentration factor α_K calculated after the English Data sheets, is giving at the hole a value of 3.24 and opposite to the hole 0.95. This does not mean that this is the real stress concentration factor. The ratio of bending stress to average stress is 0.48 ($\sigma_b = \sigma_m \pm 0.48 \sigma_m$). This rod is called ICAF test rod since we intend to do with it further programs.
The mentioned 6 groups of rods, the test of which is actually running with the full scale VENOM test, consist of the following materials:

Group	0	Perunal 755.6 (AIAG)
"	1	Perunal
"	2	Perunal
"	3	C 77 S (Northern)
"	4	DTD 363
"	5	DTD 363

The rod's ultimate tension load is 12'500 kp or 27'500 lbs.

Whereas for a whole aircraft the spectra of the air loads and of the ground loads mustbe represented separately, it is possible to combine them for each single part of an aircraft. This is true also for this kink in the spar boom and thus also for this test rod. Therefore, it is possible to present the spectrum which the 36 rods have "suffered" up to now. On march 24 th (1964) they had 12000 hours, without failure. That is the spectrum fig. 7. In this same spectrum are represented the results of 4 different constant amplitude fatigue tests which were made with this test rod, by the two respective load limits and the number of cycles to failure. Even neglecting all other load limits and only calculating with these 4 results, using Miner's theory, the cycle ratio sum is now 4.332, and we have still no failure. We expect to get finally a figure of at least 10. It is not necessary to outline the importance of this result on the economical aspect of the fatigue safety of aircrat in service!

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3. Electronic Inspection Methods

It is most probable, that the problem of automatic inspection is solved by electronics. We have not yet realized such a solution since the expense is considerable even when this has to be made only once. Since the consideration of an unique expense has not the same meaning in the U.S.A. as in Switzerland I would propose such a solution, which should be feasible, to USA.

Everybody will know the Sigma-Test apparatus of Dr. Förster, Germany, for conductivity measurements of metals. The probe coil of this instrument is energized by alternating current and placed on the surface of the part which is to be measured. Consequently the alternating magnetic field of the coil induces eddy currents in the specimen. The effect produced by these eddy currents change the electrical properties of the probe coil in function of the surface conductivity. This instrument could be specially adapted to detect cracks.

If many, say thousand of such special coils are glued on the surface of all important areas of the airframe it would be possible to measure the electrical conductivity any time during a full scale fatigue test. The measured data of each coil has to be stored separately in a computer. Each new data is compared with foregoings by the computer. If the difference signal exceeds a fixed limit, the computer will give a signal.

An automatic electronic inspector like this would be more accurate, more reliable and much quicker than a man. This method would save nearly all that standstill-time which is actually needed for the human inspection. More important: Cracks at unaccessible areas would be detected much earlier, and this will save even much more time.

E. Factor of safety against fatigue failure

1. As already mentioned, the factor of safety against fatigue failure is the ratio of the service life time Z resulting from the fatigue test to the admissible life time Z_{adm} of an aircraft ($\varsigma = \frac{Z}{Z\ adm}$)

2. Thus, it depends on a fatigue test without which a factor of safety cannot be calculated for the time being. Therefore, it also depends on how the fatigue

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