Explosive technologies for strength testing of thin-walled constructions for action of one-side non-stationary loadings

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Abstract. A set of explosive devices for generating of the one-side non-stationary loads of different physical nature is described. Two new explosive devices for the formation of low-impulse loads of microsecond duration are proposed. Methods of measuring of the response parameters of thin-walled composite constructions to dynamic and impulse loads are considered. A new method of experimental definition of non-stationary displacements of constructions at the shell stage of deformation is proposed.

It is obtained that when investigating the shell stage of deformation of fiberglass thin-walled constructions, the use of wire and foil sensors to measure the deformations provides to close results.

1. Introduction

Thin-walled composite constructions of rocket and space equipment (RSE) are under the action of flight loads [1, 2] and external loads of different physical nature [3, 4]. Flight loads are generally axisymmetric and quasi-stationary. Methods of strength calculations for loads of this type are well developed and implemented in the practice of design of RSE construction elements. However, external loads are unilateral and non-stationary in the most cases [4, 5]. The results of the strength calculations in this case are not so reliable and strength tests for one-side non-stationary loads are required.

Non-stationary effects are conventionally divided into impulse and dynamic loads depending on the time duration of their action and the causes of constructions damage. Dynamic loading conditions are realized in case of action durations comparable to period of free oscillations of thin-walled construction and at least in 10...15 times longer time of disturbance propagation through the shell thickness (this condition ensures the prevalence of shell deformation stage). Destruction of the composite constructions in case of dynamic deformation occurs due to development of unacceptable deflections and formation of delaminations and cracks.

In case of impulse loading, when duration of action not only does not exceed a quarter of period of oscillations but is comparable or less than time of disturbance propagation through thickness of thin-walled construction element, the main cause of destruction is development of wave processes accompanied by formation of delaminations (it takes place in composite material)
and spalls (it is typical for metals). An important factor facilitating the investigation of the effects of impulse loading is the possibility to select the fragment of construction which results of testing is close to that of testing the whole structure. An obvious necessary condition for the correctness of such selection is the low propagation time of the compression wave through the thickness of the fragment compared to the arrival times of the unloading waves from the edges of the fragment. This condition is not difficult to achieve for full-scale thin-walled construction.

However, the deformation process is completed by the shell stage also in the case of impulse loading of thin-walled structures when the stress waves are damped. The attenuation results in an increase in the spatial size of the wave impulse. The shell stage occurs when the size of the wave becomes comparable with the thickness of the construction. Moreover, the use of protective porous coatings and heterogeneous packages significantly reduces the role of wave processes in the destruction of the material and practically does not protect against the formation of cracks and the development of unacceptable displacements. Therefore, the final strength tests of the composite construction as a whole to the dynamic loads causing the shell stage of deformation are also necessary when only the action of impulse wave is expected during RSE flight.

As it is known [5], the available sets of modeling devices do not provide generation of low-impulse loads of microsecond duration with high simultaneous action on the RSE surface. But such non-stationary loads are required for the strength tests of thin-walled constructions. The development of low-impulse devices is relevant and is of great practical importance.

2. Explosive devices for generation of dynamic loads

Equidistant-surface charge [5, 6, 7] is useful and convenient to use for generation of dynamic loads when thin-walled structures are tested for strength to lateral non-stationary effects. This charge is an elastic sheet explosive placed on an inert substrate (fig. 1 a). The substrate is spaced by a predetermined distance from the object to form an equidistant surface. The duration of loading impulse varies by changing the distance between the equidistant surface and the test object. Simultaneous explosive detonation is achieved by multipoint initiation by one detonator with the help of tapes of equal length made of sheet explosive. Equidistant-surface charge generates loads with duration \( \tau_p = 10...100 \) \( \mu s \) and pressure impulses of \( I_p = 0.3...3 \) kPa×s.

![Figure 1](image-url)

**Figure 1.** Explosive devices for generation of dynamic loads: a) equidistant-surface explosive charge; b) explosive charge distributed in volume; c) shock tube of explosive action

The explosive charge distributed in the volume [5, 6, 7] was designed to generate dynamic loads having a duration of more than 100 \( \mu s \). Charge is made of strips of low-density sheet...
explosive (fig. 1 b). Strips are detonated from the ends closer to loaded surface. For reliable initiation, every 3-4 strips are assembled into a beam with an electric detonator inserted. In order to avoid local impact of explosion products and to obtain an aligned pressure front, the charge strips are arranged so that the distance between them is several times less than the distance to the surfer. The charge distributed in volume gives the possibility for generation of load durations \( \tau_p = 100...500 \ \mu s \) and impulses of pressure \( I_p = 0.01...2 \ \text{kPa} \times \text{s} \).

