Aircraft modal testing at VZLÚ

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1- Introduction

The modal test is designed to determine the modal parameters of a structure. In developing aircraft structures this information is employed to verify or tune up analytical models needed for flutter analysis, evaluation of structure modifications, flight test planning, and interpretation of flight test results.

The VZLÚ Modal Test Laboratory has been in operation since 1968. Since its foundation, it has been equipped with the PRODERA, a device developed originally by the French aerospace research centre O.N.E.R.A. to test the CONCORDE prototype aircraft. The facility and testing methodology were gradually modernised at VZLÚ. In 1997 a number of technical innovations were implemented and new methods to process results were introduced. The current state of the art is described in this paper.

2- Experimental

The number and type of modal test equipment depends on the size and dynamic characteristics of the structure to be tested. The system used at VZLÚ enables testing structures ranging from scale models up to the size of small transport aircraft. Modal analysis system general flow chart is shown in Figure 1.

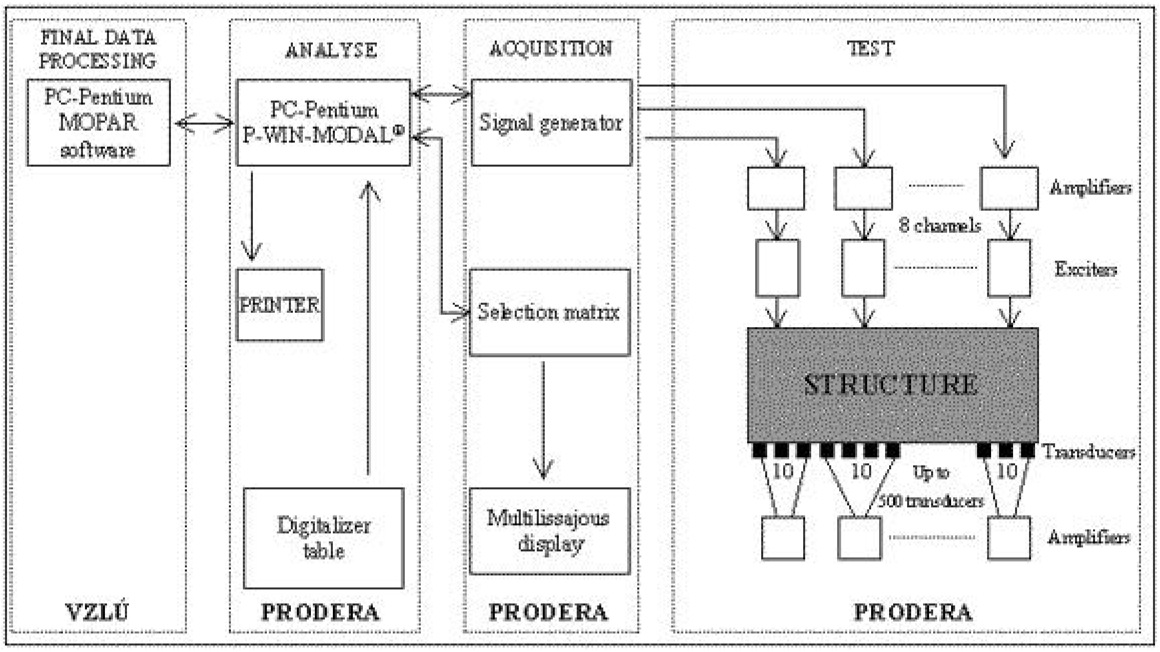


Figure 1 - General flow chart of modal analysis system used at VZLÚ

Excitation

The Modal Test Laboratory has 37 exciters offering various force magnitudes, from 3 N to 2 000 N amplitudes, which can be connected into eight-channel exciting circuits. The exciters are electrodynamic types and together with amplifiers make a unique system ensuring a constant amplitude of the force generated by the exciter, independent of the coil movement. The exciting force variation may be sinusoidal, swept sinusoidal or have a shape of various impulse types. In addition to the exciters, there is an impact hammer designed to test small structural parts and a hydraulic vibration generator MTS (25 000 N).

