“SOYUZ-2” LV STRUCTURE OPTIMIZATION

N.Vvedensky, A.Likhoded, V.Sidorov, V.Zabudkin
Central Scientific Research Institute of Machine Building (TsNIIMash), Russia

A.Kozlov
State Research and Production Space Rocket Center “TsSKB-PROGRESS”, Russia

Launch vehicle (LV) modification is one of modern ways to increase its performance. Generally the modifications cause structural loads increasing. As a result new design and qualification are required for stiffened LV bays. This is the case for “Soyuz-2” LV, in addition external acoustical environment was significantly increased at control system (CS) bay location. In such circumstances minimization of number of modified structural elements, optimization of modified structures and demonstration that expected CS equipment vibration environment would not exceed stated earlier normative levels are actual fields of LV modification activities.

Dimensioning loads decreasing is one of the powerful means to reduce the number of modified structural elements and minimize stiffening of modified bays. There was the way applied successfully in the frames of “Soyuz” LV adaptation to fairing of high diameter [1]. The approach includes flight loads statistical simulation for transonic and maximum dynamic pressure phases, and minimization of dimensioning loads so to provide acceptable failure risk. In the case of “Soyuz-2” LV the problem is complicated. New digital CS application required to upgrade the software used for statistical loads simulation. These tools were used together with LV CS simulator and LV dynamic model to generate random samplings of structural loads and angles of attack. Fairing size is significantly higher and despite of application of new CS minimizing aerodynamic loads the second stage structure was a subject of modification in addition to the third stage. Used for “Soyuz” LV concept of loads decreasing did not provide elimination of the second stage structure stiffening. This concept was based on the acceptable “risk of decision” when random winds were taken into account which are close to maximum allowable one for launch. “Design risk” concept was applied for “Soyuz-2” when all random winds realizations were taken into account. This permitted to decrease dimensioning loads so that the second stage structure stiffening was excluded.

LV CS bay is located behind inverse cone of fairing in the area characterized by high local external quasi-static pressure at transonic phase and intensive acoustic pulsations at transonic and maximum dynamic pressure phases. To increase LV performance the structure of this bay should be optimized under complex loading by structural quasi-static loads, quasi-static and acoustic pressure, and limitations caused by structural integrity requirement and equipment arrangement. Main critical condition of this reinforced bay was the collapse in the presence of permitted local buckling. This problem is sufficiently difficult one. Therefore acoustic pulsation loads were substituted by equivalent external static pressure. Corresponding mathematical model of this bay was developed and optimization was carried out. Totally the effect of dimensioning loads decreasing and stiffened structures optimization resulted in additional payload weight of 75 kg to geo-transfer orbit (GTO).

Determined in wind tunnel tests acoustic pulsations at CS bay surface were higher than expected ones. As a result the danger came up that corresponding random vibrations would be higher than normative levels specified for equipment design and qualification. To check it CS bay dynamic model was developed. As in the case of “Soyuz” LV [1] wind tunnel test pressure time histories in digital format were applied as external excitation. Such approach makes it possible to decrease response in comparison with traditional spectral model application. In the result it was demonstrated that expected random vibrations do not exceed normative levels.

Statistical Approach to Loads Decreasing

Space structure ultimate loads decreasing can significantly reduce development time and cost of mission. Expert decisions are widely used for loads decreasing. But the limits exist beyond which those decisions should be based on risk assessments. The used here approach is based on the concept of an acceptable structure failure probability and includes statistical loads calculations and required safety factors evaluation with accounting for uncertainty for static strength failure modes [2,3].

There are static strength requirements (ultimate) that significantly influence on space structure weight. It is assumed that static strength is a property of a structure to withstand peak values of quasi-static and dynamic loads. When the traditional deterministic approach is applied for space structure design, loading cases, external loads combinations including their time histories, and safety factors are specified in norms or codes for static strength failure modes analysis. The probability of a limit load or pressure not to be exceed, failure risk and confidential probability should be specified in the case of statistical method considered application, which is based on the concept of an acceptable structure failure probability. For the practical using it is desirable to specify also prescribed loading cases understanding that only during those events loads (pressures) can rich significant values.

It is assumed that vehicle structure to be analyzed is subdivided into assemblies or parts, which are traditionally subjected separately to qualification static tests. Every part goes through prescribed loading cases. Total vehicle structure failure risk is evaluated as a statistical sum of risks for all parts and cases and must be lower or equal to specified failure risk. Value of failure probability for given part and loading case can be also specified as a requirement by using expert decisions.

Statistical loading model and structure resistance model are used for failure risk evaluation. Monte-Carlo method is the most applicable for determination of structural loads distribution. Prototype static tests results (qualification and periodic) are used for structure resistance model development and corresponding statistical parameters assessment. Adequate uncertainty accounting for is a very essential part of this approach because it is impossible to provide exact knowledge on statistical characteristics of future structure resistance.

