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Satbayev University

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ИЗВЕСТИЯ

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DEFINITION METHODS MECHANICAL CHARACTERISTICS OF SOUND ABSORPTION STRUCTURES

Abstract. Design techniques of Sound Absorption Structures (SAS) used in aviation engines coincide, on the whole, with the techniques of designing honeycomb parts, sandwich structures that are of wide application. However, SAS have their own distinctive features. First of all, perforating of skins decreases parts' stiffness. SAS can have different forms (three- or five-layer SAS) and differ in honeycomb height, and can also be made of different materials. The whole of that is told on effective mechanical characteristics of SAS – stiffness in a skin plane, bending stiffness, strength of joints between separate members, and others. At present, the most sound-absorbing parts are not load-bearing structures and their mechanical damages or failures are not critical. At the same time, SAS, even those made from relatively light composites, are of heavy weight, especially in turbofans, that decreases engine performance. The abovementioned requires the development of techniques for the adequate estimation of SAS mechanical characteristics. The tendency to obtain SAS properties required for designing at lower expenses results in the necessity of their analytical prediction. In connection with this, the given work presents the analytical technique for defining SAS mechanical characteristics. The techniques of averaging are used for determining the characteristics of perforated skins and honeycomb assemblies.

Keywords: honeycomb, stiffness, bending, strength, composite, plates, turbofan.

Introduction. The existing techniques for providing the structure safety are based on the test pyramid [1], they take much time and are expensive. Understanding of SAS behavior at mechanical and acoustic loading permits to shorten tests and to reduce expenses while maintaining the required safety levels.

The design techniques of SAS used in aviation engines coincide, on the whole, with the techniques of designing honeycomb parts, sandwich structures that are of wide application (see, for example [2-4]). In spite of a relatively big height, SAS are considered as a panel or a shell in designing with corrected characteristics of stiffness. The features of SAS members (perforated skins), their different types (three- or five-layer SAS, different honeycomb height and honeycomb structures) are told on effective mechanical characteristics of SAS. Stiffness in a skin plane, bending stiffness, strength of joints between separate members and others characteristics are used in designing. This requires developing the adequate estimation techniques of SAS mechanical characteristics. For life estimation it is necessary to know the stress distribution in each member of SAS. That requires a realization of a transition from a shell structure to a three-dimensional structure. Three-dimensional models use the characteristics of each separate member of SAS.

The analytical approach of determining SAS mechanical characteristics is developed. The skins and honeycombs of SAS may be manufactured of both metal and composite materials. The technique of averaging is used for the definition of elastic characteristics of perforated skins, honeycomb assemblies, and SAS. Moreover, the Maxwell and Voigt models are used in calculation of corrected elastic characteristics of multilayer SAS. The experimental technique for defining the elastic and strength characteristics of SAS both in a layer plane and in the direction of honeycomb height is developed. The results of analytical estimations of SAS mechanical characteristics agree with experimental data.

1. Analytical definition of elastic characteristics of SAS and their members. The complex of elastic and strength characteristics of SAS is used at designing of structures. The analytical estimation of elastic characteristics is sufficiently reliable while the achievement of required accuracy at strength predictions produces some difficulties. Below the analytical technique of defining SAS elasticity characteristics is described [5-7]. SAS represent a mixed structure consisting of several skins and honeycomb layers between them. The load-bearing skin is solid, the other ones are perforated. The mechanical characteristics of skins without perforation as well as those of honeycomb material are considered specified.

1.1. Elastic characteristics of perforated skin. The mechanical characteristics of perforated skin depend on behavior of initial material as well as on the form, degree and distribution of perforation [8-10]. They are determined by numerical solution of a problem of real skin tension at a specified value of displacement u_{sp} of a sample free end (rigid loading) by using solid elements of CAD program.

Figure 1 shows the form and sizes of a typical perforated skin. The distribution of displacements and stresses in skins with 10% of perforation are given in figures 2a,b. The character of displacements and stresses distribution on the skins with other degree of perforation does not qualitatively differ from the data in figsures 2a,b.