Measurement

Mini accelerometers (1 g) are used for aircraft modal testing. 500 measuring channels with these transducers meet all necessary requirements to measure mode shapes. A smaller number of other accelerometers and displacement transducers for special applications is also available. The circuit is fitted with amplifiers, voltmeters, filters and a twenty-channel oscilloscope for "multilissajous" visualisation. The whole device is panel-built and mobile.

Test Control

Two interconnected PC Pentium computers are in operation during the modal test. One computer is a part of the testing equipment and is designed for the test control and data acquisition and pre-processing. The other computer processes simultaneously the values measured into a digital or graphic form as required by the end-user.

The testing equipment may work in three different modes :

In the manual mode the operator has direct access to frequency and force control, the computer is out of operation, in the computer-aided mode, the operator controls directly the frequency and forces as in the manual mode, but the computer is used for data acquisition, display and storage of information on vibrating structures,

in the computer-controlled mode the operator works on the computer giving it instructions on frequency, forces, measurement, data acquisition, processing and storage of results; the testing facility works as a computer peripheral unit.

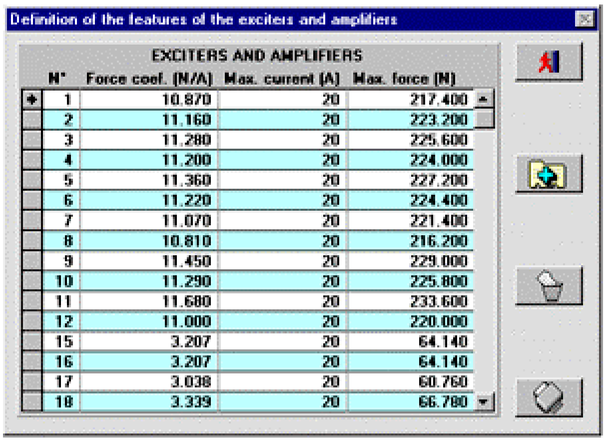
3- Software

P-WIN-MODAL®

The basis of PRODERA's software consists of newly developed procedures used in PRIN 85 systems. Some changes have been made to allow for use of practical experience gained in performing lots of modal tests of aircraft structures. Workers from the VZLÚ Modal Test Laboratory have also been engaged in the software specification. The basic functions of the P-WIN-MODAL® are described below.

Test Preparation - data file formation

a) Definition of testing equipment. The objective is to determine the characteristics of transducers and exciters with amplifiers to be used in the test and make a choice of twenty significant points (transducers) on the structure and eight connected exciters. The example in Figure 2 is a table with constants of exciters and amplifiers.



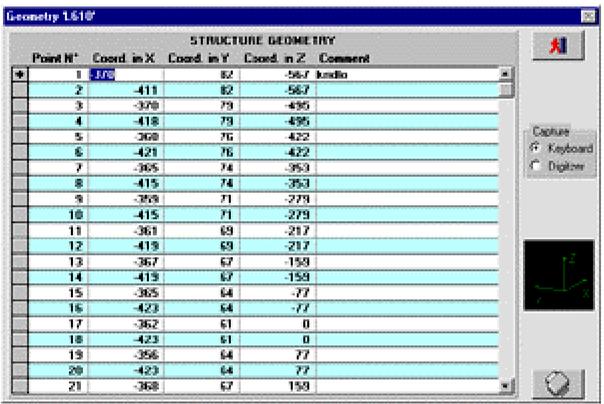
Definition of the features of the exciters and amplifiers

