THE EXPERIENCE IN GROUND VIBRATION TESTS OF FLEXIBLE FLYING VEHICLES USING PRODERA EQUIPMENT AND SOME ADDITIONAL TASKS

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The main tasks in the dynamic aeroelasticity are solved using the aircraft (A/C) mathematical model – its dynamic computational scheme. The most important tasks are: to ensure the safety from the flutter, to ensure the closed loop "A/C – flight control system (FCS)" stability, to estimate dynamic loads in the flight in turbulent atmosphere, during landing and take-off and so on. The progress in the computational facilities – hardware and software – allows now to generate sophisticated finite element schemes with hundreds thousands variables and to make the majority of the investigations using this mathematical model. Nevertheless up to now it is very difficult to create the reliable and accurate computational scheme based "only on the drawings". The safety requirements force us to check this scheme experimentally, to correct it using experimental results.

Typical scope of the works related to the aeroelasticity (AE) and aeroservoelasticity (ASE) during A/C development accepted many years in Russia [1] is given in fig. 1. The scheme shows that theoretical and experimental works continuously influence each other and partly overlap. The experimental works are made using full-scale aircraft and dynamically scaled models designed and manufactured for the wind tunnel tests [2].

Since many years TsAGI is the leading organization in the aviation industry, so it obtained unique experience in such a work. For example, almost all ground vibration tests in the country were accomplished by TsAGI specialists or by joined team of TsAGI and design bureau specialists. Only in the period 1981–1985 years 296 GVT tests were carried out including very complicated and relatively simple (about 55–60 in a year). Of course, TsAGI needed effective GVT equipment. The development and modification of such equipment in Russia was made all the time, but in the middle of the sixties the first four-channel set of the GVT equipment was delivered by the French firm PRODERA. A few years later, TsAGI and some of the design bureaus acquired 16-channel equipment with automatic data registration on the punch band.

After the first equipment testing made on the high and small aspect ratio wing models of

Design stages	AE/ASE works		
	Analysis	Experimental works	
		Model	Full scale vehicle
Conceptual design, Preliminary design stages	Statistics and experience Similarity laws AE/ASE math. model; stability margins; main parameters variations;	Special simplified models; preliminary wind tunnel tests; inflow FRF	
Main design process Experimental manufacturing First aircraft is made	Analysis: modes & frequencies, flutter, divergence, reversal; stability margins; dynamic loads; ACS efficiency; parameters variations Math. models updating	Model scheme; model design and manufacturing; GVT; wind tunnel AE/ASE tests; dynamic loads Scaled model updating	FRF of the full-sacle ACS elements using work-bench Aircraft parts tests: stiffness, GVT, wind tunnel tests First aircraft GVT
First flight Fight investigations Certification	Updated model analysis; actual margins; materials and data for the certification	Updated model wind tunnel tests: margins; dynamic loads; ACS efficiency	Flight tests: actual margins; dynamic loads; ACS efficiency
Serial manufacturing	Analysis of the differences between first and serial aircraft	Model updating to serial aircraft; "Serial" model wind tunnel tests	Serial aircraft GVT
Aircraft modifications	Modified aircraft and control system mathematical model; analysis	Model works if necessary	Modified aircraft GVT

Fig. 1

full A/C it became clear that this equipment is excellent and it was used to equip the moving laboratory. The first GVT test made by means of this laboratory was full-scale TU-144 aircraft investigation. PRODERA equipment mastering was relatively quick and simple, because TsAGI had some experience in multipoint excitation tests, which was acquired during electromechanical aerodynamic forces simulation. After the first tests PRODERA equipment was widely used for the GVT of all classes of flying vehicles, military and civil, manned and unmanned, new and serial. At the same time in TsAGI were tested all scaled wind tunnel models. For this purpose special stationary laboratory equipment was used (fig. 2).

High level of the PRODERA equipment was based on the cooperation with strength department of ONERA. Actually the ideas and the experience of ONERA specialists were realized to final industrial and commercial product by PRODERA specialists. This explains why PRODERA equipment was quickly distributed in many firms and design bureau in Soviet Union and up to now is in use. At the same time PRODERA continuously modernized using new ideas, technical solutions and computer technologies.

Fig. 2

The block-diagram of modern PRODERA equipment is presented on fig. 3. [3].

