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DETERMINATION OF LOAD SPECTRA AND THEIR APPLICATION FOR KEEPING THE OPERATIONAL LIFE PROOF OF SPORTING AIRPLANES

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Abstract

In this paper a procedure is presented which applies modern techniques for the determination of load spectra and for keeping the proof of operational life of sporting aircraft illustrated by reference to GFRP sailplanes. These planes are well suitable because they experience a strong mutual influence of gust and manoeuvre loading resulting from their way of gaining their flight energy. It is demonstrated how the measured data gained during a limited time interval are prepared by means of computers, stored in a Markov-transition-matrix and extrapolated to the total life-time of the gliders. The possibilities of forming a load spectrum adequate to the design life-time are discussed and the best suitable method is described. Furthermore, problems are considered which occur during the serviceability test when working down the load collective. Different possible solutions are shown and the results taken with the different solutions are compared to each other.

Introduction

For transport and commuter aircraft as well as for military aircraft the missions to be flown or single phases of these missions are well known. There are enough flight data measurements allowing the derivation of load spectra with a good probability.

For military aircraft the frequency of their sorties for a mission may extremely differ from aircraft to aircraft. Therefore the aircraft loadings are continually recorded so that the load history of every individual aircraft is known at any time.

With the knowledge of crack endangered areas from the load testing, with the knowledge of the speed of crack propagation and the resulting determination of inspection intervals, and with the verification of a damage tolerant design it is possible to detect cracks in metal constructions early enough and to certificate such aircraft with an "open end".

Conditions are totally different for modern sporting aircraft. Sporting aircraft are used for the most different purposes (touring, school flying, exercising, simple acrobatic flying) and with different frequency without recording of the occurring loads.

The next point is that modern sailplanes of today with only few exceptions and modern motor aircraft for sportive usage more and more are built of fibre reinforced plastic. At the time being no test methods are known the application of which allow the determination of cracks during an inspection of the assembled aircraft.

The missing knowledge of the load history together with the impossibility to detect causes of damage in time thus call for fundamental reflections about the derivation of load spectra for the determination of the life-time of sporting aircraft and shall be illustrated on the basis of load derivation for gliders. These planes are well suitable because they experience an extremely strong mutual influence of gust and manoeuvre loading resulting from the way of gaining the flight energy.

Bases of the fatigue proof of gliders in Germany at the time being are measurings of gust densities and frequencies in low flight levels, which had been made by H.W.Kaul in 1938 on the bases of c.g. acceleration measurements.(1) However, he counted only extreme values and he thus did not consider the elastic behaviour of the aircraft which is additionally yielding the overshooting of the wing and its postvibrating.

Proceeding from these measurings W.Thielemann/F.K.Franzmeyer of the Institut für Flugzeugbau und Leichtbau (IFL) of the Technische Universität (TU) Braunschweig formed theoretical load spectra for the new-developped glass fibre reinforced plastic (GFRP) gliders in the mid 60's (Fig.1).(2) For influences not based on measurings estimations were made representing the state of the art and the then foreseeable development and were incorporated into the load

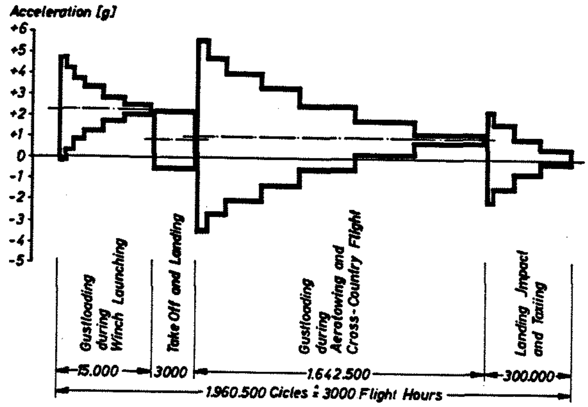

Fig. 1 Glider Load Spectrum According to W.Thielemann and F.K.Franzmeyer

spectra. Thus, a life-time of 3000 hours was supposed i.e. 15 years with 2oo flight hours, respectively, and the common way of flying was considered when composing the flight phases. Several fatigue tests together with static structural tests have been performed based on the above mentioned load collectives and let suppose that no fatigue damage within the proven life-time would occur. This assumption has been proved by day-by-day flights. Until the present day no fatigue failure of any primary GFRP glider structure sized according to these load assumptions has become known.