EXCITERS AND AMPLIFIERS

N°	Force coef. (N/A)	Max. current (A)	Max. force (N)
1	10.870	20	217.400
2	11.160	20	223.200
3	11.280	20	225.600
4	11.200	20	224.000
5	11.360	20	227.200
6	11.220	20	224.400
7	11.070	20	221.400
8	10.810	20	216.200
9	11.450	20	229.000
10	11.290	20	225.800
11	11.680	20	233.600
12	11.000	20	220.000
15	3.207	20	64.140
16	3.207	20	64.140
17	3.038	20	60.760
18	3.339	20	66.780

Figure2 - Definition of the exciters and amplifiers

b) Definition of structure tested. The structure is represented by a matrix of nodal points with three co-ordinates each. One up to three transducers oriented in the axes of the co-ordinate system are associated with each nodal point. The example with definition of the structure by co-ordinates of nodal points is in Figure 3.



Geometry 1.610'

STRUCTURE GEOMETRY

Point N°	Coord. in X	Coord. in Y	Coord. in Z	Comment
1	-370	82	-567	kridlo
2	-411	82	-567	
3	-370	79	-495	
4	-418	79	-495	
5	-360	76	-422	
6	-421	76	-422	
7	-365	74	-353	
8	-415	74	-353	
9	-359	71	-279	
10	-415	71	-279	
11	-361	69	-217	
12	-419	69	-217	
13	-367	67	-159	
14	-419	67	-159	
15	-365	64	-77	
16	-423	64	-77	
17	-362	61	0	
18	-423	61	0	
19	-356	64	77	
20	-423	64	77	
21	-368	67	159	

Figure3 - Definition of the structure by coordinates of nodal points

Visualisation of Structure Sinusoidal Vibration in Real Time

a) *Complex Response*. The PC continuously reads the real and imaginary components of the twenty selected transducers, writes their values into a table and displays them in the complex plane.

b) *Visualisation of Mode Shape*. The animated mode shape from real or imaginary components can be rolled or magnified. Any change in the excitation conditions (frequency, force) takes effect on the mode shape displayed.

Frequency Responses in Ten Selected Points

The purpose of this function is to quickly show the distribution of natural frequencies of the tested structure in the frequency range of interest. The excitation is multipoint, impulse-type, and the temporal signals or frequency responses of the complex components or magnitudes of the signal measured can be displayed. The illustration of frequency responses is in Figure 4.

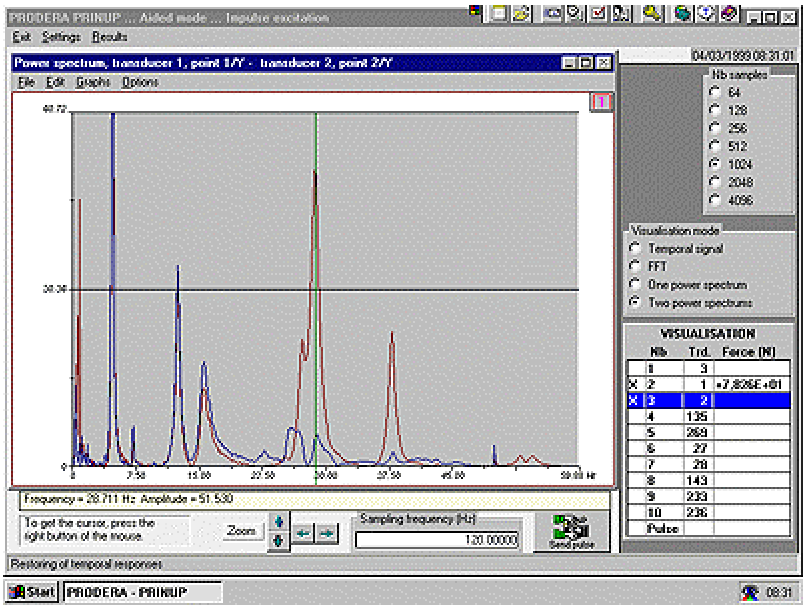


Figure4 - Frequency responses in ten selected points obtained using impulsional excitation

Study of Modal Parameters

a) Sinusoidal Excitation of Isolated Modes.

