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ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
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NAS RK is pleased to announce that News of NAS RK. Series physico-mathematical journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of chemistry and technologies in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of chemical sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Физикалық-математикалық сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын усынады. ҚР ҰҒА Хабарлары. Химия және технология сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді химиялық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия физико-математическая» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по химическим наукам для нашего сообщества.

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3 D AERODYNAMIC ANALYSIS OF AWING WITH 2-WAY FLUID-STRUCTURE INTERACTION

Abstract: the aircraft wings facing different weather conditions start to deform and oscillate with an unpredictable velocity and amplitude. Most of the previous studies were conducted assuming the wing as a rigid body. However, the wing analysis with Fluid-Structure Interaction (FSI)has significant effectson the results. This paper compares the strongly coupled 2-way FSI analysis of the flexible wing with a geometry of NACA 23012 and a rigid body 2D wing analysis. Both studies were carried out at a Mach number of 0.075 and Reynolds number of $0.6\times10^6$for different angles of attack. Moreover, the analysis of the wing deformation at the start of the flight is also presented. Finally, it was shown that FSI analysis gives closer results to the experimental measurements, proving the worthiness of the extra efforts of the two-way FSI analysis.

Key words: NACA 23012 airfoil, Fluid-Structure Interaction, ANSYS, strongly coupling study, deformation of the wing.

Introduction. Aircraft is one of the most useful and outstanding transport vehicles. The study of the aircraft wings is very important for aerodynamic efficiency, safe and comfortable flight. The wing geometry plays an important role in its aerodynamic efficiency by the reduction of parasite drag, induced drag and increase of lift. The first studies about the wing topology were carried out by Hemke in 1928 [1] and Mangler in 1938 [2]. Every wing depending on its design has its own maximum angles of attack beyond which might lead to sudden drop of lift force, a condition is called stall [3]. Knowing the maximum angle of attack is very important, otherwise, it might lead to catastrophic events. Recently, the wing investigations can be performed on computers. Several studies were done without any deformations on the effects of geometries of wings [4, 5]. However, the deformation of the wings has a significant effect on the results of the simulation. Deformations are highly dependent on the aircraft speed and angles of attack [6]. According to [6], the difference in the lift-to-drag coefficient of a rigid body and deformable shape is about 6%. This is the reason why recently researchers are focused on analysis in 3D FSI.

Materials. There are several computer software to conduct Fluid-Structure Interaction simulations [7-9]. The computations could be performed on a combination of the TAU-Code and the FEM Carat++ solvers [10], or ANSYS (CFX + Mechanical) [11], as well as OpenFOAM [12]. The CFD solver has to be coupled with CSD solver, then to exchange data between them, either through loosely coupled one-way or strongly two-way FSI simulations. Moreover, both solvers can be run in parallel for fast turnaround time. The aerodynamic forces deform the wing in the CSD solver and the deformed geometry data are transferred to the CFD solver where the influence on flow dynamics is evaluated through deformed boundaries and meshes [7].

ANSYS is one of the most popular software and there are several studies conducted using this package. Habib [3] studied the wing with the design of Eppler 395 using FSI simulation with ANSYS. The authors studied how the lift force varies as the wing shape changes, manufactured the aircraft with the design of Eppler 395 and tested it successfully [3]. Another work performed on ANSYS workbench was the simulation of AGARD 445.6 wing for the Mach number of 0.9. The paper showed geometry variation caused by air pressure, leading to the frequency change [9]. In another study [3], the analysis of wing deformations was performed with strongly coupled fluid-structure interaction simulation with ANSYS for different Mach numbers to search the most appropriate velocity for the aircraft. The study concluded that for the given geometry Mach 0.85 is the most desirable velocity because the wing generates the best aerodynamic performance with small deformations [8]. Significant decrease in lift and negative effects on the efficiency, mean thrust and propulsion systems could be seen from the wing bending and twisting [13] and wing camber deformations [14]. Thus, the FSI studies for flexible wings give much better results than studies of rigid ones and those investigations could be conducted on ANSYS successfully.