It is interesting to mention here that special set of equipment with 5000 N exciters was used for the GVT of "Energia-Buran" pack (fig. 4). For this experiment it was necessary to build special workbench (100 m height) and special suspension devices.

At the same time in Soviet Union also was developed GVT equipment, including high accuracy exciters, amplifiers and registration parts. This equipment was manufactured in restricted series [4].

As a part of GVT equipment the suspension devices also can be considered. In cooperation with TsAGI a set of pneumatic suspension units was developed and manufactured. These units allow to controllably suspend any vehicle with weights from a few tons up to several hundreds tons with lower rigid body frequency lower than 0.5 Hz. For example,

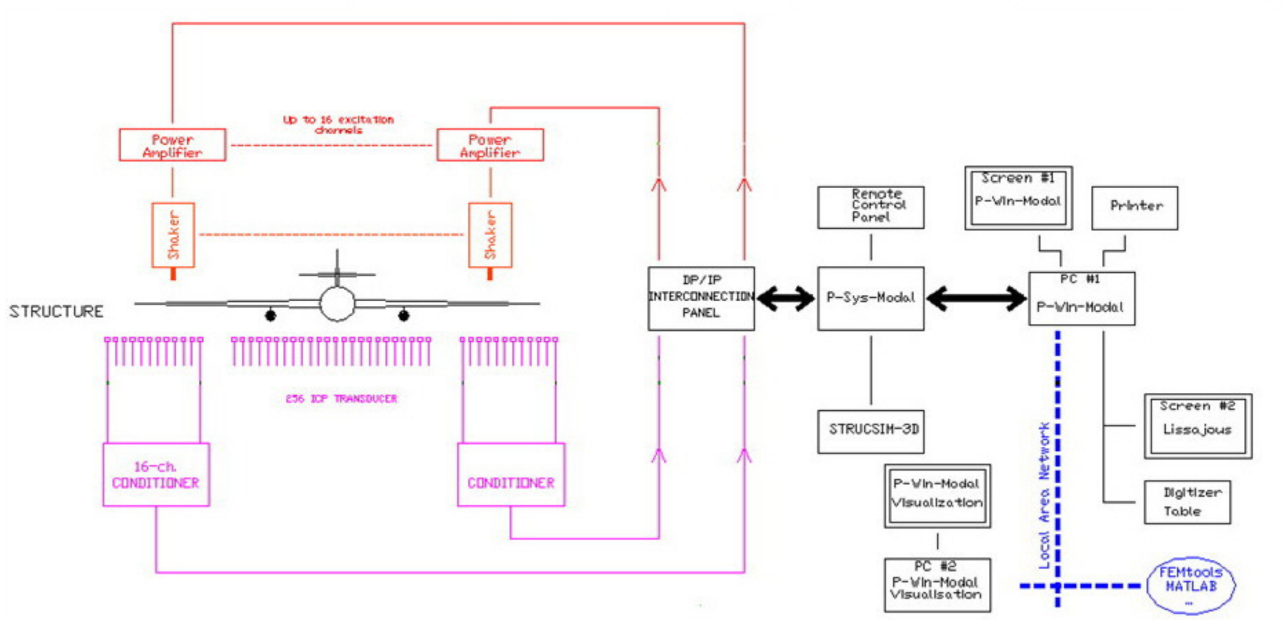

Fig. 3

mentioned above "Energia-Buran" pack was suspended using such units.

The GVT methods were also "filtered" by practice. Up to now, the so-called phase resonance method is one of the most reliable. The multipoint excitation tuning allows separating successively mode by mode. Each extracted mode is registered. This method is used to determine eigenmodes, eigenfrequencies, damping and generalized masses for the main structure modes. For higher modes it is possible to measure these characteristics as the first approximation. The measurements are made under harmonic excitation, so it is possible to estimate the influence of the nonlinearities. For the control surfaces with turned on hydrosystems this part of the experiment is obligatory and the characteristics are measured as function of the vibration amplitude [4].

The broadband (random, impulse, polyharmonic) excitation methods are also used as auxiliary, facilitating GVT. Modern computers allow to evaluate the frequency response functions, which are measured during such tests, and to acquire almost the same modal data as in phase resonance method.