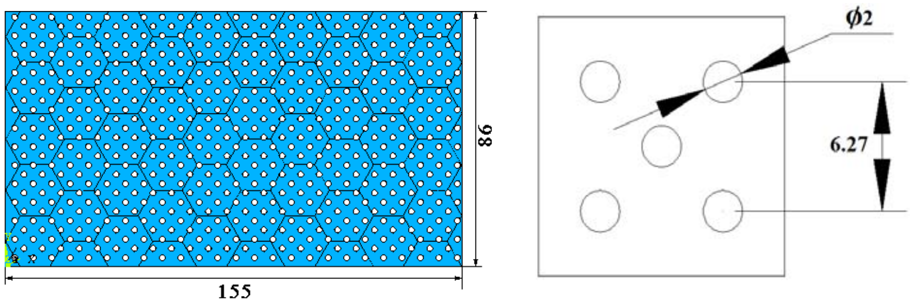

Figure 1 – The form, distribution and sizes of a typical perforated skin

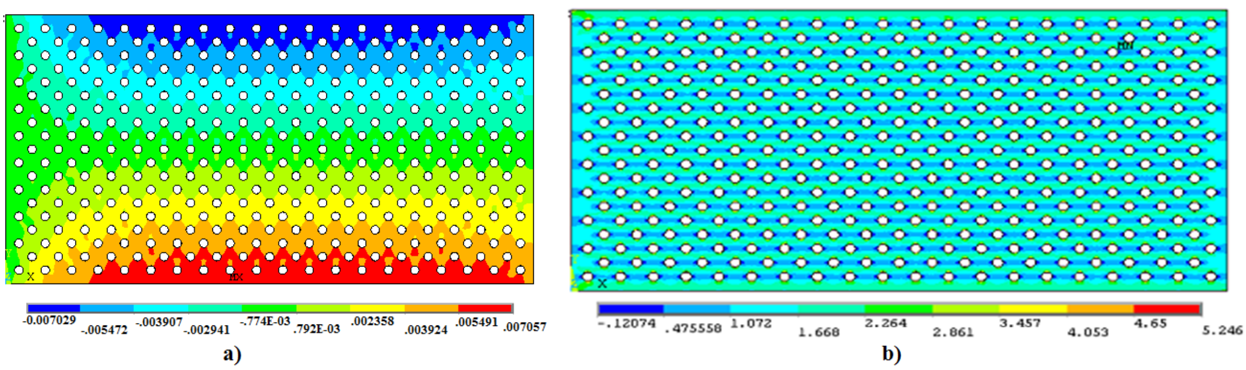

Figure 2 – a) Transversal displacements of perforated skin at tension (10% of perforation);
b) Longitudinal stresses of perforated skin at tension (10% of perforation)

The distribution of axial displacements u_x along the skin length is even, the longitudinal strains εx are permanent. The stress distribution in the cross-section is complicated. The average value of longitudinal stresses $\sigma_{x,mean}$ in nodes of the skin cross-section is calculated. Relation between mean stress $\sigma_{x,mean}$ and longitudinal strain ε_x is taken as a relative elastic modulus [11,12].

$$E_x^{rel} = \sigma_{x,mean} / \varepsilon_x, \ \nu_{xy} = -\varepsilon_y / \varepsilon_x, \quad (1)$$

Here, parameter ν_{xy} is Poisson's coefficient. The elastic modulus at soft loading by force P is determined from relation

$$E_x^{rel} = P / (F_{rel} \cdot \varepsilon_x), \ \sigma_x = P / F_{rel} \quad (2)$$

Value of F_{rel} is an area of "alive" cross-section of the perforated skin. Effective elastic modulus is calculated from equality

$$E_x^{eff} = (F_{rel} / F) E_x^{rel} \quad (3)$$

Here, F is a cross-section total (including voids) area. If materials of the perforated skins are anisotropic or in the case where either a character of perforation arrangement or perforation form are the reason of the dependence of mechanical characteristics on loading directions then the described above actions should be carried out in the main axis of anisotropy [13].

1.2. Elastic characteristics of honeycomb sandwich. The honeycomb sandwiches have an increased stiffness along honeycomb height. The honeycomb stiffness in the skin plane is minor, and the influence of honeycomb sandwich is neglected [14].