This paper will conduct comprehensive study of two-way 3D FSI of NACA 23012 [15] (figure 1), as this type is widely used for wing profile. Paper will demonstrate the effect of different angles of attack on the lift coefficients, compare results of rigid body simulation and FSI analysis using two-way transient fluid structure interaction by coupling the mechanical and flow systems. Moreover, shape deformation of the wing versus time will be presented and discussed. In order to make a fair comparison, the results of the rigid wing study and flexible one will be compared with the results of experiment, conducted by Pouryoussefi et. al. [16]. For this study, researchers have used the Mach and Reynolds numbers of 0.075 and 0.6×10^6, respectively. In addition, they have measured lift and drag coefficients under different angles of attack (figure 2) and weather conditions. The wingspan was 0.75 m and camber length was 0.354 m.

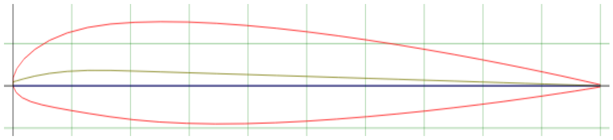

Figure 1 – Design of NACA 23012

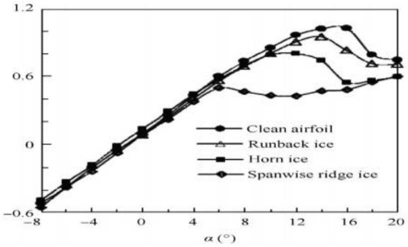

Figure 2 – Lift coefficients versus different angles of attack

1 Methodology of the study

Governing equations and numerical methods. For the study of turbulentaerodynamic flow, the Reynolds – Averaged Navier–Stokes (RANS) equations, and turbulence model k–epsilon, k–omega and SST models were used. The RANS continuity, momentum and energy equations are ((1) and (2)):

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \quad \text{and} \quad \frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}(\tau_{ij}+\tau_{ij}^R)+S_i \quad ; \; i=1,2,3 \tag{1}$$

$$\frac{\partial(\rho e_t)}{t}+\frac{\partial(\rho e_t u_i)}{x_i}=\frac{\partial\left(k\left(\frac{\partial T}{\partial x_i}\right)\right)}{x_i}-\frac{\partial(u_i p)}{x_i}+\frac{\partial(u_1\tau_{xx}+u_2\tau_{xy}+u_3\tau_{xz})}{x}+\frac{\partial(u_1\tau_{yx}+u_2\tau_{yy}+u_3\tau_{yz})}{y}+\frac{\partial(u_1\tau_{zx}+u_2\tau_{zy}+u_3\tau_{zz})}{z} \tag{2}$$

For ideal gas case the relation between the density, pressure and temperature is:

$$\rho=\frac{p}{R_{air}T} \quad \text{and} \quad R_{air}=\frac{R_{universal}}{Air\_Molecular\_Mass} \tag{3}$$

The Reynolds number, lift and drag coefficients could be calculated by the following equations:

$$Re=\frac{\rho U l}{\mu} \qquad C_l=\frac{2\times F_l}{r\times U^2\times A} \qquad C_d=\frac{2\times F_d}{r\times U^2\times A} \tag{4}$$

The equation for the force distribution acting on the dynamic mesh is:

$$f(x)=\sum_{j=1}^{M} F(X_j)\delta_h(x-X_j)\Delta s \tag{5}$$

The velocity interpolation equation is:

$$\tilde{u}(X_k) = \sum_x \tilde{u}(x)\delta_h(x - X_k)h^2 \qquad (6)$$

The flow governing equations were solved numerically by the finite volume discretization method and PISO scheme for unsteady flows based on asemi - implicit time integration scheme. Deformation of a three-dimensional flexible solid wing structure is described by the dynamic structural equations of continuum mechanics, which are solved by ANSYSM echanical LS-DYNA explicit structural dynamic finite element method (FEM).