It is necessary to note, that standard GVT are obligatory for any new aircraft. For example, CS-25 (Certification Specifications) prescribes:

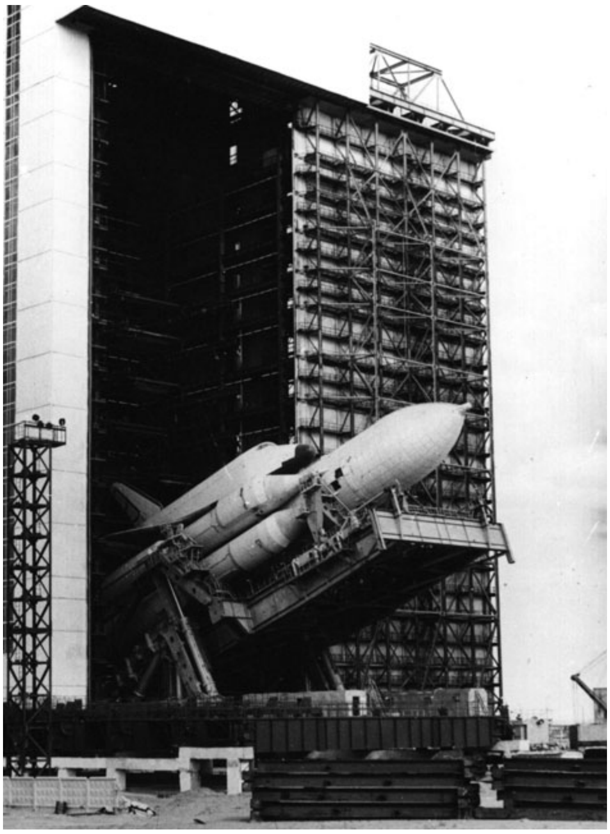

Fig. 4

> CS 25.629 Flutter, deformation, and failsafe criteria
>
> (a) G*eneral.* Compliance with this paragraph must be shown by calculations, resonance tests, or other tests found necessary by the Agency.

Corresponding requirement is also in Russian regulation AP-25.

It is evident, that the responsibility of the certification tests requires the maximal reliability and accuracy. The correction of the mathematical model is intermediate usage of GVT data. More general task is to agree all the data − computational and experimental, including all wind tunnel and flight test results. This task is solved during all the design process stages, sometimes during aircraft exploitation period. And this is the most important GVT data usage.

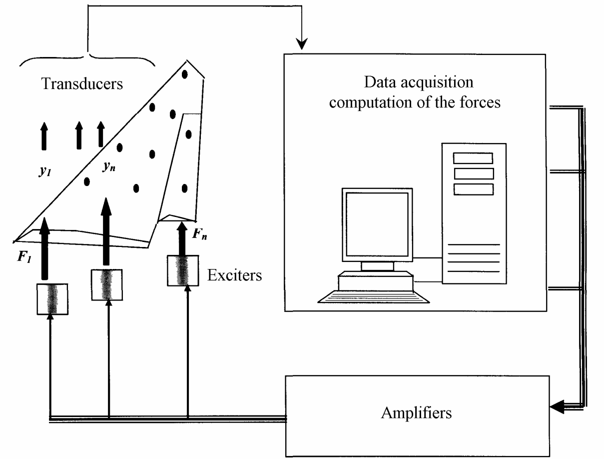

Fig. 5

On the other hand GVT equipment can be successively used in some other tasks. One application is the electromechanical modeling (EMM) of the aerodynamic forces acting on the structure [5]. This is test-bench flutter simulation of the scaled model (full scale aircraft, any aircraft aggregate) without airflow. The aerodynamic forces are calculated as function of some points of the structure displacements (and/or velocities) and are reproduced by actuators. This approach is intermediate between pure computation and pure experiment; it joins mathematical and physical modeling. It is possible to use any aerodynamic theory and to simulate any "flight conditions". But of course, distributed aerodynamic forces are replaced by the concentrated forces acting from exciters. When this replacement is correct and the transformations from transducers signals to the excitation forces are almost instant, these artificial forces correspond to actual airflow forces.

The benefits of EMM are: no restriction on Mach numbers (except transonic region) and airflow density, "flutter amplitudes" are restricted by exciters (no hard crashes), it is possible to repeat "flutter point" if necessary. When full-scale aircraft or missile is tested, all the structure specific features are real including damping, nonlinearities, and failures for example. In addition easy visual control facilitates the tests.