However, the honeycombs may contribute to elastic characteristics in SAS plane in conditions of low stiffness of perforated skins and constrained strains. The technique of elastic characteristic calculation coincides with the above-described technique for perforated skins. Relation between the longitudinal stress σ_x and the longitudinal strain ε_x is considered as a relative elasticity modulus $(E_x^{rel})_I$ in i-nodal point. The mean value of modulus $(E_x^{rel})_i$ at all nodal points of cross-section is taken as a relative elasticity modulus. The ratio of transversal strain ε_y to longitudinal strain ε_x with the inverse sign is taken as Poisson's coefficient. A transversal strain ε_y is taken as a ratio of sample contraction to its width. The maximum degree of perforation of the mentioned below perforated skins does not exceed 10%. In this case, the calculation shows that the influence of honeycomb stiffness in the skin plane is negligible (less than 3%).

1.3. Elastic characteristics of SAS. Two techniques are used for the analytical estimation of the effective elastic characteristics of SAS. The effective elastic characteristics of SAS in the direction of a load-bearing layer base were found by mixture rule (Maxwell's model) including well-known behaviors of each layer

$$E_x^{eff} = v_k (E_x^{eff})^k, \; \nu_{xy}^{eff} = v_k (\nu_{xy}^{eff})^k \quad (4)$$

The transversal characteristics and shear modulus were determined by Voigt's relations

$$E_y^{eff} = [v_k / (E_y^{eff})^k]^{-1}, \; \nu_{yx}^{eff} = v_k (\nu_{yx}^{eff})^k, \; G_{xy}^{eff} = [v_k / (G_{xy}^{eff})^k]^{-1} \quad (5)$$

Here, k is the number of SAS member, $v_k = h_k/h$ – relative thickness of k- elements, h ($h = \sum h_k$) – total thickness of SAS cross-section.

The solution of a compound structure tensile-stressed plate problem at given displacement of the free end is the second technique of effective elastic characteristics estimation. In this case, the mechanical characteristics of all SAS members are considered well-known – they may be determined by either above-described analytic technique or experimentally. The definition technique of the SAS relative and effective characteristics coincide with the above-described technique for perforated skins. The calculated relations between SAS relative elastic characteristics and elasticity modulus of the load-bearing layer are given in table 1. Figure 3 presents the distribution of SAS stresses defined by CAD program.

Table 1 – Relative values of SAS relative elasticity modulus defined by two approaches

Approach	Estimated characteristics		
	Elasticity modulus, GPa	Poisson's coefficients	
	E^{exp}_x/E_x	ν_{xy}	ν_{xz}
Finite element	0,97	0,31	0,31
Relations (4)-(5)	0,98	0,3	0,3
Experimental	1,0	0,3	0,3

The SAS elasticity moduli defined by using FE software ANSYS and relations (4)-(5) have identical values.

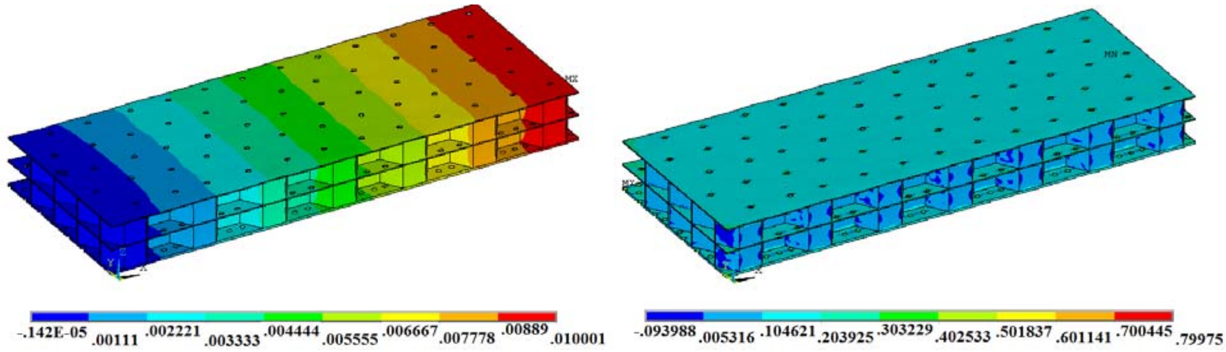

Figure 3 – Longitudinal displacements and axial stresses distribution in SAS at tension

SAS is considered as a perfect structure when determining effective elastic characteristics by developed analytical technique. In practice, all SAS contain technological imperfection [4] in the form of fiber ruptures, matrix or (and) interface damages, hole surface defects, face wrinkling and crimpling, burrs in the area of honeycomb and skins joints, and other. All this is not taken into consideration for the described analytical approaches. The results of analytical predictions must be confirmed by tests, on the other side, they can serve as a criterion of perfection of SAS manufacturing technique.