Using GFRP the aerodynamic efficiency - the lift-drag-ratio - could be raised by 50 per cent. At the same time, it was possible to increase the wing loading yielding higher maximum and cruise speeds. Additionally, the flight performance was improved by the more and more precise knowledge about shape and strength of upwind distributions and by the use of better avionics for judging the upwinds during the flight. As a result of these facts, today, distances up to 1500 km are flown at average cruising speeds of about 110 km per hour. For example, a modern glider has flown a triangular course with a range of about 1000 km within Germany with its rather unfavourable gliding conditions for such distances.

Two facts contributed to the achievement of these high flight performances: a strong change in the way of flying and a drastic increase of exercising efforts. For example, it demands special dive-in manoeuvres to take best advantage of upwind arrays which up to now have not been considered in the load assumptions because these loads and their frequencies were not yet known. The high training efforts common today result in a higher annual utilisation of gliders, and thus, allowable years of service of the low-maintainance, long-living GFRP gliders of today are reduced when fixing the number of total flight-hours allowed and proved now.

So it is highly necessary to know the loads and their frequencies occurring during present time service conditions. Otherwise it is neither possible to certificate the life-time of gliders exposed to these rougher service conditions nor to permit new materials and technologies.

A survey of the possibilities of today and how to use them is given in Fig.2. Characteristic signals are measured during the flight and are prepared to form load collectives by means of a computer which are finally existent in a Markov-transition-matrix. The load collectives stored in this way then can be fed to a computer which controls a servo-hydraulic loading facility. The load cycles for the loading device are randomly taken from the Markov-transition-matrix until the matrix is worked "down", i.e. emptied. Thus, the load cycle sequence is very close to the reality. This loading machine applies the measured loads to the component to be tested and the life-time at a given maximum stress-level can be attained as a result of such tests.

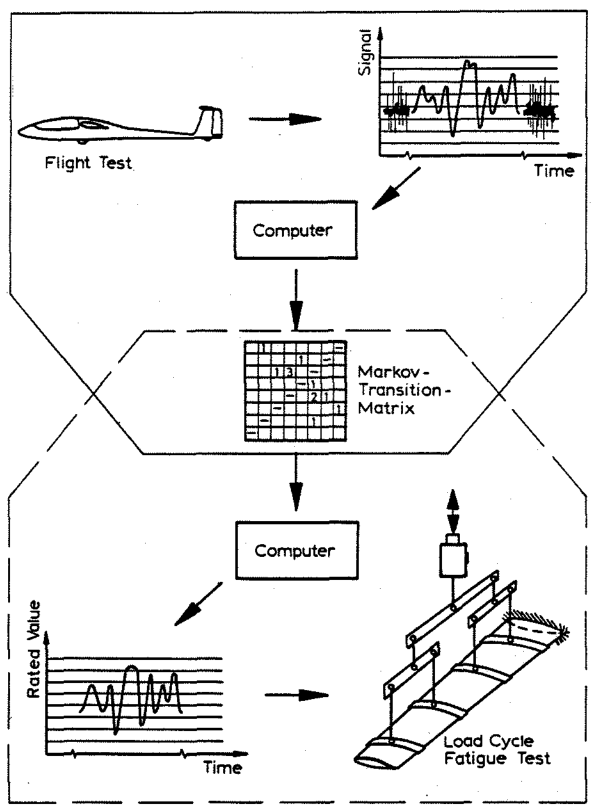

Fig. 2 Load Cycle Fatigue: Flowchart from Flight Test to Load Cycle Fatigue Test

Determination of Load Spectra of Sporting Airplanes

Under contract of the Bundesministerium für Verkehr (BMV), the IFL of the TU Braunschweig together with the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt Braunschweig (DFVLR) have performed in-flight load measurings. The plane used was the "Janus" glider of the DFVLR equipped with a 16 channel PCM-unit and the necessary transmitters.

As the most important primary structure of a glider is the wing and as its endurance has to be proved in the fatigue test, it is necessary to know the time-dependency of the characteristic value, which in this case is the statistical distribution of the bending moment $M_{br.}$. To measure it four strain gauges switched to a full bridge were applied in the wing beam connection area near to the wing root rib (Fig.3). The calibration of the measuring devices was performed on the ground by single-mass loading of the wing and the standardizing unit was found during a stationary gliding flight in calm air (1-g-flight).