To isolate a vibration mode, the operator can use 20 Lissajous patterns, real-time displayed complex components and vibration vectors from twenty points, and real-time animated vibration (imaginary or real components) of the whole structure. A structure linearity test will make it possible to select vibration levels at which modal parameter measurements are to be made. The modal parameters may be determined by the complex power method or by the method of forces in quadrature. Functions whose graphic representation indicate the quality of the result, form a part of the two methods. The shape of the investigated mode is recorded at the natural frequency.

b) *Frequency Response Functions*

- Impulsional excitation
  The operator selects points (up to eight) and force magnitudes, frequency range and type of impulse. The data acquisition finished, the PC calculates FRFs for all the transducers (up to 500) and stores them on a disc along with the excitation distributions for further use. Any FRF can be displayed on the PC, the cursor picks out a frequency (e.g. resonance peak), the PC will read values from all the transducers at this frequency, and the corresponding mode shape of the structure may be recorded or animated.

- Swept Sinusoidal Excitation.
  The operator selects points (up to eight) and force magnitudes, frequency range and a step of sweeping. The recorded FRFs may be used further as with the impulse excitation.

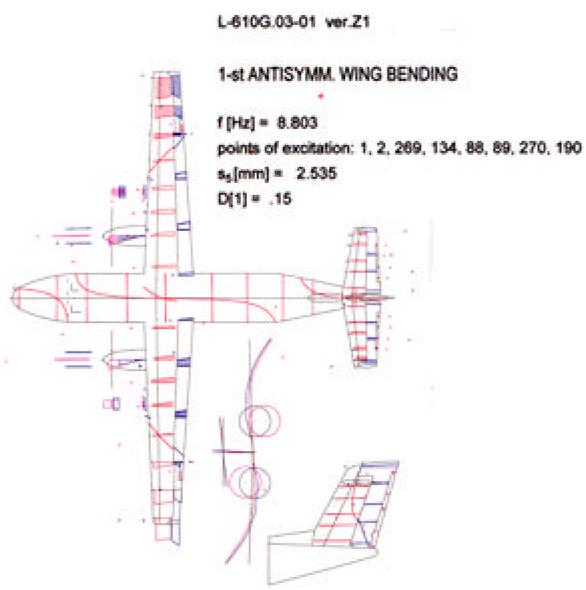
Structural Dynamics Toolbox

Software working in the MATLAB environment has been designed as a system for combined use of experimental and analytical linear models of structures with a high modal density and non-proportional damping. A part of "Toolbox" is formed by methods to identify normal and complex modes from the FRF file as received from the multipoint input and output.

MOPAR

To make a final evaluation of modal test results, VZLÚ developed software for the following jobs :

- mode shape representation of aircraft vibration in direction of co-ordinate axes with node lines distribution, Figure 5 illustrates antisymmetric first wing bending of L-610G aircraft;
- deform lines representation of aircraft structural parts, deform lines of antisymmetric first wing bending of L-610G aircraft are shown in Figure 6;
- modal vectors transformation (natural mode shapes) into another network for orthogonality verification or for identical way of representation of analytical and experimental mode shapes in order to make comparison;
- calculation of full matrix of generalised masses (orthogonality) and correlation criteria of mode shapes (MAC, Auto-MAC);
- change of mode shape normalisation and relevant generalised mass;
- correction of effects of additional masses and stiffness of exciters, transducers and elastic suspensions on measured natural frequencies and generalised masses;
- correction of measurement errors (e.g. defective transducer) with respect to deform lines or node lines;
- exciter and transducer calibration by comparing with Bruel & Kjaer 3506 calibration system.