2. Experimental determination of SAS characteristics. The complex of SAS elastic and strength behaviors is determined experimentally. SAS represent compound structures, and SAS failure may take place in either their separate members or in the areas of their joints. In this case, the SAS stiffness and strength characteristics are determined in the tests of samples of different forms [15-18].

2.1. Test results. Below some test results of SAS are presented.

2.2.1. SAS characteristics in skin plane. Elasticity modulus and Poisson's coefficient are determined at 50% of limiting strain.

The failure of practically all samples took place in linear strain area, as a rule with exhaustion of carrying capability of perforated skin with the greatest of perforation degree (see figure 4a). This circumstance demonstrates the uniformity of strains in separate members of SAS.

a) b) c)

Figure 4 – a) Typical failure at tension in SAS skin plane;
b) Samples tested for tension along honeycomb height; c) Typical failure of SAS samples at shear

The tests showed that both the effective modulus and the strength of SAS samples having small height more than 2 times exceed such parameters of samples with big height. It is possible that the SAS height influences their mechanical characteristics.

Finally, it should be noted that the analytical and experimental results differ slightly (see table 2).

2.2.2. Honeycomb sandwich characteristics.

a. Tension. The results of samples tension test are presented in table 2. The elasticity modulus and strength limit at tension were determined by tests of different samples. Figure 4b shows failure type of samples. The tested samples have failure in the area of honeycomb sandwich joint with inside perforated skin having low height. It is necessary to notice that the dispersion of elasticity modulus is not statistically essential whereas dispersion of strength is more essential.

b. Compression. The results of samples compression test are presented in table 2. Again it can be seen that the dispersion of elasticity modulus is not considerable. However, their values are less than the values of elasticity modulus at tension by a factor of 1.5. Apparently, this experimental result can be explained in the following way. The middle perforated layer influences the sample total resistance at tension, and at compression the honeycomb sandwich only contributes to load-carrying capacity. The influence of honeycomb height on strength value is not determined. At the same time, the samples with bigger height had lower strength at compression. Loss of stability is a typical failure of honeycomb samples with large height.

Table 2 – The results of samples tension test are

	Strength		Elasticity modulus		Limited strain
	σ^{eff}	σ^{rel}	E^{eff}	$E^{rel,}$	
Tension	0.091	2.048	0.509*		–
	0.080	1.802	0.515*		–
	0.092	2.063	0.496*		–
	0.074	1.667	0.579*		–
	0.101	2.27	0.582*		
Compression	0.148	3.314	0.367	8.23	0.0009
	0.237	5.326	0.380	8.61	0.0008
	0.142	3.188	0.362	8.11	0.00075
	0.211	4.73	0.355	7.97	0.00085
	0.193	4.320	0.343	7.70	0.0008

The adhesion between honeycomb and skins does not have such influence on the ultimate strength at compression as it has as at tension. In connection with this, the strength at compression exceeds the one at tension by a factor of eight.

2.2.3. SAS characteristics at shear. The results of testing the samples of two types are presented in table 3. The tested samples differed in honeycomb height. The typical mode of samples' failure at shear is shown in figure 4c. Summarizing, one can notice:

– the tests at shear were more time –consuming,

– the elasticity moduli of samples with small height are higher than those of samples with big height,

– the honeycomb shear strength values exceeded their strength values at rupture.

Table 3 – Results of shear tests of different height samples

Samples		Strength	Elasticity Modulus a	Ultimate strain
High	1	0.31	70	1.12
	2	0.7	61	1.77
	3	0.53	65	0.81
	4	0.64	66	1.29
	5	0.47	65	1.1
		0.56; 0.15; 27%	65.4; 2.8; 5%	1.22
Low		0.52; 0.15; 29%	83; 11.9; 14%	2.39

Conclusions. The calculation technique of elastic characteristics definition for both the SAS members and the SAS as a whole has been developed.

The tests for definition of elasticity and strength characteristics at longitudinal tension in the skin plane at both tension and compression along the honeycomb height and finally at shear in the skin plane have been carried out. The procedure of SAS panels testing for strength has been developed.