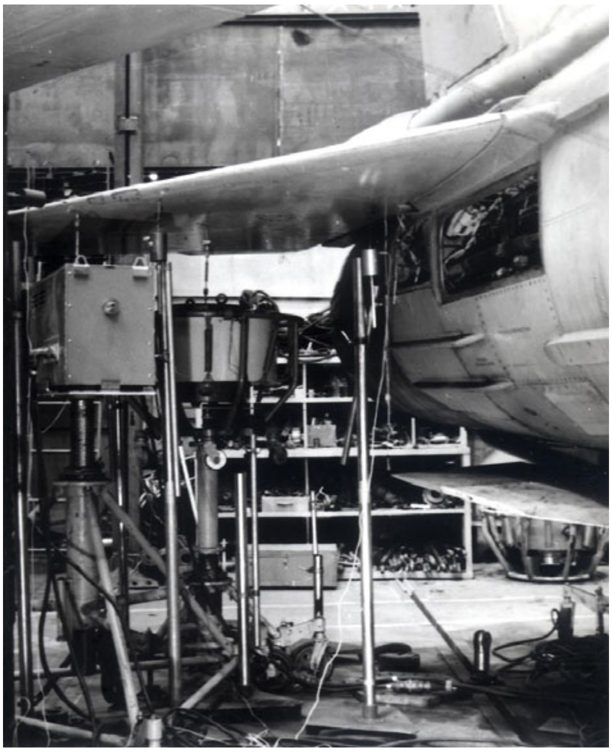

Fig. 6

This type of experiment is useful as preliminary overview before expensive high speed wind tunnel tests of scaled models. It allows to check all the equipment, and to prepare optimal test program.

During EMM of unmanned vehicles it is possible to tune flight control system and to ensure safety margins for the closed loop.

It is also possible to measure the frequency response functions "in flight conditions" with turned on flight control system and under any type of excitation, which can be added to "aerodynamic forces". It is also easy to measure transient response of the structure and limit cycle oscillations.

An example of such experiment installation is presented on fig. 6. The flutter of full-scale horizontal tail of the fighter was investigated by EMM [6] using 4 exciters. All-flying stabilizer had the free-play, so the damping of the rotation mode depended on the amplitude. This function for different flight conditions is shown on fig. 7.

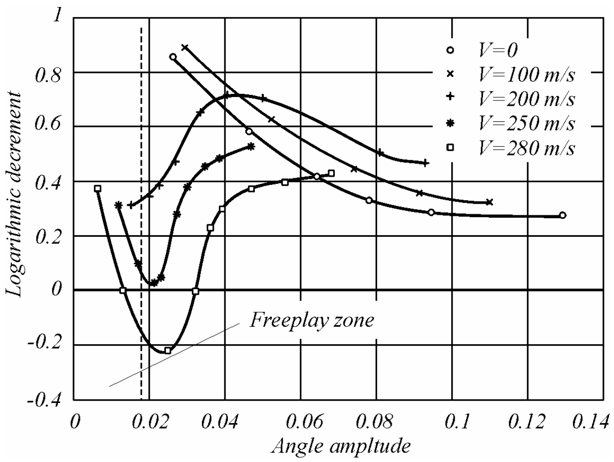

Fig. 7

The same structure was used to investigate the behavior near flutter conditions under additional random excitation, qualitatively simulating the flight in turbulent atmosphere [7]. It was detected that flutter with restricted amplitude can randomly appear and disappear. The airflow conditions and random excitation level influenced the probability of flutter appearance.

It is necessary to note, that this approach can be used also when any mathematical model is absent. In this case it is possible to use measured modes for the generalized aerodynamic forces calculation, but the accuracy is not higher than in the conventional unsteady aerodynamic theory.

Second approach relates to the engine unbalance simulation. Mentioned CS-25 and AP-25 contain the requirement to check the case of engine blade brake. It is necessary to show the safety of the aircraft in such a case. Rotating misbalanced engine generates periodic force with frequency depending on rotation speed. If the engine is turned off the rotation speed can decrease from nominal up to autorotation speed. And this frequency can coincide with aircraft eigenfrequencies. Standard GVT equipment allows investigating this case by simulation.

