The method of the folding wing's design and mass optimization for the naval aircrafts

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Abstract
The aim of this research is to define structural mass increment caused by wing folding. First, we calculate the weight of a wing compartment which includes a folding joint. Secondly, the influence of each element of the folding joint on the general aircraft weight is estimated. As a result the diagram of the folding wing's elements weight changing depending on the folding axis location and the load distribution is built and the elements which influence more are found.

1. Introduction

The essential mass increment caused by the folding of some units is one of the problems of the naval aircrafts design. A wing folding is the most wide spread. It permits to reduce substantially aircraft dimension and to place more vehicles on the ship board.
However it causes some shortcomings, the main of which is the aircraft weight increment. It's necessary to know the absolute and relative weight of the aircraft's units at the early stages of vehicles' design. Nowadays methods don't allow to calculate the folding units' weight. So, the aim of this work is to create a classification of methods of the folding wings' design, to detect the factors influencing the structural mass increment and to create a folding wing's mass formula.

2. The classification of the folding wings' typical designs

The limited dimensions of the naval planes lead to various schemes of the wing folding. As a result of the folding wing design's research was made the classification of typical methods of their design (Fig. 1).
"The simple" type of the wing's folding is the most widespread. The rotation is made round the axis which is parallel to the wing chord and which is based on the upper surface of the wing. This type is the most practically feasible and reliable and also it brings minimal weight increase. We can name two subtypes: when the folding axis is parallel to the plane of the aircraft symmetry and when the folding axis is not parallel to the plane of symmetry, but it is placed in the plane of the swept wing's ribs. Sometimes the double folding wing is used.

3. The folding wing's weight formulas analysis

Many different formulas are used for the lifting surfaces' mass estimation. The authors of such formulas are Badiagin, Kozlovsky, Torenbeek, Sheinin and others [1-3]. The analysis of the nonfolding wing's weight formulas shows that many of them are variations of the following formula [1]:

$$m_{wing}^{nonfold} = a_1 \frac{n m_0 l_{wing}^2}{\sigma h_{wing} \cos^2 \chi} + a_2 \frac{n m_0 l_{wing}}{\sigma h_{wing} \cos \chi} + a_3 \frac{n m_0 l_{wing}}{\tau} + a_4 n m_0 + a_5 S \quad \textbf{(1)}$$

The first member determines the mass of the material which receives bending (panels, spars booms). The second member determines the joints' mass. The 3rd determines the mass of the material which receives shearing (spars' webs). The 4th member determines the mass of the material which receives the local loads (strengthened ribs, engine's and undercarriage's fixed joints). The 5th determines the mass of the flaps, slats, mechanization and normal ribs).
Based on the wing geometry, the take-off mass and the g-load these formulas permit to calculate the wing mass

during the aircraft weight estimation but they don't take into account the inner peculiarities of the framework. So these formulae don't permit to calculate the folding wing's mass.