The results of the work show:

– calculated values of elastic characteristics agree with experimental data,

– dispersion of elastic characteristics is less than those of strength ones,
– elasticity moduli at tension and compression along honeycomb height are different,
– loss of honeycomb stability is a typical failure mode at compression along honeycomb height,
SAS panels of lower height are stiffer at shear.

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МЕТОДЫ ОПРЕДЕЛЕНИЯ МЕХАНИЧЕСКИХ ХАРАКТЕРИСТИК ЗВУКОВОЙ АБСОРБЦИОННОЙ СТРУКТУРЫ

Аннотация. Методы проектирования звукопоглощающих конструкций (SAS), используемые в авиационных двигателях, в целом совпадают с методиками проектирования сотовых деталей, многослойных конструкций, которые имеют широкое применение. Однако у SAS есть свои отличительные особенности. Прежде всего, перфорирование шкур уменьшает жесткость деталей. SAS могут иметь различные формы (трех- или пятислойные SAS) и различаться по высоте сот, а также могут быть изготовлены из разных материалов. Все это говорит об эффективных механических характеристиках SAS - жесткость в плоскости слоя, жесткость на изгиб, прочность стыков между отдельными элементами и другие. В настоящее время большинство звукопоглощающих деталей не являются несущими конструкциями, и их механические повреждения или поломки не являются критическими. В то же время SAS, даже изготовленные из относительно легких композитов, имеют большой вес, особенно у турбовентиляторов, что снижает производительность двигателя. Вышеуказанное требует разработки методик для адекватной оценки механических характеристик SAS. Тенденция к получению свойств SAS, необходимых для проектирования при меньших затратах, приводит к необходимости их аналитического прогнозирования.

В связи с этим в данной работе представлена аналитическая методика определения механических характеристик SAS. Методы усреднения используются для определения характеристик перфорированных слоев и сотовых сборок.

Ключевые слова: соты, жесткость, изгиб, прочность, композит, пластины, турбовентилятор.

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ДЫБЫСТЫҚ АБСОРБЦИОНДЫҚ ҚҰРЫЛЫМНЫҢ МЕХАНИКАЛЫҚ СИПАТТАМАЛАРЫН АНЫҚТАУ ӘДІСТЕРІ

Аннотация. Авиациялық қозғалтқыштарда қолданылатын дыбыс сіңіргіш конструкциялардың (SAS) құрылғысын жобалау әдістері, тұтастай алғанда көп қабатты құрылымдарда кеңінен қолданылатын ұялы бөліктерді жобалау әдістерімен сәйкес келеді. Дегенмен, SAS өзінің ерекшеліктері бар. Ең алдымен, қабатты ұрып-соғу бөліктердің қаттылығын азайтады. SAS әртүрлі түрлері бар (үш немесе бес қабатты SAS) және ұяшықтың биіктіктері әртүрлі және сондай-ақ түрлі материалдардан жасалған болуы мүмкін. Мұның бәрі SAS тиімді механикалық сипаттамаларын анықтайды, яғни – қабат жазықтығының қаттылығы, иілу қаттылығы, жекелеген элементтер арасындағы буындардың беріктігі және т.с.с. Қазіргі уақытта дыбыс сіңіргіш бөлшектердің көпшілігі тірек конструкциялары емес және олардың механикалық зақымдануы немесе сынуы маңызды емес. Сонымен қатар SAS, әсіресе турбиналық желдеткіштер үшін, тіпті салыстырмалы жеңіл композиттерден жасалсада ауыр болады, бұл қозғалтқыштың жұмыс өнімділігін азайтады. Жоғарыда айтылғандар SAS механикалық сипаттамаларын барабар бағалау әдістемесін әзірлеуді талап етеді. Осыған сәйкес, SAS қасиеттерін арзан бағамен жобалау үшін талап етілетін үрдіс, оларды аналитикалық болжау қажеттілігін қажет етеді.

Осыған байланысты, осы жұмыста SAS механикалық сипаттамаларын анықтаудың аналитикалық әдісі көрсетілген. Орташа әдістер перфорацияланған қабаттар мен ұялы құрылымдардың сипаттамаларын анықтау үшін қолданылады.

Түйін сөздер: соттар, қатаңдық, иілу, төзімділік, композит, пластиналар, турбиналық желдеткіш.

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