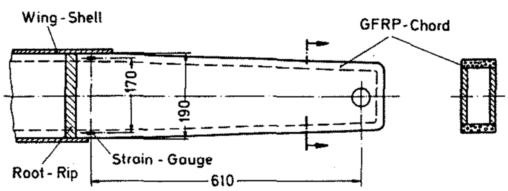

Fig. 3 Location of the Strain-Gauges in the Wing-Connection-Area

The reception and preparation of the signals is shown in Fig.4. On board of the glider the signals coming from the transmitters are amplified, digitalized, arranged in a serial manner, provided with a synchronous value, and recorded on tape. The individual flight phases like launch, landing, training flight, etc. are coded to enable separate assignment. These measured values must now be prepared in several steps by means of computer programs+. After synchronizing the signals the data are examined and digitalized to enable computer-adapted tape recording. Then the serial data are assigned to the parallel measuring units (bending moment, ramming pressure, upward acceleration of the center of gravity etc.) and runaway values i.e. obvious noise data are eliminated. For the digitalization the measuring range is subdivided into $2^{10} = 1024$ classes which later on are densified to 32 classes.

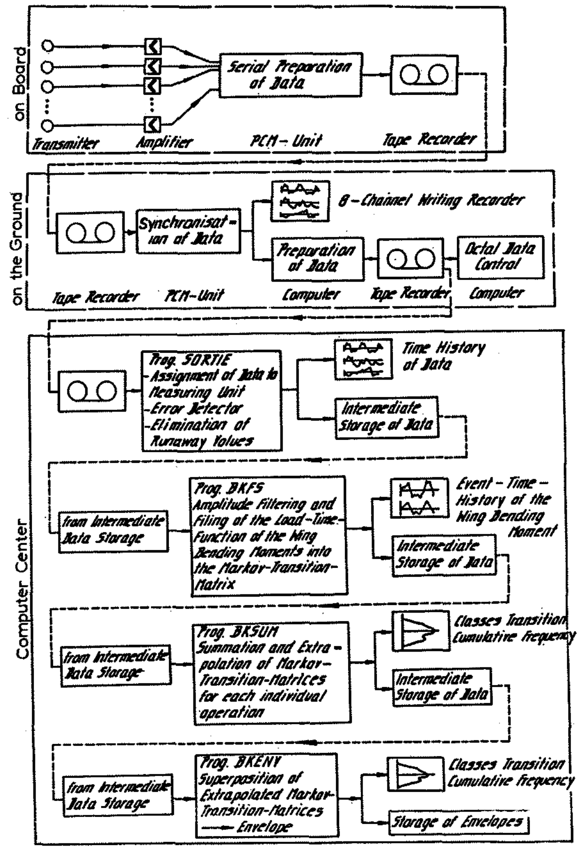

Fig. 4 Flowchart for the Load Spectrum Determination from Flight Measurements

After a respective time interval Δt the corresponding class is taken from the measured analogous signal which is running in that scanning pattern. The digitalized value of the measured signal is formed in this way. If the very fine class pattern with many little high-frequency oscillations is reduced without filtering (Fig.5, top) the dashed curve is obtained. By filtering it is possible to eliminate little vibrations between two adjoining classes which otherwise would be stretched to greater vibrations. This filtering is done by setting the condition that e.g. at least more than one class border ($DX > 1\Delta X$) has to be crossed before the amplitude value is put to the average value of the reduced class (Fig.5, bottom).

These prepared data are now stored in so-called Markov-transition-matrices. The proceeding for doing this is as follows. The number of transitions from one class to another one is recorded in a matrix-scheme (Fig.6). It must be noticed that any information on the time parameter is lost at this proceeding. This will not cause any problems for metals; for fibre