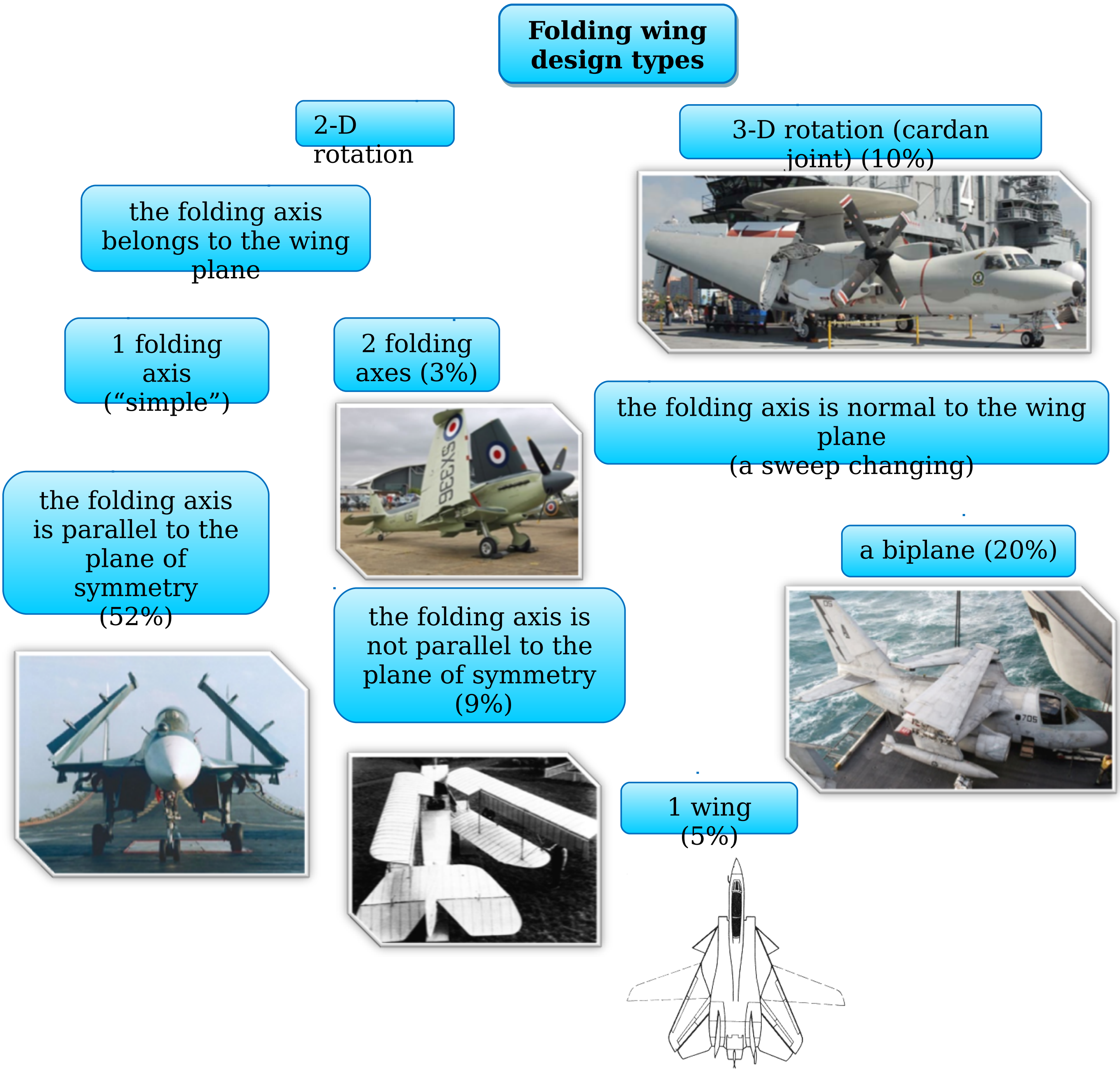

Figure 1: The classification of the folding wings' typical designs (a character of the frequency is shown in the brackets)

We have already discussed the problem of the weight analysis and the folding wings' design in the several publications, e.g. [5]. So, it is necessary to create a formula which will take into account the mass increment of the folding wing. Basing on the one of well known formulas this formula should include the additional member Δm_{fold} - the wing's mass increment caused by folding or the additional correction index $\Delta \overline{m}_{fold}$ – the relative mass increment.

As the multifunctional aircraft design is the most interesting, so we will base on the formula which enables to account the relative nonfolding wing's mass of the supersonic manoeuvrable aircraft $\overline{m}_{wing}^{nonfold}$ [2, p.134]. According to the proposed changes the folding wing mass formula will be the following:

$$\overline{m}_{wing}^{fold} = \overline{m}_{wing}^{nonfold}\left(1+\frac{\Delta m_{fold}}{m_{wing}^{nonfold}}\right) = \left[k_t\varphi \cdot n_p\sqrt{\lambda S}\left(3{,}6\cdot 10^{-6}\frac{\lambda}{\overline{c}_0}+\frac{0{,}7\cdot 10^{-3}}{\lambda}+1{,}7\cdot 10^{-4}\right)+\frac{5{,}5}{p_0}\right]\cdot\left(1+\Delta\overline{m}_{fold}\right) \quad \textbf{(2)}$$

where: $\Delta\overline{m}_{fold} = \frac{\Delta m_{fold}}{m_{wing}^{nonfold}}$ - the relative mass increment caused by wing folding.