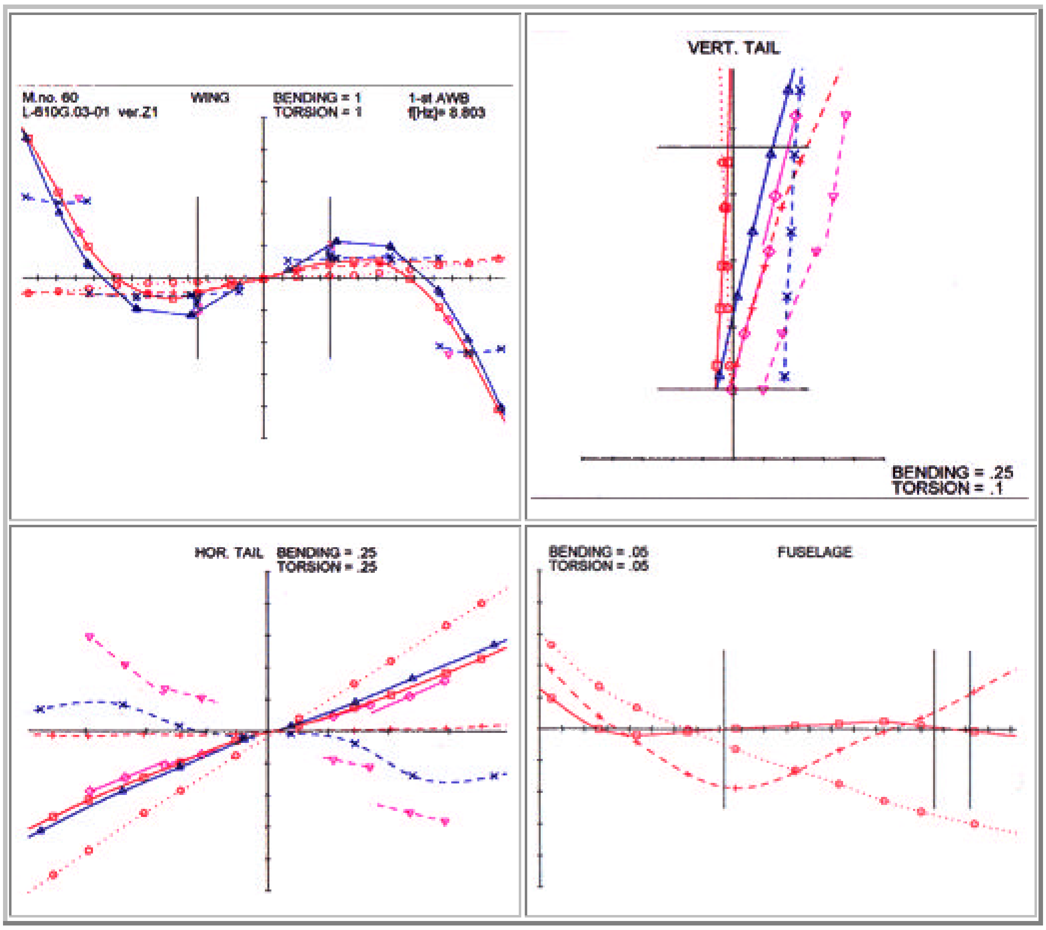


Figure 6 - Deform lines of antisymetric first wing bending of L-610G aircraft

4- Examples of Tests

Modal Test of L-610G Aeroplane

The L-610G is a high-wing monoplane with a T-shaped tail and a pressurised cabin powered by two General Electric turboprop engines. Maximum take-off mass with forty passengers is 15 000 kg. The test was intended to determine the effect of significant structural changes on aeroplane's modal characteristics and to obtain data to tune up an analytical finite-element model and also to carry out detailed investigation into flight control circuits in all failure-present conditions tolerated by the rules.

