TESTING OF CARBON FIBER-REINFORCED PLASTICS UNDER ULTRASONIC HIGH-FREQUENCY ECHO-METHOD

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Paper is devoted to improvement of echo-method of ultrasonic testing of composite materials and, mainly, carbon plastics.

Carbon fiber-reinforced plastics are referred to reinforced polymers or polymeric composite materials (PCM) and represent polymeric base (matrix) containing thin reinforcing high-strength fibers of carbon. PCM's are applied from 1950'sin various branches of industry. Wide application of PCM's in aviation industry is related with the fact that these materials make it possible to reduce weight and to increase structure strength significantly. Currently, aircraft strength members, vertical and horizontal plane cowlings, tail fins, wing mechanization, honeycomb panels and many other items are produced of PCM. However, insufficient level of design and technological solutions, as well as deviations committed in the production technology result in violation of integrity of some composite units in the process of their production and operation especially under combined impact of power loads and climatic factors. Therefore, elaboration of methods and means for nondestructive testing of PCM articles is one of the most important problems.

Presently, ultrasonic high-frequency echo-pulse method is started to be applied successfully for testing carbon fiber-reinforced plastics. Previously, high-frequency shadow method, as well as low-frequency methods like impedance method, local natural oscillations method (NOM), velocimetric method, method of rapping, etc. were used mainly for PCM testing. Echo-method was not used due low resolution of used equipment and low acoustic properties of PCM-made structures resulted in appearance of considerable uncontrolled (dead) near-surface zones. Development of production technologies has led to that current acoustic properties of end structures of PCM's do not differ strongly from ones of metal materials, while modern equipment high-sensitive testing of PCM parts of various thickness (2.5 to 25 mm) to be carried out with dead zones not exceeding 0.2-0.7 mm.

Application of echo-method for testing by itself contains no special novelty; abroad, this method is applied everywhere. In FGUP «VIAM», researches directed toward development of methods and means for PCM's testing and, in particular, carbon fiber-reinforced plastics under high-frequency echo-method using longitudinal acoustic waves are carried out for several years already. First such methodology - TR 1.2.1942 – devoted to the testing of ribbed and waffle panels of carbon fiber-reinforced plastic KMU-7e was elaborated in VIAM in 2007. Its implementation and intensive application at two branch enterprises during 2008-2009 has revealed the number of aspects that were not taken into account during elaboration. This has required additional studies to be carried out. At the same time, in 2009, under order of the Yakovlev Experimental-Design Bureau, scientific research on adaptation of echo-method to large-size panels of carbon fiber-reinforced plastic for the article MS-21 (advanced near- and medium-range aircraft)was carried out. These researches have resulted in significant revision of the methodology TR 1.2.1942 and elaboration of MM 1.2.116-2009 «Manual ultrasonic testing of integral structures of polymeric composite materials». In the course of works performed in FGUP «VIAM» on studying of acoustic properties (attenuation of ultrasound and echo-signals from flaws) of various panels and structures of carbon fiber-reinforced plastic VKU-17KE0.1 of adhesive prepreg KMKU 3.150.E0,1.45, possibility of application of various ultrasonic piezoelectric probes (PEP) for testing monolithic zones of such panels and structures, establishment of physical reasons of echo-signal appearance and drop of the bottom signal amplitude observed with some studied panels, as well as detectability of inclusions of various types, recommendations on selection of testing equipment, requirements to working reference specimens (WRS) and methods of their attestation, requirements to applied coupling liquids, recommendations on selection of scanning pitch and speed, as well as on time corrected gain, etc. were elaborated and taken into account during further elaboration of methodologies.

Main differences between new methodologies and previously applied ones consist in the following:

It was decided to deny application of dual-transducer probes. During insonification of a material with strong anisotropic layout (collected from packs with predominantly unidirectional layout of prepreg layers), amplitudes of all echo-signals (both noise signals and signals from a flaw) vary strongly during rotation of a PEP around its axis, which impedes adoption of the rejection decision. Dependence of sensitivity on the depth of reflector location near entry surface of such PEP's is considerably non-linear. This requires manufacturing of additional reference reflectors (RR) in WRS in order to equalize sensitivity. Sensitivity zone of such PEP's for reflectors located at small depths represents narrow band extending along PEP acoustic insulation even when probe case has round shape. Poor mutual orientation of PEP and narrow elongated flaw can result in reduced probability of its detection. With equal setting to reference reflector of 10 mm diameter, dual-transducer probe will be more sensitive, as a rule, to small admissible flaws and structural irregularities, which can result in over-rejection. Instead, it was decided to use wide-band combined normal probes with exchangeable wedge (or delay line). Diameter of the PEP's piezoelectric element must be within 12 to 13 mm (previously, it was not specified causing inconsistency of testing results obtained at different enterprises). Length of delay line (L_d, mm) must be sufficient for second echo-signal from the end face of delay line to be observed following bottom signal in a panel of maximal thickness H_{max}, mm. This is met under condition:

$$L_з \geq H_{\max} \cdot \frac{c_з}{c_y} + 1$$
,

where: c_d – is velocity of longitudinal wave in the delay line material, mm/µs; c_c – is velocity of longitudinal wave during its propagation across layers in the tested carbon fiber-reinforced plastic, mm/µs.