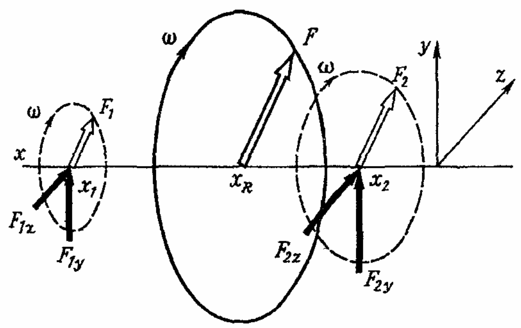

Fig. 8

The first experiments of this type were accomplished in TsAGI using PRODERA equipment about 1994 [8]. The forces acting on the aircraft from the pylon after blade separation, were simulated by two pairs of the exciters (two horizontal and two vertical) in two planes. Excitation signals were shifted in phase. The variation of the excitation amplitudes in planes allows moving the equivalent rotating force along the engine axis (fig. 8). The excitation frequency variation allows changing the rotation speeds. As it was shown by the analysis, when the engine forced angle vibrations are significant, it is necessary also to account for the gyroscopic forces. By using four exciters it is easy to reproduce this case without actual engine rotation.

We can mention here the investigations of the engine unbalance by simulation method us-

Fig. 9

ing PRODERA GVT equipment: the A-318 aircraft (fig. 9 – Courtesy DLR) and also A-340-500/600 [9], for example. Of course, it is reasonable to make such investigation during standard GVT tests, because no additional equipment is required.

When we talk about new aircraft design process, the existence of any type mathematical model is evident. GVT results are used to correct and tune this model. But sometimes it can happen that no drawings or mathematical model are available or they are lost, for example the aircraft is old, or the design bureau disappeared. If we need to investigate aeroelastic characteristics in this case, the GVT results can also be used as a source of initial data. This idea – to use measured modes as generalized coordinates for the flutter calculation – was discussed many years ago, when we had no computers. The manual calculation of each mode required a lot of time, resonance testing seemed to be easier.

Now GVT equipment is much more accurate, the data registration and evaluation are automated and computerized. Generalized characteristics – damping, masses, modes and frequencies are calculated immediately after measurements. So it is easy to continue the calculation and to find flutter boundary using this independent mathematical model, derived from GVT results.

Conventional flutter equation looks like:

$$C\ddot{q} + D\dot{q} + Aq + \frac{\rho V^2}{2} Q(k,M)q = 0$$

where q – generalized coordinates; ρ – air density; V – airflow velocity. This equation contains four matrices: C – structural inertia matrix; D – structural damping matrix; A – structural stiffness matrix; $Q(k,M)$ – generalized aerodynamic coefficients matrix – function of Mach number M and reduced frequency $k = \frac{\omega b}{V}$, ω – vibration frequency (in radians per time unit); b – characteristic length.

The order of matrices N is equal to the number of modes selected for the flutter problem.

In the case when experimental modes are used as generalized coordinates, structural matrices are assumed to be diagonal and real. The aerodynamic matrix is not diagonal and its coefficients are complex.

Equation is valid only for sinusoidal oscillations, not for arbitrary movements, because aerodynamic coefficients are derived under this assumption. There are several approaches to solve the problem. We can mention popular **p-k** method and relatively new **g**-method. These methods are well known, realized in flutter software and do not need any comments.

All the matrices in the equation except aerodynamic $Q(k,M)$ are determined from GVT results. Generalized aerodynamic coefficients matrix $Q(k,M)$ must be calculated using conventional algorithms and measured modes. The single problem must be solved here – modes interpolation. It appears because aerodynamic grid points and mode measurement points are different. Conventional way is to use surface splines.

Another problem is the choice of the modes which must be included into equation. This is important question, because during typical GVT all the modes (sometimes more than 100) in the specified frequency range are measured. Not all of them can influence the flutter behavior. On the other hand the problem becomes inconsistent when the order is too high.

It is reasonable to start from simple combinations of main modes. As a rule the flutter is defined by group of 3–4 modes. Other modes are not very important. After a few attempts it is possible to find the combination which has the lowest flutter speed.

The accuracy of such computation depends significantly on the measured generalized characteristics errors. The latter depend not only on the equipment characteristics, which become better and better. An important role is played by the structure. We assume that it is linear. Actually it is relatively linear in some amplitude ranges. The investigator needs to be very attentive analyzing any structure.

We mention in this paper some historical aspects concerning standard GVT. At the same time the usage of GVT equipment can be more wide and useful. The progress in the hardware and software opens new possibilities, which also can facilitate the flying vehicles development.

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