The explosive devices discussed above are designed to simulate a single action. However, the mechanical action of the radiation may be more effective in impulse-frequency irradiation modes. In such modes, plasma becomes partially transparent in the time between impulses and the zone of absorption of radiation energy approached region nearer the surface. In addition, the most dangerous resonance conditions for thin-walled structure can be realized in case of multiple action when loading is performed in phase with its oscillations. A multi-barrel shock tube of explosive action [5, 6, 7] is conveniently used to reproduce a sequence of dynamic loadings of a thin-walled constructions. This shock tube is a set of barrels with flanged connections allowing to increase their number and length (fig. 1 c).

Barrels are connected with transition camera provided with nozzle. Structure of shock tube allows to detonate explosive charges at different times in each of barrels and to obtain impulse sequence. The membranes are used to protect charges from shock waves coming from adjacent cameras. The change in charge masses makes it possible to generate loads with equal or different pressure values in each action. The sequences of the decreasing or increasing impulses of pressure with \( I_p = 0.1...3 \ \text{kPa} \times \text{s} \) and \( \tau_p = 20...200 \ \mu s \) can be generated by the offered shock tube.

Note that the shock tube structure provides the possibility of loading of thin-walled RSE elements in resonance regimes. The analysis of parameters of construction response to the first action is performed in real time. Time intervals between subsequent pressure impulses are assigned by the electronic logic device in accordance with the results of this analysis. Response parameters (deflection, deformation, velocity, or acceleration) are measured by a sensors connected to a logic device that controls the detonation sequence.

3. Explosive devices for generation of impulse loads

Tape charge [8] and controlled initiation charge [9] are the most promising explosive generations of low-impulse loads of microsecond duration. The tape charge is made of explosive tapes which are placed on circular tubes (see a figure 2 a). Tubes are equidistant from surface of loaded object. Multipoint beam initiation system of explosive tapes is used to provide simultaneous loading of surface.

The charge with the controlled initiation is produced in the form of thin (\( \leq 3 \ \text{mm} \)) shell from fibrous material. The shell has milled channels filled with plastic bonded explosive (PBX) (fig. 2 b). Placement of PBX in channels offers a number of advantages over other methods of localization of explosive (e.g. by solid layer or sectors on a porous substrate). Controlled initiation is implemented by the method taken from the technology of generation of pressure of megabar level [10, 11].

Note that the set of devices [5, 6] supplemented by these new developments has wide capabilities. The use of this set is planned for strength testing of thin-walled RSE constructions to thermal and mechanical actions of radiation and particles fluxes of different physical nature and impact of compact solids.

The explosive launching device [12] shown in fig. 2 c is used in laboratory to generate impulse loads. Flat-wave explosive lens (1) made of phlegmatised hexogen A-IX-1 and paraffin insert accelerates the striker (3). The speed of the aluminium striker with diameter of 90 mm and thickness of 7 mm at the exit from the steel ring (2) is 1.13 km/s in this variant of the device.
Figure 2. Explosive devices for generation of impulsive loads: a) tape explosive charge; b) explosive charge with controlled initiation; c) explosive launching device (1 – explosive lens, A-IX-1/paraffin, \( D = 100 \) mm; 2 – focusing ring, steel, \( D_{ext} = 150 \) mm, \( h = 16 \) mm; 3 – striker, D16T, \( D = 90 \) mm, \( h = 7 \) mm; 4 – tested sample)

4. Measurements of non-stationary parameters of construction response

Wave stage of deformation. In the study of wave processes in materials, kinematic (particle velocity and BC velocity) and force (pressure between layers of the tested package of materials) characteristics are usually chosen as measured parameters.

The electromagnetic method is used to measure the particle velocity of the material inside the sample [13, 14]. The essence of the method is the generation of electromotive force in a conductor (sensor) moving in a magnetic field. The sensor is located in the sample perpendicular to its axis (loading direction). The sample is placed in the magnetic field during the tests. When the sample is loaded, the sensor is driven to a speed equal to the particle velocity of the surrounding substance. As a result, the working plane of the sensor crosses the magnetic field lines and the difference of potentials is generated that is proportional to the particle velocity of the material. The use of a two-stage sensor makes it also possible to measure the shock wave velocity.

Wave profiles of the particle velocity of the substance in the area of the rear surface of the sample are measured by capacitive sensors (in the case of metal samples) [15] and laser Doppler velocimeter [16]. Analysis of the profiles of the particle velocity of the rear surface of the samples from the homogeneous material allows to find its shock Hugoniot and determine the spall strength [12].

One of the essential response parameters determining the strength of the multilayer sample at the wave stage is the pressure at the boundary of the different layers. Closed type resistive sensors are used for pressure measurements. For example, a N2T-TR-A06-00370 pressure sensor is suitable (manufacturer is VPG MicroMeasur). The initial resistance of the sensor is 37 ohms (this value varies from 36 to 38 ohms in reality). The material of the sensor is highly pure nickel. The resistance-to-pressure coefficient is 5%/GPa for this material. The external view of the sensor is shown in fig. 3.