During the test the aeroplane was standing on under-inflated tyres of the main landing gear, the nose fuselage was elastically suspended. Illustration of L-610G model test arrangement is shown in Figure on envelope. A total of 19 exciters were used for excitation, the response was measured in 280 points. The flap plays, which cause disturbing shocks and deteriorate measurement results, were eliminated by additional masses of 20 kg suspended on the trailing edges by soft rubber bundles. The additional mass natural frequency was less than 1 Hz and so it did not have to be considered in the aeroplane total weight. The rubber bundle stiffness was taken into account in making calculation corrections for additional masses and stiffness of exciters and transducers and for aeroplane suspension.

The initial part of the test consisted in identification of the aeroplane natural frequencies. An important part of the test are FRFs from all 280 transducers measured as recorded in different configurations of swept sinusoidal excitation.

The aeroplane modal parameters were investigated by the method of sinusoidal excitation of isolated normal modes (method of appropriated forces). Relative damping and generalised mass were measured by two techniques, the complex power method and the method of forces in quadrature.

One problem of every modal test is **evaluating the quality** of received natural frequencies, generalised masses, damping and modal vectors. Factors influencing modal test results fall into three categories :

- *properties of the structure tested* - modal density; linearity; damping intensity and distribution; access to vibrating structural parts;

- *effect of the experiment* - suspension of the structure tested; number, position and magnitude of exciting forces; number and position of transducers; influence of moving parts of exciters, transducers and suspension; method used; time for experiment available; experimenter's skill;

- *technical level of experimental facilities* - calibration; proper use of particular circuits.

The disturbing effect of the factors mentioned above must be minimalised. After measuring each mode the result must be evaluated immediately so as to clear up uncertainties, if any, or repeat the measurement. At the L-610G test several criteria were used for verification of linearity, effects of moving parts of the test equipment and quality of natural modes isolation. Mode shapes were checked by their graphic representation and also by verifying their **orthogonality** and by **Modal Assurance Criteria**.
Table 1 shows the matrix of generalised masses verifying orthogonality of the L-610G symmetric modes. Table 2 contains Auto-MAC values calculated for the same modes for all 280 measured points. In the two matrices there are following modes :

Mode	f[Hz]		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SWB1	4,17	1	100																	
SEMVB	6,69	2	4,7	100																
FVB1	8,41	3	0,1	-4,4	100															
SWHB1	9,34	4	6,4	0,8	2,5	100														
SWB2	10,83	5	3,1	-2,6	6,7	2,8	100													
SEY	11,57	6	4,5	-2,4	-4,2	-3,2	-2,9	100												
SEP	14,05	7	-2,4	3,4	-4,5	-4,7	-3,3	0,8	100											
SEMHB	15,13	8	5,9	-7,0	-1,4	12,9	1,5	12,8	-5,3	100										
SHTB1	15,88	9	-0,9	0,9	0,8	2,2	0,0	-0,4	-0,7	9,1	100									
SWHB2	21,47	10	2,5	-0,9	-1,3	3,7	7,3	5,5	4,9	25,5	1,5	100								
SWB3	22,8	11	-0,3	-3,2	-7,8	-4,2	-1,6	-0,7	7,4	0,2	1,1	23,0	100							
SWT1	27,81	12	6,2	4,0	0,1	9,9	3,8	14,0	-4,9	5,2	-0,4	5,5	13,6	100						
SWB4	36,78	13	-7,0	-2,9	4,1	15,7	7,5	-4,1	-7,6	3,5	1,4	-0,3	-6,3	13,4	100					
SWHB3	46,1	14	-2,2	1,5	4,4	0,9	3,7	-1,6	-13,3	3,4	-0,6	-8,9	3,6	1,8	18,9	100				
SWT2	46,6	15	4,8	-2,2	4,4	-8,1	-1,2	6,5	-1,5	3,3	1,3	10,6	12,1	1,0	-2,0	25,4	100			
SHTHB1	54,0	16	-4,2	5,3	21,0	-1,8	-5,9	-9,5	-1,0	-5,9	-3,9	19,9	4,7	-2,0	-4,0	-4,3	-3,2	100		
SHTT1	56,46	17	0,7	-0,1	7,6	0,3	-7,0	0,8	-3,8	0,7	10,2	-2,3	-2,8	0,1	0,5	0,8	0,0	25,1	100	
SHTB2	60,1	18	0,6	-1,0	-4,5	-1,2	-5,5	-1,9	2,5	-0,7	-4,5	4,5	3,1	-1,0	0,8	-1,5	-1,0	-6,4	12,2	100
Table1 - Orthogonality of L-610G aircraft symmetric mode shapes																				