Periodic qualification tests results analysis of decades of structures of different design has shown that Gaussian type of resistance distribution is an acceptable assumption that provides significant simplification of procedure. These results are also used to develop resistance scattering statistical model. Variation coefficients distribution for representative type of structures is determined as the result of special data processing. Static qualification tests results are used to develop resistance mathematical expectation distribution for representative type of structures by application of special processing. This processing procedure takes into account that the most part of tests are finished without loss of structural integrity. It was demonstrated that there is practically no correlation between variation coefficient and average values. This fact provides sufficiently simple procedure for resistance statistical simulation when Monte-Carlo method is applied.

The method of structure failure risk evaluation provides possibility to take into account verification plans (acceptance, qualification, periodic tests) and corresponding results to tailor initial resistance model to particular project.

Using loads and resistance models, ultimate loads are determined that provide acceptable failure risk and corresponding limit loads are defined as ultimate ones divided by normative safety factor. Sufficiently detailed approach description is presented in [2,3]. The approach was widely applied last time for space structure loads decreasing including:

♦ Several Russian Earth observation spacecraft (SC) launched by “Proton” LV: ground transportation, lift-off, 1st stage cut-off and separation loading cases; design modifications caused by payload weight increasing or LV change and corresponding requalification were excluded.

♦ Commercial communication SC’s (ICO, Astra-2A, GE-12, Echo, Intelsat-10) launched by “Proton” and “Proton-M” LV: ground transportation, lift-off loading cases; SC base and separation system requalification were excluded.

♦ “Breeze-M” – upper stage for “Proton-M” LV: main fuel tanks pressure loading; design modifications caused by test demonstrated insufficient strength and corresponding requalification were excluded, main tanks thickness were decreased without requalification; 30 kg of payload was saved (GTO).

♦ “Zenit – See Launch” LV: main fuel tanks pressure loading; test safety factor was decreased for all main tanks qualification; 4 tanks subjected to qualification testing were saved and used for launch; recently it was quantitatively proven that all main tanks fabricated with modified technology can be launched without qualification test.

♦ “Soyuz” LV fairing and third stage modifications for “Cluster-II”, “Mars-Express”, “Amos-2”, “Galaxy-14” SC’s launches: transonic and maximum dynamic pressure regimes; structure stiffening was minimized to provide LV performance capability and weight was saved for vibration damping cover installation at CS bay.

♦ “Rockot” LV: lift-of case; allowable ground wind velocity was increased.

♦ SC’s launched by “Rockot” LV: 1st stage cut-off and stages separation loading case; SC/LV interface tension loads were decreased to acceptable level for commercial SC and their separation systems.

♦ “Dnepr-M” LV: maximum dynamic pressure regime: structure modifications were excluded for some critical bays.

♦ “Soyuz-2” and “Soyuz-ST” LV: transonic and maximum dynamic pressure regimes; structure modifications were excluded for the most of critical bays and minimized for others; time and cost of modification were decreased; LV structure weight was decreased.

This paper is devoted to mentioned method application to “Soyuz-2 (ST)” LV.

Atmosphere Flight Structural Loads Statistical Simulation and Processing

Atmosphere flight loads determination requires multi-disciplinary analysis application with accounting for CS operation, structural dynamics and loading. Developed and delivered by CS design organization software for CS operation simulation was incorporated into software for statistical parameters generation and loads analysis. This combined tool was applied for loads statistical simulation [4]. All significant random parameters including environments and LV ones were generated as statistical input and used for statistical dynamic loads calculations by Monte-Carlo method. Available atmosphere wind and turbulence statistical models for Baykonur launch site were used for loads sampling generation. All wind realizations were taken into account independently on applied procedure for decision to permit launch in particular wind conditions. Structure failure risk evaluation with application of such loads sampling can be characterized as "design risk" concept. In earlier application for "Soyuz" LV only those wind realizations were taken into account, which are close to maximum allowable one for launch. Such approach can be characterized as "risk of decision" concept. New approach made it possible to provide additional loads decreasing. The samplings of angle of attack, its product by dynamic pressure and structural loads in critical LV sections were statistically processed to define distribution type and corresponding parameters. Typical processing result is presented in Figure 1. It was supposed for shown load parameter (x) that it has the following distribution

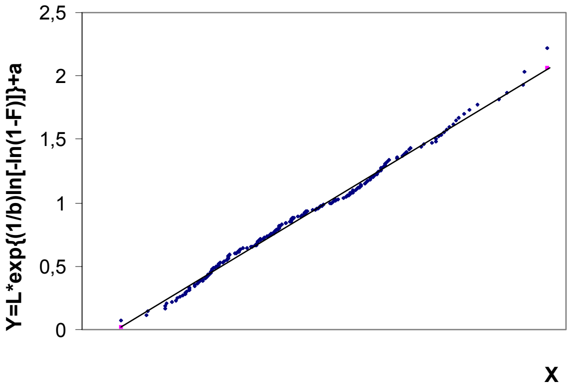

Fig. 1. Typical loads distribution

$$F(x) = 1 - \exp\left\{-\left(\frac{x-a}{L}\right)^b\right\}$$

where a, L, b– distribution parameters.