Model setup. For the solid and fluid bodies meshes were created separately in Analysis Systems Coupling Settings "Transient Structural" and "Fluid Flow (FLUENT)", respectively. The "Transient Structural" received the force data from the fluid body and "Fluid Flow (Fluent)" got the displacement data from the solid body. CFD and CSD solvers were coupled by the dynamic mesh method with mesh smoothing, using "System Coupling". The connection between them is through "Setup" cells, which controls the solution data transfer process between these systems. The aluminum wing was fixed at its root and the wing tipwas free to deform. The transient analysis settings were calculated for 1 sec with 20 steps. From the validation of 2D flow simulation, the SST turbulence model was explored. The NACA 23012 wing type was used with a chord length of 0.354 m. During the study Reynolds number was 0.6×10^6, the free stream velocity was 0.075 Mach, the air temperature was 20 °C and the angles of attack ranged from -8° to 20°.

2 Results and discussion

Geometry. To create the geometry of the wing, points were created on the website airfoiltools.com and imported to ANSYS. Then, the surface was createdby joining the points with smooth lines. To reduce computational costs, it was decided toperform simulations with rigid wing in 2D, anddeformable wing in 3D. On FSI simulation, as the wingdeformed in x, y and z directionsand would experience flap, edgewise and torsional displacements, as its root was fixed while its tip was a free end.

Mesh verification study. Meshing is a very important part of the study. To get better results, optimal mesh needs to be generated and verified so that the computational costs would not be too high while sufficient accuracy was ensured. Mesh verification for 2D study was started from the meshes that had the 300 divisionson the wing surface. Stall appeared at 14° with such a mesh, which is insufficient comparing with experimental results. As a result, this mesh was not optimal and it had to be refined or changed. Figure 3 presents the refined meshes. Those meshes include the inflation layers near the wing surfaces. Table 1 demonstrates the mesh verification results, from which we can conclude that the relative error between meshes 3 and 4 is not significant and one of them could be used as the optimal one. However, the absolute errors for all of the mesh types were inacceptable. The reason for that was used turbulence model. Thus, the suitable turbulence model had to be chosen and the turbulence models of k-epsilon, k-omega and k-omega SST were compared (figure 4).

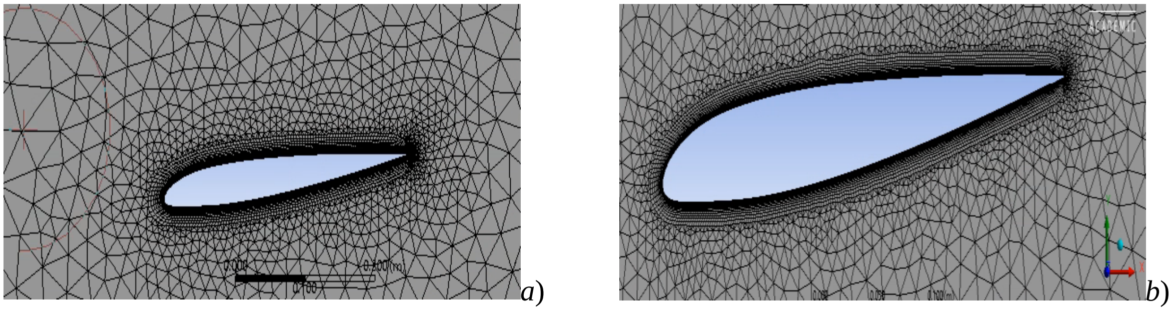

Figure 3 – Mesh verification study: a) fine mesh in the second meshing with inflation; b) the third mesh with inflation and finer meshing

Table 1 – Mesh verification for the airfoil

Meshes	Elements	Lift coefficient	Relative error (%)
Mesh 1	3542	1.16	
Mesh 2	7864	0.89	23.42
Mesh 3	10564	1.03	15.56
Mesh 4	14624	1.12	9.07

Validation. The validation of the turbulence models was performed with three types of turbulence models used for comparison (figure 4). The stall appears at 14° for k-epsilon and at 16° for k-omega, while the stall measured by the experiment was at 18°. Finally, k-omega SST model is considered the most accurate model, especially when there is flow separation during stall.