It is necessary to mention that when we design a naval modification of the aircraft not only the part of the wing which contains the folding unit is changed. It is often required to improve the lift devices and the structural scheme of the unit. Thus it is rather difficult to calculate exactly the mass changing. In this article we will stop just at the estimation of the mass' growth caused by the wing's unit with the folding mechanisms' modification.

To determine the mass increment index Δm_{fold} we need to analyse factors influencing on the folding wing's mass. The whole wing mass is described by the general factors such as the wing load, its' geometrics, etc. The increment mass first of all is influenced by the location of the folding axis. The coordinate of the folding axis location z_{fold} determines the load received by the wing structure in a folding section (the cutting force $Q(z)$, the bending moment $M_{bend}(z)$ and the torsion moment $M_{tor}(z)$). It also defines the rotary wing section's mass with a glance of a pay load situated on it m_{rws}, width $b(z)$ and relative height $\overline{c}_Z$ of a wing torsion box in the place of the folding joint.

Varying the folding axis location we change the folding mechanism mass, first of all because of the lifting hydrocylinder's size changing. In other words the more weight this mechanism is to lift the more powerful and heavy its hydrocylinder is.

Besides the mass increment index depends greatly on the structural scheme of the unit. The wing mass will grow because of the necessity of the broken longitudinal elements (stringers and spars) bonding. Thus, the more closely to the fuselage, the more folding weight increases. So,

$$\Delta m_{fold} = f\left(\overline{z}_{fold}, structural\_scheme, M_{bend}(z), m_{rws}, b(z), \overline{c}_Z\right). \quad \textbf{(3)}$$

4. Calculation of the folding unit elements' masses

To derivate the formula that defines the folding wing's mass at the early stages of design we need to make an elementwise calculation of the folding joint mass for the several locations of the folding axis.

We will examine a part of the wing which concerns the folding elements and have width Δz situated at the distance z_{fold} from the aircraft's plane of symmetry (Fig. 2).

When the wing is nonfolding and haven't a folding joint the examined part of the wing is regular. Then elements sizes and masses are calculated by strength estimation methods [4]. When there is a folding joint this zone is considered irregular. It divides a wing into immovable and rotary parts. Due to necessity of the broken longitudinal elements bonding in this zone we can see the appearance of the strengthened block which consists of two parts. One part belongs to immovable part and another – to the rotary part. Each of them contains torque and swivel junctions with eyelets that provide the rotating.