Determined distribution parameters were used to generate table distribution with sufficient for failure risk assessment probability range [2].

Structure Failure Risk Assessment and Dimensioning Loads Evaluation

Applied for risk assessment structure resistance statistical model was based on static test results for sufficiently wide class of space structures to cover all critical LV structural items. Using this model in conjunction with loads statistical simulation processed results, corresponding dimensional loads were determined on the base of available normative risk and confidential probability values. In the result structural loads were decreased up to 25% in comparison with traditional deterministic approach. In addition conservative but realistically decreased limit angle of attack was determined that was used for local external pressure determination at CS bay behind inverse cone of fairing and corresponding acoustic pulsations evaluation. Loads decreasing were sufficient to avoid modification of LV second stage structure and minimize LV third stage stiffening. Typical failure risk uncertainty distribution is shown in Figure 2. Resulting failure risk is correspondent to normative value of confidential probability.

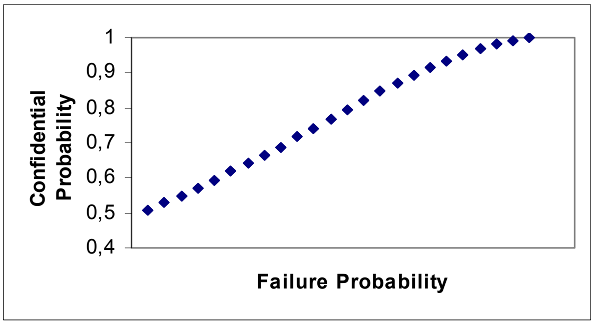

Fig.2. Typical failure risk uncertainty distribution

The effectiveness of applied approach is illustrated in Figure 3 where relative bending moment at “Soyuz” LV fairing/LV interface is presented for different wind models used in Russian space industry during last 40 years. It was divided by value corresponding to Ariane-5 model. Referred to 1995 year model was used for “Soyuz” LV/ “Cluster-II” loads determination, referred to 2000 year model was used for “Soyuz-2” LV loads definition.

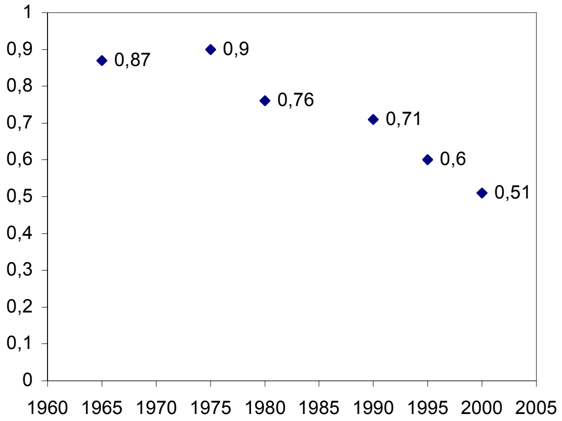

Fig. 3. Retrospective comparison of Russian wind models application

Control System Bay Structure Optimization

Despite of loads decreasing located behind inverse cone of fairing third stage dry bays (CS and engine ones) structure had to be stiffened in the frames of LV modification due to application of fairing with lager size. These bays are subjected by combined loading of bending moments, axial and shear forces, external pressure and intensive acoustic pulsations at transonic and maximum dynamic pressure phases. Structural optimization was required to minimize weight of these bays that are reinforced thin-shell structures [4]. In addition to combined loading the optimization was carried out under limitations caused by equipment arrangement and technology requirements. The presence of local buckling was considered as permissible condition and corresponding several hundreds modes were not taken into account that had lower critical load than collapse one. As a result desirable stiffening was defined at expert level to provide quasi-optimal structural weight. Acoustic pulsations loading were simulated by equivalent external static pressure. It was demonstrated that proposed stiffening provided sufficient but minimum margin of safety. One of collapse modes is shown in Figure 4. Totally the effect of dimensioning loads decreasing and stiffened structures optimization resulted in additional payload weight of 75 kg to GTO.