+ Program development was done at the IFL by Dipl.-Ing. W. Reinke

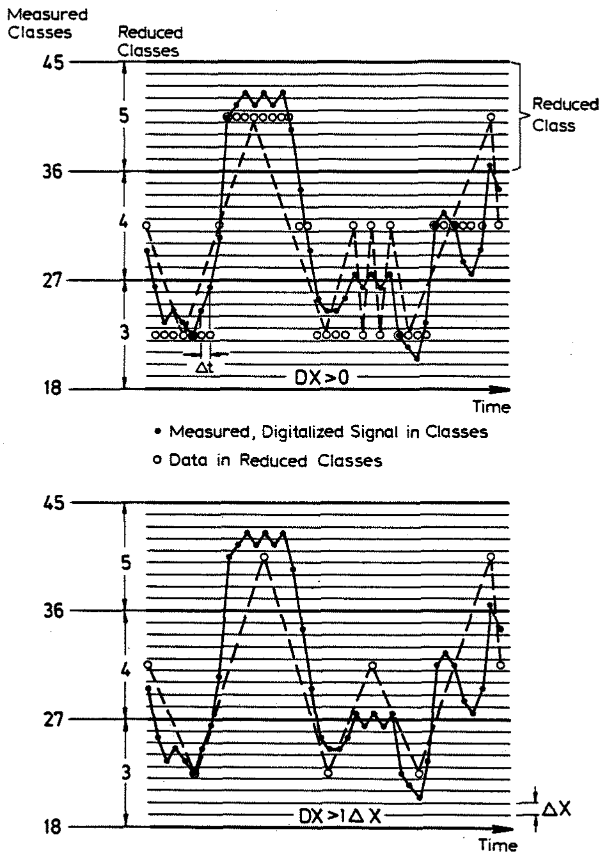

Fig. 5 Reduction of the Number of Classes and Amplitude Filtering

reinforced plastics, however, you will have relaxation processes during the load-cycles. For instance, it was found that the number of load-cycles to failure in a one-step-test is increased by 3 decades when the loading frequency is increased by one decade (from 2 Hz to 20 Hz).(3) So you must try to preserve the time history of the measured loading. This is done by calculating the freuquencies of the half-waves which are also stored in Markov-matrices divided in classes of frequencies (Fig.6).

Since each flight phase could be flown only for a limited number of hours the frequencies found during the measuring flights must be increased according to their part of the foreseen total lifetime.

The loads are statistically distributed. If the number of flight hours is increased the height of extreme values must increase, too, compared with the measured extreme values of the relatively short test flying. So, an extreme value extrapolation has to be performed to compose the real increased Markov-transition-matrix (Fig.7). This procedure may be imagined as lofting preserving certain conditions resulting from the probability theory.

By means of several random samples it was found out that every intersection AA through the maximum of the Markov-transition-matrix (Fig. 8) yields a different distribution of cumulative frequencies but that the traces of the curves beginning the cumulation at the right-hand side and at the left-hand side up to the intersection point, respectively, can be approximated by a distribution function of the form

$$H(x) = \frac{a}{c} e^{(b+cx)}$$

where x denotes the class of the Markov-transition-matrix.

The distribution function itself can be derived the more precisely the bigger the number of classes of the Markov-transition-matrix and thus the less the reduction of measured data is. A bigger number of classes, however, requires an exponentially increasing need for storage.

This distribution function enables a relatively simple mathematical treatment of the extrapolation problem. By logarithmizing the distribution function together with the equation

$$\log H(x) = \log e \cdot \ln H(x)$$

becomes

$$\log H(x) = k + mx$$

where

$$k = \log e \left(\ln\frac{a}{c} + b\right)$$

$$m = c \log e$$

With a semi-logarithmic scaled distribution function and spatial view we get at ideal conditions a cone above the Markov- transition-matrix with its top above the place of the maximum number of transitions (Fig.8).

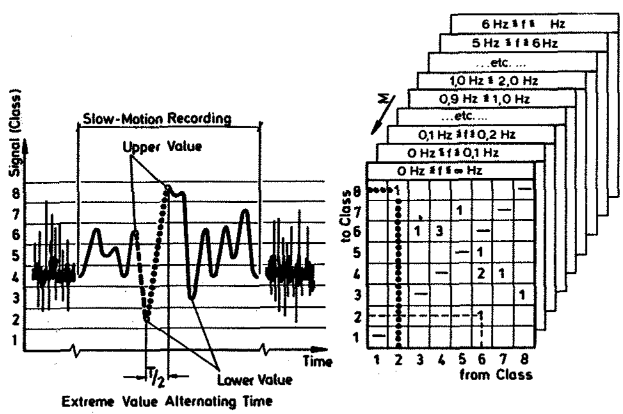

Fig. 6 Derivation of the Markov-Transition-Matrices Classified in Frequency-Classes