Geometry and mesh verification study for 3D wing. Figure 5 shows the geometry of the wing. All the characteristics are the same with the 2D wing, the span equal to 0.75 m and there is no change in the chord length. Mesh verification was conducted for zero degree of angle of attack, using the parametric study. Table 2 compares the mesh type and contains the information about the element number, lift coefficient and relative error, which shows the best choice for next studies. According to the mesh verification study, meshes 2, 3 and 4 could be chosen, because the relative errors for them are less than 10%, which are acceptable. However, for the final results the third mesh was used (figure 6).

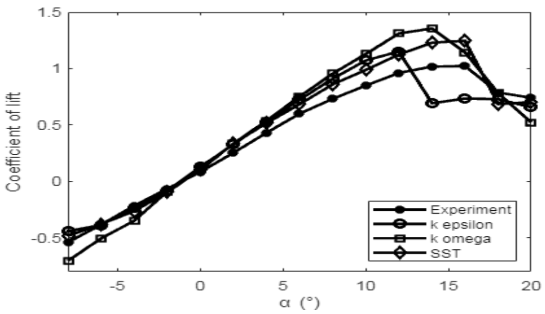

Figure 4 – Validation results of turbulence models

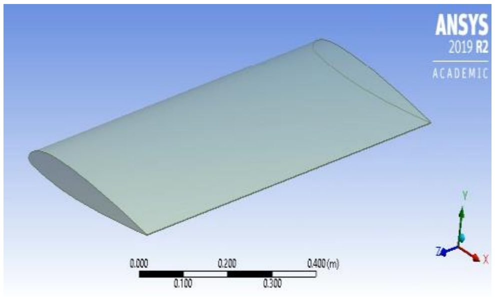

Figure 5 – Illustration of the 3D wing

Table 2 – Mesh verification of 3D wing

Meshes	Element numbers (Fluid)	Element number (Solid)	Lift coefficient	Relative error (%)
Mesh 1	426911	18197	0.1649	
Mesh 2	487270	23764	0.1369	16
Mesh 3	584379	28465	0.1286	6
Mesh 4	598496	31546	0.1245	3

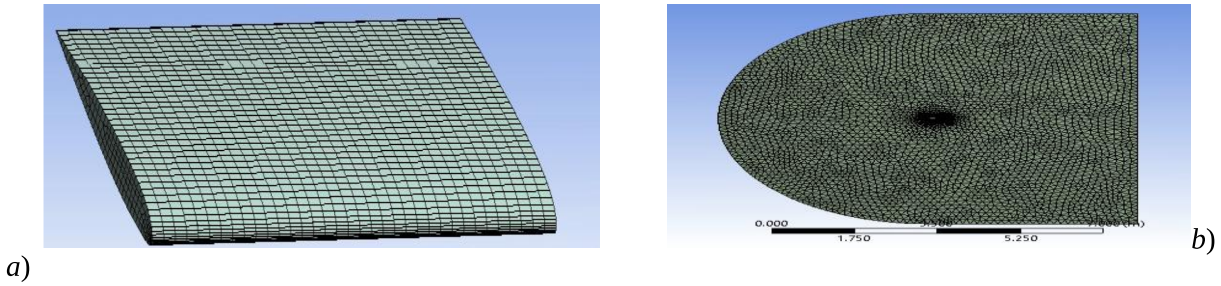

Figure 6– Illustration of mesh created for 3D model: a) wing b) air

FSI calculation. With the aim of better visualization of the air behavior, streamlines and velocities of the air flow are shown in figure 7. As it was said earlier the velocity of the air is higher above the upper surface comparing with the lower side of the wing, and at the leading edge, the air velocity is close to zero as the stagnation point. The wing experienced deformation that could affect the results and it was calculated using the dynamic mesh coupling approach. Figure 8 demonstrates the free end of the wing initially started to oscillate in flap-wise direction, and then it became stabilized with insignificant oscillations. For higher velocities and angles of attack, the influence on the results might be more significant.