Estimations show that the error of pressure measurement by this
gauge does not exceed 25%.

**The shell stage of deformation.** As a rule, displacement, deformation, and accelerations (*g*-load) are measured during researches of deformation and fracture of a thin-walled constructions at shell stage of deformation.

The shell stage of deformation of thin-walled constructions under mechanical action of radiation and particles is characterized by small (up to hundreds of m/s) speeds and relatively large (up to several centimeters) displacements. The requirements for temporary resolution of the displacement measurement methodology are moderate. A disadvantage of traditional laser Doppler interferometry is the small depth of field of the optical system. The contrast of the interference picture is degraded at displacements greater than 1 cm and registration becomes impossible. Therefore, the method of measuring the non-stationary displacements is based on registration of the change in illumination of the moving surface is developed and used.

The surface is highlighted by a point source (in this case, the dependence of illumination on distance will be quadratic). A powerful (4.5 W) laser diode is used. Radiation is delivered to sample surface by means of optical fiber.

Radiation reflected from the surface enters the second fiber and is registered by a photodetector based on a photodiode and a two-stage amplifier. Receiving fiber is diaphragm-shaped with thin steel tube. As a result, the reflected radiation is collected from a small area on the illuminated spot. The radiation power of the source is sufficient to create electrical signals of tens and hundreds mV depending on the distance. The common measuring scheme is shown in fig. 4. Radiation from the laser diode 4 through the fiber 3 enters the fiber sensor 2 and is reflected from the surface of the sample 1. The reflected radiation collected by 2. The retro-reflective film is adhered to the surface of the sample to improve the reflection of the radiation. Radiation enters photodetector 5 through second fiber 3. The electrical signal is registered by the oscilloscope 7. The pulse timing generator is driven by a contact sensor located on the detonator cap (it is not shown in fig. 4) and provides the trigger to the oscilloscope 7 and to the laser power supply 6. Total error of the offered method of displacement measurement does not exceed 15%.

Deformations are measured by electrotensometric technique with the balanced single bridge scheme. Wire strain sensor KB-10-200 (it is manufactured by CNIIMASH, Korolev, Russia) and foil strain sensors BF120-3AA, BF350-3AA (it is manufactured by ZIMEC, China) are used. Sensors allow measuring of the relative non-stationary deformations up to 4% with error not exceeding 15% [5].

High-frequency vibration-resistant accelerometers with high conversion coefficient and maximum values of measured accelerations up to $10^4 g$ (for example, it is ADP-10-1 accelerometer having measurement error of not more than 20% [5] are used to measure *g*-loading.

**5. Fiberglass shell test results**

Strength tests of the fiberglass cylindrical shell ($h/R = 0.06$; $L/R = 3$) were done to compare the performance of various (production of CNIIMASH and production of ZIMEC) non-stationary strain sensors. The choice of fiberglass as a composite shell material is due to the fact that strain measurements in fiberglass give more reliable results than for many other composites.
For example, organoplastics produced by means of thread winding [17] are characterized by substantial non-uniformity of structure. In this case, the correct measurement of deformations becomes very problematic.

Shell was firmly connected with two steel bottoms by means of bolts and steel straps. The all construction was installed at to a ballistic pendulum to measure the pressure impulse. The shell at the pendulum with the explosive device is shown in fig. 5.

Strain sensors were glued at an inner surface at points (\(\varphi\) is a circular coordinate): \(\varphi = 0^\circ\), \(\varphi = 90^\circ\) and \(\varphi = 180^\circ\) (from the center of a loaded surface). In a point \((\varphi = 0^\circ)\) the wire sensor KB-10-200 was duplicated by the foil sensor BF350-3AA. The results of comparisons of circular deformations measured by different sensors are shown in fig. 6 a. It can be seen that wire and foil sensors in one experiment register deformations that differ by 5... 15% relative to each other. Time dependences are also consistent with good accuracy, but the signal of sensor KB-10-200 is more noisy.

Data of strain sensors in points \(\varphi = 90^\circ\) and \(\varphi = 180^\circ\) (wire sensors KB-10-200 were used at these points) are shown in fig. 6 b.

Note that the load parameters were insufficient to significantly destroy the test shell (cracks, delaminations and spalls were not observed). Relatively small (up to 0.2%) deformations did not result in delamination of strain sensors.
6. Conclusions

Explosive technologies can be successfully applied to modeling of the mechanical action of energy fluxes of different physical nature at the RSE. At present there is a tested set of explosive gas-dynamic devices and a set of techniques to measure the parameters of response for carrying out experimental investigations of strength of thin-walled composite constructions of RSE in a wide range of spatial-time characteristics of lateral non-stationary load.

The proposed two new explosive devices for generation of low-impulse loads significantly expanded the capabilities of this set for testing of thin-walled constructions.

It is obtained that when investigating the shell stage of deformation of fiberglass thin-walled constructions, the use of wire and foil sensors to measure the deformations provides to close results.

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