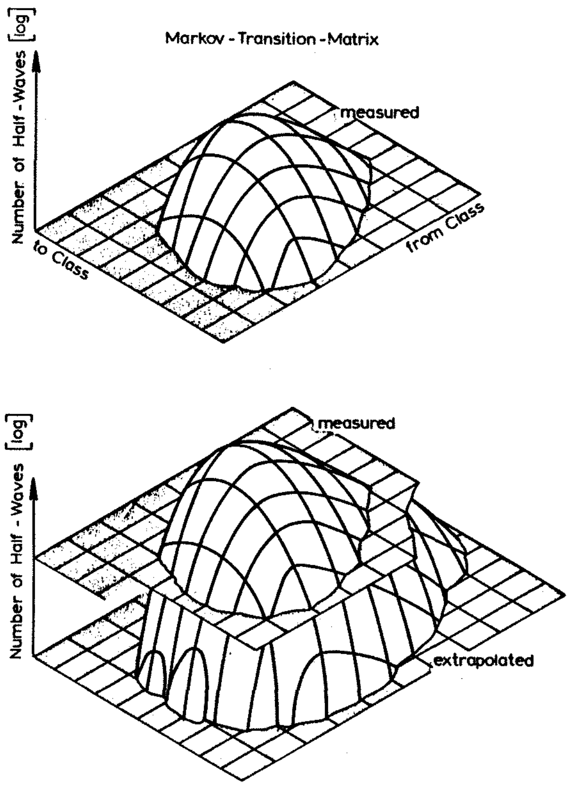

Fig. 7 Extreme Value Extrapolation

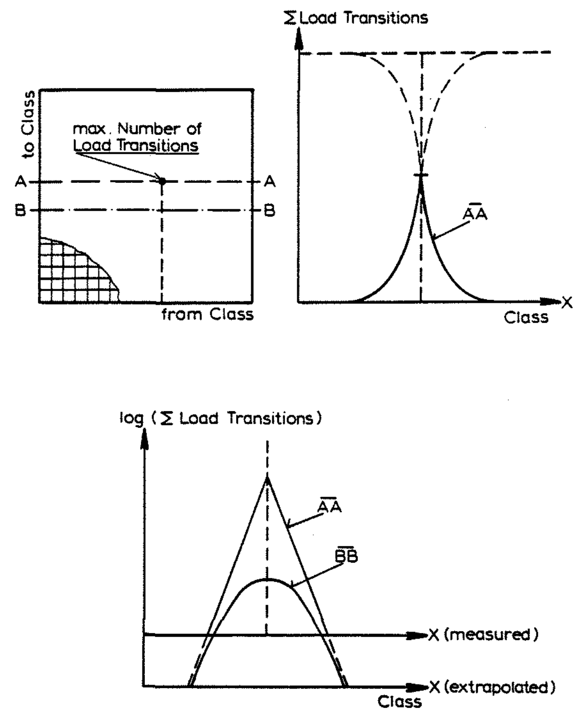

Fig. 8 Extrapolation Procedure

The intersection $\overline{BB}$ cutting the cone parallel to its axis thus represents a parabolic conic section at semi-logarithmic scale.

By extending the cone up to the desired plane of extrapolation, thus, the extreme values in this new plane can be calculated from the single conic sections.

If you now want to derive a total load spectrum there are two possibilities:

1.) You find out or estimate the time ratio of the individual flight phases during the life-time of an aircraft and then compose the Markov-transition-matrix for the desired total life-time out of the summed up shares of the individual flight phases. They can be derived for every arbitrary value by an extrapolation of the measured values.

    The time ratio of the flight phases in Germany in 1979 has been investigated by the IFL by means of an inquiry: It was answered by the owners of almost 1/3 of the about 6000 gliders registered in Germany.

    This method to compose a total load spectrum, however, envolves the disadvantage that the individual shares of the flight phases vary extremely according to the usage of the respective glider as a school, training or high-performance glider. So an additional uncertainty for the special case of application exists, when the shares of the individual flight phases contributing to the total life-time shall be determined.

2.) You extrapolate each flight phase to the desired total life-time and develop the envelope of all flight phases. In this case all different uses of the aircraft during the foreseen life-time are covered. That is the reason why this method for the derivation of a new load spectrum is to prefer.

Measurements have been performed for the following flight phases:

Cross-Country Flight
School and Training Flight
Cross-Country Flight in the Alps - Mountains
Lee-Wave Flight
Traffic-Circuit, Aerotow-Launching
Traffic-Circuit, Winch-Launching

The circuit is composed out of one launch (aerotowing or winch-launching), one landing and a training flight phase, resulting in a total flight-time of 10 minutes. On the basis of 6000 flight-hours life-time this will result in a total of 36000 circuits.

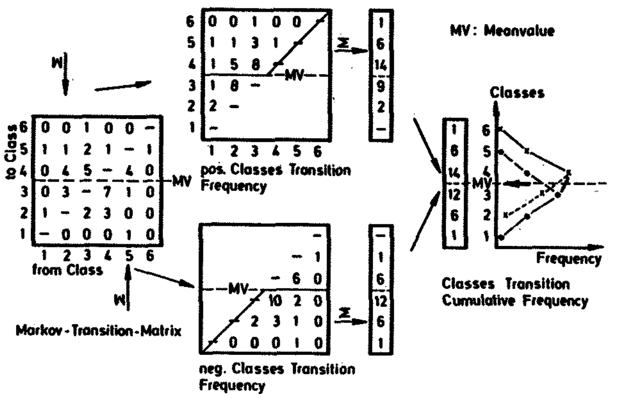

Fig. 9 Determination of Transition Cumulative Frequencies from the Markov-Transition-Matrix

Since loads are randomly distributed and you may not exclude very seldom occurring extreme loads the measurements have been extrapolated in this case to 18000 flight hours, that means the application of a scatter factor of 3 as used in fatigue tests, and then they have been standardized to a life-time of 6000 flight hours. The fractional figures resulting from dividing by 3 have been approximated to the next higher integer figure and thus the most severe load-cycle occurring during 18000 hours has been preserved.