Finally, lift coefficient analysis was performed for different angles of attack. Comparing with the experimental data, the results are much better than the rigid body simulations (figure 9). The 3D effect captured more accurately can also help to improve the overall accuracy of the 3D simulation. But by comparing the results of the 3D deformable wing with those of the mesh verification study using rigid wing also confirms that the FSI simulation does generate better results. However, for higher angles of attack absolute error is increasing as it was with the rigid body. Noteworthy is a stall, which appeared at 18°, as it was similar to the experimental value.

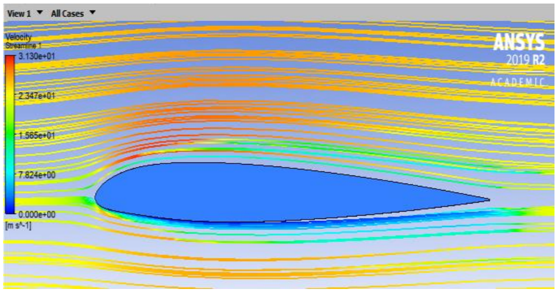

Figure 7 – Illustration of streamlines of the air

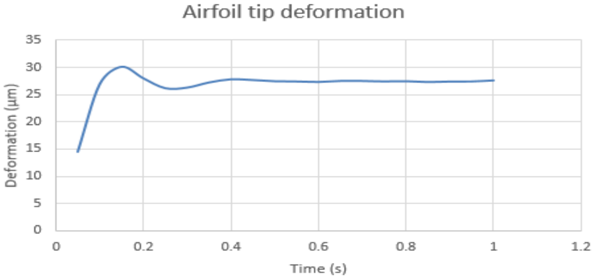

Figure 8 – Deformation of the wing tip at zero angle of attack

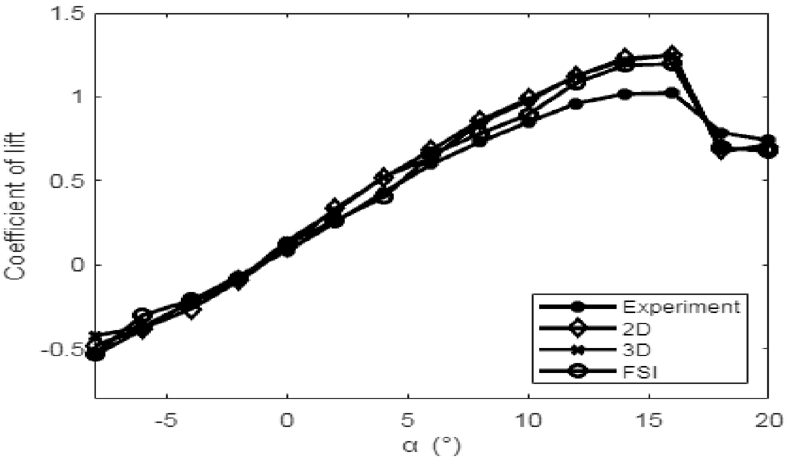

Figure 9 – Results of 3D wing simulations on FSI analysis

This paper has compared the simulation studies of NACA 23012 wing under Reynolds number of 0.6×10^6 assuming it as a rigid body (in 2D and in 3D) and 3D flexible wingwith 2-way fluid-structure interaction. All studies were conducted successfully and for all of them stall appeared at the same angle of attack as in the experiment. However, for the rigid body the absolute error in lift coefficient was higherthan the FSI analysis. Thus, as other researchers mentioned earlier, on average, the difference in absolute error was 6%. For FSI analysis, the absolute error slightly exceeded 10% only for four angles of attacks out of 14 studies and maximum lift coefficient was at 16°. In addition, the behavior of the wing at the start of the flight has been demonstrated. Initially, the wing deformed with higher amplitudes, and then it started to become stabilized and oscillated with lower amplitude.