Thus, for delay line of polystyrene (c_d = 2.4 mm/µs), at velocity in carbon fiber-reinforced plastic c_c = 3 mm/µs and maximal thickness of 8 mm, delay line of length L_d not less than 8 mm should be selected, while at maximal thickness of 16 mm – nor less than 14 mm.

Above indicated r5equirements are satisfied with PEP's like Panametrics V606-RB, V609-RB with delay lines WTD-5-1/2" for thin panels (monolith thickness of less than 10 mm) and WTD-5-1" for articles with monolith thickness within 10 to 25 mm or similar probes GE IT of DFR series. It is possible also to use PEP's like C545-SM and C541-SM (R/D Tech), which are specially designed for testing polymeric composite materials (PCM) in aviation with SPE3-0L-IHC-C, SPE3-0L-WP5, DLH-2 delay lines.

For tested parts with thickness of up to 10 mm, it is recommended to use probes for 4-6 MHz frequency, which provides, as a rule, dead zone depth not exceeding 0.5 mm, while for larger thicknesses – probes for 2.0-3.5 MHz frequency (dead zone does not exceed 0.7 mm). Correspondingly, requirements to electric circuit of flaw detector are stated, which make it possible to ensure the required resolution. As a rule, it is achieved by generator of impact excitation emission pulses (or generator allowing formation of rectangular pulses of adjusted length) within composition of flaw detector and possibility of operation of receiving amplifier in wide-band mode.

Initially, methodology TR1.2.1942 required from flaw detector operator to follow up bottom signal amplitude in order to monitor the quality of acoustic contact only. Practical application of this methodology has shown that zones of increased attenuation can present in tested panels, where bottom signal amplitude drop is observed, which is not related with acoustic contact. Under new recommendations, with bottom signal amplitude drop by more than 6 dB, this zone should be marked and studied from backside, as well as by inclination of a probe in order to make sure that disappearance of bottom signal is not caused by curvature of entry surface and its non-parallelism with bottom surface. If disappearance of bottom signal is not caused by curvature of entry surface and its non-parallelism with bottom surface, this zone should tested from both sides at 2-2.5 MHz frequency under echo-pulse method. If during testing at 2-2.5 MHz frequency, bottom signal amplitude drop exceeds 6 dB in relation to bottom signal in WRS, this zone should be marked in defectogram as zone of increased attenuation, while 12 dB – as defective one. For monitoring the bottom signal amplitude, application of second AFM (automatic flaw monitor) strobe was introduced. In fact, described measures represent implementation of mirror-shadow method in addition to echo-method without significant increase of testing labor intensity. Besides, in connection with the fact that tested panels can differ from each other and from WRS by average ultrasound attenuation, corresponding adjustment of flaw detector gain can be required. Adjustment is performed once prior the beginning of scanning. Attenuation of ultrasound is evaluated by the ratio of bottom signal amplitudes in a panel and WRS.

Equipment testing methodology was developed initially for under customer's demand had no function of time corrected gain (TCG). In practice, most flaw detectors applied in industry for PCM testing do not possess with this function; therefore, it was decided to activate TCG during testing of panels with thickness of more than 6 mm in order to compensate attenuation of ultrasound and equalize sensitivity across thickness. For the event of difference between acoustic properties of test object and working reference specimen, methods of TCG fine-tuning were elaborated.

List of applied flaw detectors is extended and requirements to flaw detector selection are stated. Flaw detector must be equipped with depth meter and automatic flaw monitor (AFM). Flaw detector must be able to set digitally the amount of additional gain in every DAC (distance-amplitude correction curve) point. Most modern digital flaw detectors like UD2V-P46, USD-50, USD-60 (LLC NPC «Kropus»), UD2-70 (LLC NPK «Luch»), Epoch 4+, Epoch XT, Epoch 1000 (Olympus NDT), USM35 (GE IT) meet these conditions.

Since paint-and-lacquer coating (PLC) is applied subsequently on the entry surface of UST panels immediately following their formation, requirements to applied coupling liquids were made more stricter under technologists' demand. During testing of articles prior application of PLC's, it is admitted to use distilled water or distilled water-ethyl alcohol mixture only. During testing of panels with applied PLC, it is admitted to use also glycerin and "Ultragel" coupling lubricant.

Requirements to reference specimen were modified cardinally. Instead of initially envisaged artificial flaws (reflectors) in the form of round fragments of fluoroplastic film embedded during laying out, it was decided to use flat-bottom holes produced by milling from the bottom surface of specimen. Selection was made by results of studies including production of reflectors in the form of various films and packages, as well as removable wedges embedded during specimen molding. With carbon fiber-reinforced plastics obtained of adhesive prepreg, it was not possible to achieve stable repetition of acoustic properties of reflectors in the form of embedded films. Besides, methods of metrological attestation of WRS's with such reflectors give rise to unfavorable criticism. Reflector in the form of steel wedge is good from the point of view of reproducibility during production. However, we have failed to elaborate trustworthy setting methods ensuring detection of a reflector of the given area.

In 2010, FGUP «VIAM» proceeded to elaboration of methods for testing carbon fiber-reinforced plastics using multi-element probes (phase arrays). This development of echo-method being popular abroad is able to provide qualitative improvement of performance, information content and trustworthiness of PCM testing.

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