If the number of load transitions of a Markov-transition-matrix is plotted above the corresponding fields of the matrix, you get a three-dimensional graph which is, however, very difficult to draw. Therefore, the Markov-transition-matrix is transformed into a plain, namely two-dimensional appearance, for better explanation. The load-cycles then are plotted as class transition cumulative frequency. In Fig.9 the procedure is demonstrated by a schematic example.

The individual columns of the positive and the negative part of the Markov-transition-matrices are summed up, respectively, and thus, the positive and the negative class transition frequencies are set. By summing up the individual rows of the matrices containing the class transition frequencies you get the class transition cumulative frequencies for the positive and negative part, respectively. The result found in this way can now be plotted in a two-dimensional way. Above the average value the class transition cumulative frequency of the upper values and below that value the class transition cumulative frequency of the lower values is drawn. The class transition cumulative frequencies for the different missions found this way are given in the following figures.

In Fig. 10 cross-country flight, school and training flight, cross-country flight in the Alps Mountains and lee-wave flight are represented. Contrary to general expectation, the lee-wave flight curve is covered by the curve of the high-mountain flight though the load factors occurring during the climbing through the rotor for gaining the lee-wave are included.

Cross-country gliding results in even bigger positive loads and in a higher frequency of smaller ones which is probably caused by the overshooting of the wing and its postvibrating. The curve of school and training gliding covers nearly

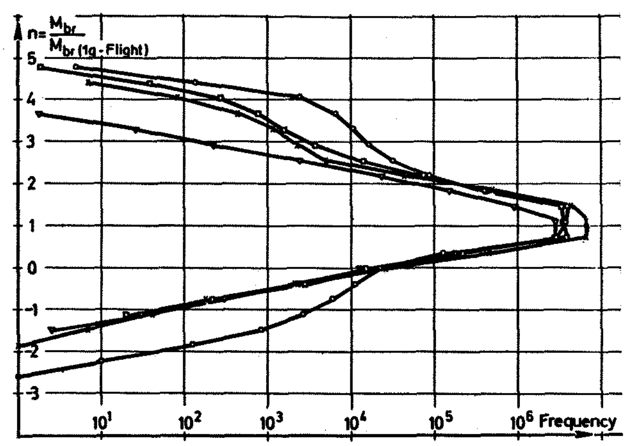

Fig. 10 Class Transition Cumulative Frequency of the Flight Phases:
□ Cross-Country Flight
o School and Training Flight
x Cross-Country Flight in the Alps Mountains
▽ Lee-Wave Flight

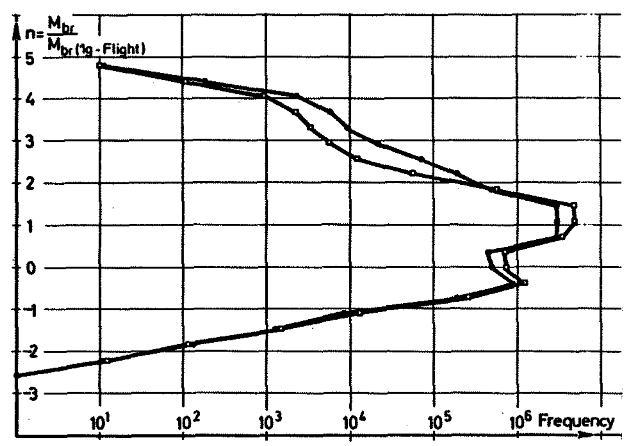

Fig. 11 Class Transition Cumulative Frequency of the Flight Phases:
□ Traffic-Circuit:Aerotowing
● Traffic-Circuit:Winch-Launching