Conclusion. In conclusion, as the deformation of the wing is inevitable, the effect of the vibration and the shape alteration on the wing behavior cannot be neglected. This paper presents an approach for the wing FSI study with better results, which helps to predict the wing aerodynamic performance. As under even higher velocities the shape alteration could have effects that are more significant which could be captured accurately by the proposed method. This paper presents the first study of 3D aircraft wings with 2-way FSI analysis for the NACA 23012 wing.

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СҰЙЫҚ ПЕН ҚҰРЫЛЫМНЫҢ ЕКІ ЖАҚТЫ ӨЗАРА ӘРЕКЕТТЕСУІМЕН ҚАНАТТЫ 3D АЭРОДИНАМИКАЛЫҚ ТАЛДАУ

Аннотация: әр түрлі ауа-райы жағдайында ұшақтың қанаттары деформацияланып, күтпеген жылдамдық пен амплитудада дірілдей бастайды. Алдыңғы зерттеулердің көп бөлігі қанат қатты деген болжаммен жасалған. Алайда, сұйықтық пен құрылымның өзара әрекеттесуі (FSI) функциясын пайдаланып қанатты талдау нәтижелерге айтарлықтай әсер етеді. Бұл мақалада екі жақты икемді қанатты талдау NACA 23012-мен және адгезияның күшті геометриясымен, сонымен қатар дененің екі өлшемді қатты денесімен анализі салыстырылады. Екі зерттеу де шабуылдың әртүрлі бұрыштары үшін Мах саны 0,075 және Рейнольдс 0,6 × 10^6 санымен жүргізілді. Сонымен қатар, ұшу басталған кезде қанаттың деформациясын талдау ұсынылған. Нәтижесінде FSI талдауы эксперименттік өлшеулерге жақын нәтижелер шығаратындығы дәлелденді, осылайша екі жақты FSI талдауды жүргізудің құндылығы дәлелденді.

Түйін сөздер: NACA 23012 ауа қабығы, сұйықтық құрылымының өзара әрекеттесуі, ANSYS, тығыз байланыстыруды зерттеу, қанаттардың деформациясы.

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3D АЭРОДИНАМИЧЕСКИЙ АНАЛИЗ КРЫЛА С ДВУСТОРОННИМ ВЗАИМОДЕЙСТВИЕМ ЖИДКОСТИ И КОНСТРУКЦИИ

Аннотация: крылья самолета при различных погодных условиях начинают деформироваться и колебаться с непредсказуемой скоростью и амплитудой. Большинство предыдущих исследований проводилось в предположении, что крыло является твердым телом. Однако анализ крыла с помощью функции «Взаимодействие жидкости и конструкции» (FSI) оказывает значительное влияние на результаты. В этой статье сравнивается двухсторонний анализ гибкого крыла с геометрией NACA 23012 и с сильным сцеплением, а также двухмерный анализ твердого тела. Оба исследования проводились при числе Маха 0,075 и числе Рейнольдса 0,6 × 10^6 для разных углов атаки. Кроме того, представлен анализ деформации крыла в начале полета. В результате было показано, что анализ FSI дает более близкие результаты к экспериментальным измерениям, тем самым доказывая ценность проведения двустороннего анализа FSI.

Ключевые слова: профиль NACA 23012, взаимодействие жидкости и конструкции, ANSYS, исследование сильной связи, деформация крыла.

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