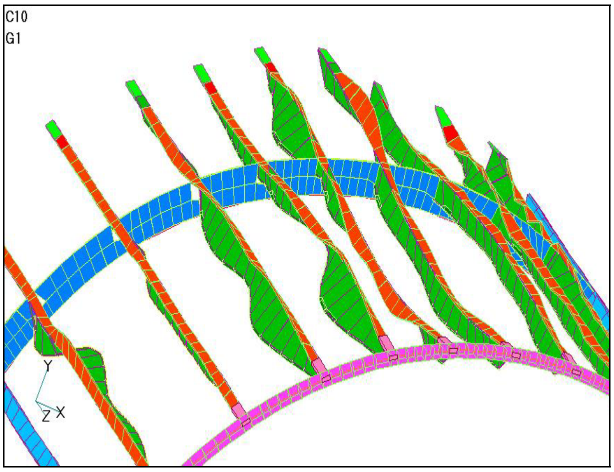

Fig. 4. CS bay collapse mode example

Control System Equipment Vibration Evaluation

CS bay is located behind inverse cone of fairing in the area characterized by intensive acoustic pulsations at transonic and maximum dynamic pressure phases. Determined in wind tunnel tests acoustic pulsations at CS bay surface were higher than expected ones. As a result the danger came up that corresponding random vibrations would be higher than normative levels previously specified for equipment design and qualification. The assessment of vibration by spectral-correlation approach has shown that corresponding levels at equipment interfaces are higher than permissible ones. To decrease them it was taken into account that actually pressure pulsations have non-stationary nature especially at transonic regime. Direct solution of the CS bay dynamic response problem in time domain was used for vibration assessment. Acoustic environment was simulated as the set of time-dependent external pressures applied at different bay zones. Corresponding pressure time histories were determined from wind tunnel test measurements. Evaluated by this approach application RMS (in considered frequency range) at equipment interfaces was by 1.5…2.0 times lower than for spectral method [4] and it was acceptable for CS units. Typical dynamic model of a bay is presented in Figure 5.

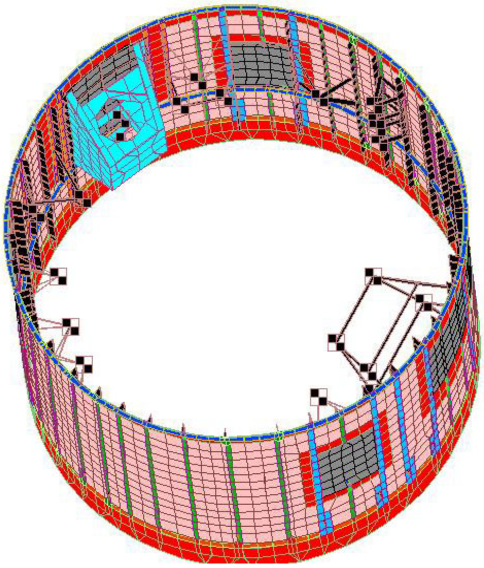

Fig. 5. Typical dynamic model used for vibration analysis

Conclusion

Multi-disciplinary investigations of “Soyuz-2” structure loading, optimization and equipment vibration evaluation were conducted in the frames of LV modification. Statistical approach was applied for loads and structure weight decreasing that made it possible to avoid second stage modernization, minimize third stage stiffening and as a result to provide additionally 75 kg of payload to GTO. Direct loading of CS bay by time dependent acoustic pressures instead of spectral approach application made it possible to decrease vibration levels and demonstrate that equipment vibration response is in the bounds of earlier stated specifications.

References

[1] A. Likhoded, I. Kildibekov, A. Kozlov, N. Panichkin, V. Sidorov, V. Vjilomov, N. Vvedensky. Modeling of LV Control System Bay Vibrations Induced by Acoustical Loading. *Proceedings, ISMA 25th Conference.* September 2000, LEUVEN, Belgium.

[2] N.Vvedensky, A.Likhoded, N.Panichkin, V.Zabudkin, V.Sidorov, P.Kalnin, A.Kozlov, Space structure ultimate loads decreasing by using statistical approach. *IAF Paper 98-I.1.07.* Melbourne, 1998.

[3] N.Vvedensky, A.Likhoded, V.Sidirov, V.Zabudkin. An Application of Statistical Approach for Space Structure Loads Decreasing. *Proceedings, Symposium – Aerospace Technologies of the XXI Century: New Challenges in Aeronautics.* August 2001, Moscow, Russia.

[4] N.Panichkin, N.Vvedensky, V.Zabudkin, A.Kozlov, A.Likhoded, V.Sidorov. Coupled control system, structure dynamics and loading modeling to provide increased performance of “Soyuz” LV family. *Proceedings, 5th International Conference on Launcher Technology. Space Launchers: Missions Control and Avionics.* November 2003, Madrid, Spain.