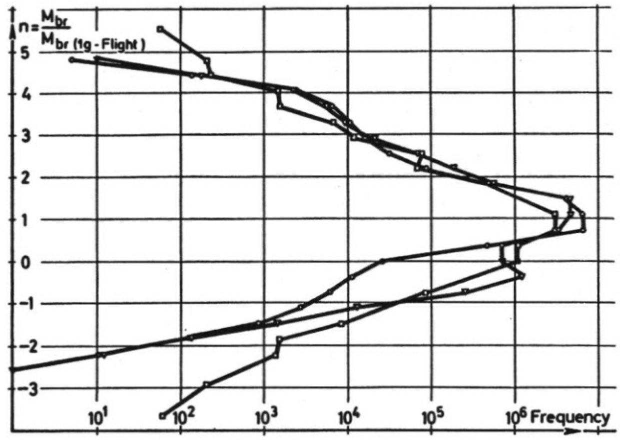

Fig. 12 Class Transition Cumulative Frequency of the
o Flight-Phases (Fig.10)
∇ Traffic-Circuits (Fig.11)
□ Thielemann/Franzmeyer Load Spectrum

the whole range of the three flight phases mentioned before. Take notice of the higher negative load cycles of the school and training gliding.

Fig. 11 shows the curves for circuits with either aerotowing or winch-launching. Here, as expected, it is the winch-launching that is reponsible for the higher positive loading while the aerotowing yields more load cycles with little amplitudes. The negative loads resulting from landing are identical in both cases. This result is not surprising since the relevant negative loads are only influenced by the way of landing.

The envelope of Fig. 10 representing the envelope of all cruise phases and the envelope of Fig. 11 representing the envelope of the two different kinds of traffic-circuits are compared in Fig. 12. It is obvious that the total envelope is clearly ruled by the circuit. The Thielemann-Franzmeyer collective for 3000 flight-hours has been linearly increased to 6000 hours and is now shown in a correspondingly adapted manner in Fig. 12, too.

You can see that this semi-theoretical collective is rather a good approximation to the presented measured and extrapolated data. The higher positive values at lower numbers of cycles result from Thielemann-Franzmeyer's assumption of higher speed-flight gust loading. The measured higher negative values at high numbers of load-cycles obviously result from a stronger influence of the wing mass during the taxiing after the landing impact.

In the previous section the total envelope has been derived for better illustration by superposition of class transition cumulative frequencies of the individual flight-phases. In a similar manner a Markov-matrix can be derived from the matrices of the individual flight-phases with a computer then representing the Markov-transition-matrix of the total envelope.

Proof of Operational Life Time by Markov-Transition-Matrix Stored Load Collectives

The "envelope-Markov-matrix" determined this way yields the load collective which has to be worked down for the proof of life-time which is 6000 flight hours in the given example (Fig.2).

Such a test is performed by means of a digital computer controlling a servo-hydraulic loading facility (Fig.13). The computer takes the reversal points from the Markov-matrix, interpolates between these points a cosine half-wave and transfers this nominal value as a signal via a D/A-transducer to the control unit of the loading device which applies the analogous loads.

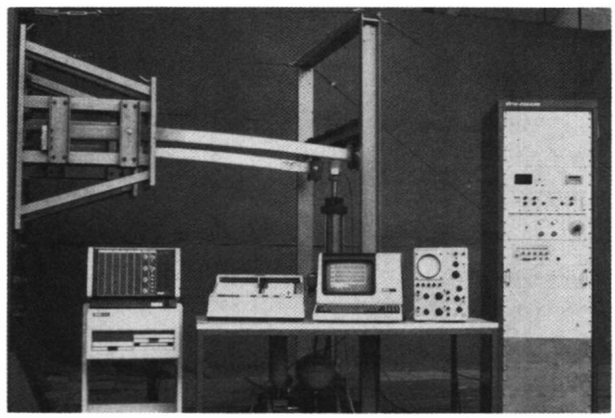

Fig. 13 Two GFRP Cantilever Beams during Fatigue Testing by Means of Markov-Transition-Matrix Stored Load Cycles

If reversal points of the Markov-transition-matrix are to be worked down randomly, the sequence of these extreme values to be taken from the matrix must be determined by a random generator in such a ways that a positive transition is always followed by a negative one and vice versa. If not any further conditions are implemented, however, the Markov-transition-matrix is generally not completely worked down, because the computer sooner or later comes to a column of the matrix the positive or negative part of which is already worked down. Thus, no transition to further yet occupied places is possible.

For completely working down Markov-matrices with a Gaussian frequency distribution a method is described in (4). This method can furthermore be applied if only the partial row and the partial column sums for all matrix classes are identical, i.e.

$$\sum_{j=k}^{32} H_{kj} = \sum_{i=k}^{32} H_{ik} \text{ and } \sum_{j=1}^{k} H_{kj} = \sum_{i=1}^{k} H_{ik}$$

where

- H_{ij} Markov-transition-matrix element
- i index of columns
- j index of rows

Markov-transition-matrices derived from a load sequence measured under operational conditions, normally do not show a symmetry with reference to the main or secondary diagonal. Furthermore, they generally have a difference between the sum of the positive and the sum of the negative load transitions, caused e.g. by elimination of erroneous measurings. So the above mentioned method (reference (4)) cannot be applied in the given status.