Mode	f[Hz]		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SWB1	4,17	1	100																	
SEMVB	6,69	2	24,3	100																
FVB1	8,41	3	0,3	0,4	100															
SWHB1	9,34	4	13,9	2,1	16,8	100														
SWB2	10,83	5	23,3	2,4	6,3	11,3	100													
SEY	11,57	6	8,2	1,2	10,3	5,0	15,8	100												
SEP	14,05	7	19,2	14,8	15,0	9,1	4,1	2,4	100											
SEMHB	15,13	8	1,8	1,5	12,2	5,1	0,5	11,0	15,0	100										
SHTB1	15,88	9	0,6	0,1	16,4	6,9	11,5	22,2	5,5	18,7	100									
SWHB2	21,47	10	0,1	0,7	0,2	3,6	2,4	4,2	2,8	7,2	0,1	100								
SWB3	22,8	11	6,7	4,2	0,1	3,7	20,4	9,5	34,8	3,1	0,3	3,2	100							
SWT1	27,81	12	22,0	11,5	0,5	0,6	0,6	4,1	11,2	1,6	0,0	0,0	1,1	100						
SWB4	36,78	13	3,8	2,1	0,1	0,2	0,2	1,4	4,9	0,7	0,0	0,1	0,5	16,5	100					
SWHB3	46,1	14	0,4	2,0	0,0	0,3	0,3	1,4	2,4	2,9	0,3	1,1	1,5	2,1	2,8	100				
SWT2	46,6	15	0,0	0,0	0,0	1,0	1,2	0,3	1,4	0,6	0,0	2,1	0,1	5,1	13,8	19,0	100			
SHTHB1	54,0	16	0,0	0,1	4,3	0,2	0,9	0,6	0,4	0,0	1,9	0,5	0,3	0,0	0,4	0,7	0,0	100		
SHTT1	56,46	17	0,0	0,0	0,2	0,1	0,4	0,0	0,0	0,1	0,6	0,0	0,0	0,0	0,0	0,1	0,0	30,3	100	
SHTB2	60,1	18	0,0	0,0	0,6	0,2	0,1	0,0	0,0	0,4	4,1	0,0	0,0	0,0	0,0	0,1	0,0	19,5	1,2	100
Table2 - Auto MAC of L-610G aircraft symmetric mode shapes																				

SWB1 symmetric first wing bending
SEMVB symmetric engine mounting vertical bending
FVB1 first fuselage vertical bending
SWHB1 symmetric first wing horizontal bending
SWB2 symmetric second wing bending
SEY symmetric engines yaw
SEP symmetric engines pitch
SEMHB symmetric engine mounting horizontal bending
SHTB1 symmetric first horizontal tailplane bending
SWHB2 symmetric second wing horizontal bending
SWB3 symmetric third wing bending
SWT1 symmetric first wing torsion
SWB4 symmetric forth wing bending
SWHB3 symmetric third wing horizontal bending
SWT2 symmetric second wing torsion
SHTHB1 symmetric first horizontal tailplane horizontal bending
SHTT1 symmetric first horizontal tailplane torsion
SHTB2 symmetric second horizontal tailplane bending

In the two matrices the values are given in per cent. Most non-diagonal elements are very small under 10 per cent. Only a few values are slightly greater. Most of them are "horizontal" modes with movement in longitudinal direction. In this direction there was limited number of measured points on fuselage and engines. It is assumed that this is the reason why these values are rather higher. With the Auto-MAC values the situation is similar, the elements over 10 per cent have again "horizontal" mode shapes and in addition, mode shapes of engines. But it may be seen that higher values may also be found with some shapes featuring good orthogonality. MAC depends to some extent on choice of the points (and directions) on the structure whose measured displacements were incorporated into the calculation. In analysing orthogonality and particularly the Auto-MAC values, it was useful to assess the effect on the resulting value of motion components in the co-ordinate axes of particular aeroplane parts.