For completely working down a Markov-transition-matrix the necessary condition must be satisfied that as many transitions to a class as transitions from a class must be given. This postulate, which is satisfied if the corresponding partial column and row summations are equal, can principially be achieved on three ways: by addition, by subtraction, and by a combination of addition and subtraction of transitions.

If the contents of the existing load collective shall be altered as little as possible it is demanded that:

a) The total sum of transitions shall not be less than the one in the originally given load collective.
b) The number of changes in the matrix shall be as little as possible.
c) No transitions shall be added which lead to classes beyond the range of the original matrix so that the given maximum load level is not increased.
d) Load transitions occurring very rarely should be neither increased nor decreased, i.e. changes should be done at load cycles occurring often.
e) A limit for the maximum allowable number of classes to be skipped shall be set, i.e. changes are allowed only in the proximity of the main diagonal so that the original load collective is not adulterated by addition or subtraction of big load skips even within the allowed range.

By the postulate a) the three possible solutions are reduced to two methods:

i) Addition of load transitions.
ii) Addition and subtraction of load transitions.

For both possibilities computer programmes have been developed considering the conditions mentioned above. The selection of transitions is done by means of a quasi-random method, i.e. the random generator calculates the new random figure from the previous one after the random figures had been standardized to the range 1 to 32 according to the number of the given matrix classes.

The initial class of the first load transition is determined by taking serial random figures as long as an occupied matrix column is found. In the same way an element greater than zero within the column thus found is selected. The row-index of this element then denotes the class into which the first skip is done. For the new initial class thus gained, again an element greater than zero is derived by means of the next random figure and so on.

At the same time the contents of the corresponding element is reduced by one after every transition so that all elements yield a zero after completely working down the matrix. For selecting the matrix transitions approximately corresponding to their frequency the following method is applied: The transitions of a partial column are standardized to the range 1 to 32 with the largest element in it. The values of the standardized elements are compared with the derived random figure and in the direction of increasing element numbers the first element is chosen which is greater than or equal to the random figure.

The addition or subtraction of transitions can be done at different moments:

In case 1 it is performed after the load transitions have been worked down so far that for the continuation of the process a manipulation becomes necessary. Then additional transitions have to be found for the remaining rest. This contributes to a number of additional transitions as little as possible, for at this moment the range of yet occupied matrix elements and so the possibility for the addition of transitions is already restricted. Considering the limitations mentioned in c, d, and e, at adding a transition in the beginning that class is taken which contains the maximum number of remaining matrix transitions. The transition is determined by means of a random figure.

Demonstrative calculations have shown that for completely working down a Markov-transition-matrix following method i) with only adding transitions averagely 3% to 4% additional transitions are necessary.

In case 2 adding (method i)) and adding and subtracting (method ii)) of transitions is performed at the original matrix which is then worked down according to (4). Here, the number of changes is minimized in the following way:

Every matrix element H_{ij} (i not equal to j) exists in a partial column sum of the class i (i.e. sum of transitions from class i) as well as in a partial row sum of the class j (i.e. sum of transitions to class j). If thus two classes i and j are found in which differences with different signs exist between the number of transitions to these classes and the number of transition from these classes, then the necessary changes become a minimum if the addition or subtraction of transitions is beginning at the element H_{ij}. This method is applied to all classes of the matrix in a certain sequence and the total number of modifications depends on the selection of the initial class. The minimum is then found by comparing the number of the respectively determined necessary additional transitions after every class has once become the initial class.

Demonstrative calculations have shown that the number of additional transitions for case 1 and case 2 of method i) are equal. Comparing methods i) and ii) for case 2 it can be seen that method i) needs four times the additional transitions of method ii).

Concluding Remarks

With these methods illustrated in the previous sections it is possible to derive a representative load collective from load measurings performed during the various flight-phases. This load collective is stored in a Markov-transition-matrix and covers for an intended life-time all flight-phases of sporting airplanes. Furthermore, possibilities are shown enabling a complete work down of the load collective stored in the "envelope-Markov- transition-matrix".

According to the lower part of Fig. 2 there is now the task to determine by random fatigue testing the allowable stress level at a given life-time for common wing and beam designs of today. If the relaxation of GFRP is also to be looked at the selection of frequency classes has additionally to be considered in the work down procedure.

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