Measuring Dynamic Characteristics of Hydraulic Control Surface Actuators

The hydraulic actuators dynamic characteristics are given by their **dynamic stiffness** P_j/x_j on the output and **transfer functions** x_j/x_i between output and input. Measurement of actuators dynamic characteristics is slightly different from conventional tests of aircraft structures, it calls for different test facilities and methodology. The reason for this are specific properties of hydraulic actuators (non linearity) and requirements on the range of values measured (magnitude of exciting forces and frequency range of interest).

Non Linearity

There appears useful to use sinusoidal excitation at aircraft structural tests in order to achieve required accuracy, to better characterise the behaviour of a tested structure at various excitation levels, and to understand non linearity effects. Practical applications have swept sinusoidal forms over the frequency range of interest. The difference is in the type of excitation control : in the frequency range studied there is either a **constant exciting force** or a **constant response amplitude**. With the constant force sweeping, vibration amplitudes are big at natural frequencies, and small at the antiresonance region. In the course of measurement there appear natural frequencies shifts and damping changes due to non-linear behaviour of the structure. If the structure response has a constant amplitude in the whole swept sinusoidal frequency band, then the structural stiffness and damping properties will remain constant and the measured function will be "linearized" for the given amplitude even if the structure itself may be very non linear.

Range of values to be measured

When preparing the test, the **magnitude of exciting** forces is very important. Relatively small exciting forces will be sufficient if the excited amplitudes are near resonance regions. But if the dynamic stiffness or the constant amplitude transfer function of the actuators output are to be recorded, then the exciting forces in an antiresonance region may be many times higher than with excitation in natural frequencies. The actuator's output is excited by forces whose amplitude amounts to thousands of Newtons. **The frequency range of interest** begins from zero level. The dynamic values measured should follow static values. Virtually it means to start measuring frequencies for the order of tenths of Hertz.

An experimental set-up was designed to measure the dynamic stiffness of the L-159 control surface actuators, meeting successfully the above mentioned requirements. The actuator mounted onto a rigid frame is on output excited by an MTS 208.03F-04 (25 kN) hydraulic vibration generator. The generator is rotary-linked to the frame and its exciting force acts in the axis of an eye of the actuator output lever. When measuring, the output lever of the actuator is fixed to the frame in the middle position. Between the hydraulic vibration generator and the actuator output lever there is a force transducer, the LTC120 Vibrometer. Amplitudes of the output lever are measured by an LVDT transducer CPT-8. Signals from the LVDT amplified by an MTS 406 controller and from the force transducer amplified by a dynamic bridge VISHAY 3210 come to input channels of an HP33670A analyser fitted with a module for sinusoidal sweeping. An auto-sweep analyser function enables the measuring process to be automated in the whole frequency range of interest, the auto-level function controls the force P_j so that the output level amplitude x_j should be on a preset level. The measurement is repeated for several amplitudes x_j to cover the whole range of the actuator.

The measurement of transfer functions is made in a similar way, but instead of the hydraulic vibration generator an electrodynamic exciter is used for excitation of the actuators input.

5- Conclusion

The damage tolerant approach, new materials, complex configurations (various stores under wing) and upgraded flight control systems might influence the aircraft's aeroelastic stability and impose new requirements on experimental methods and modal tests. New techniques of modal tests and their analyses make the data acquisition and processing easier but at the same time call for a better knowledge of all the factors involved.

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