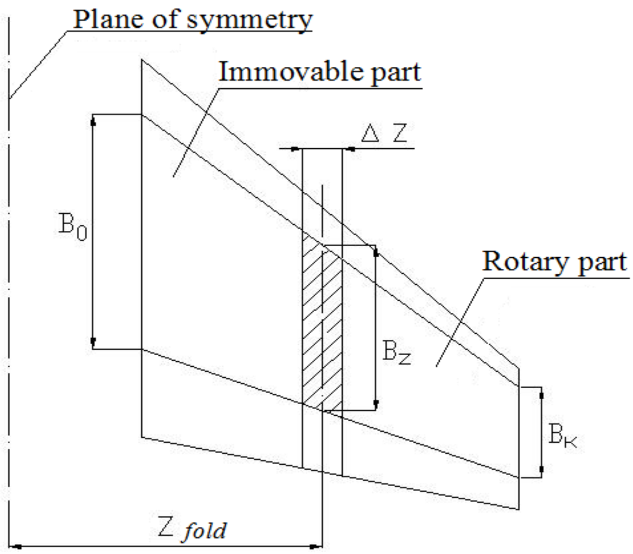

Figure 2: Parameters of the irregular zone of the wing

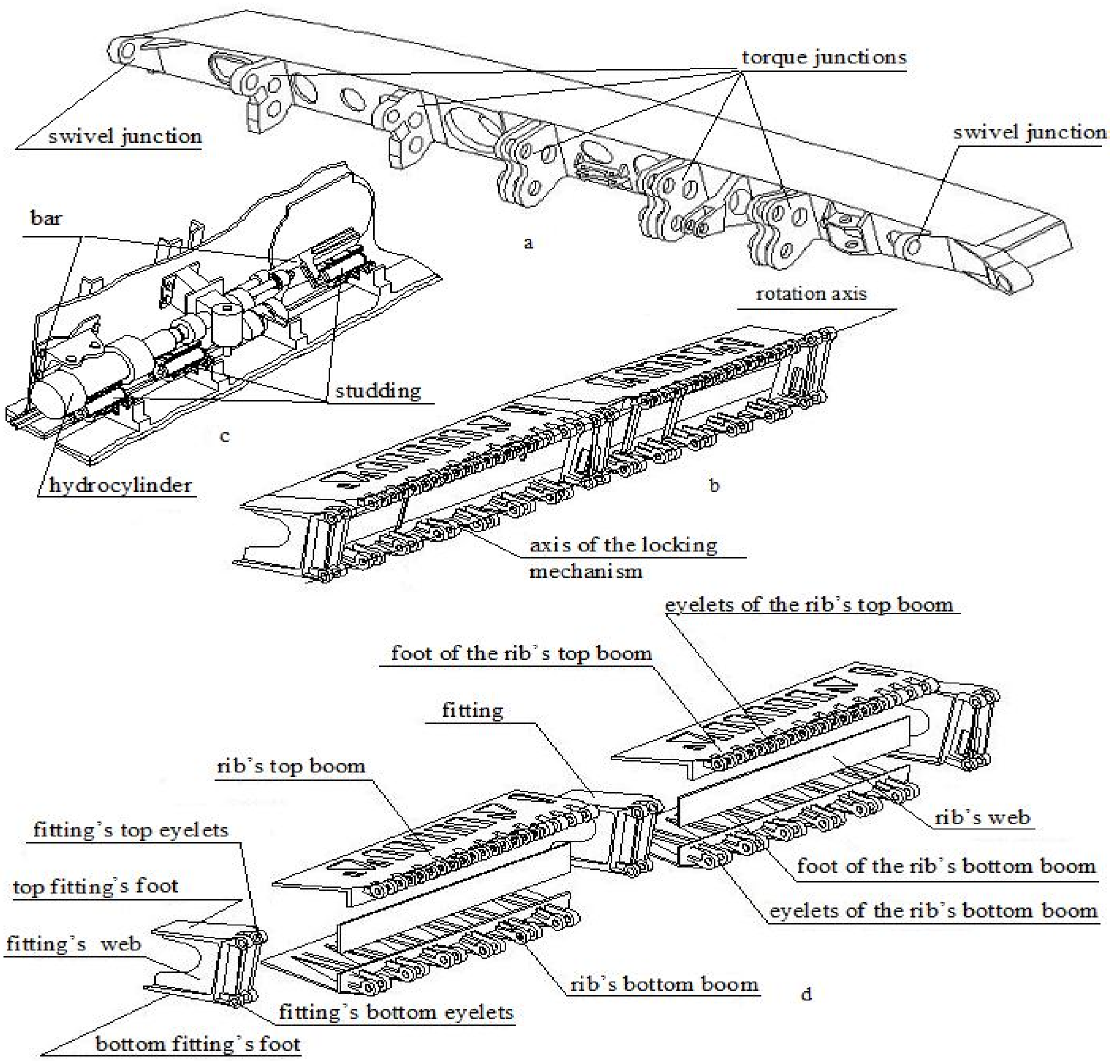

Figure 3: Variants of the folding unit elements design

Let's examine some cases of the bending moment perception by the wing structure. There are fittings on the ends of the spars at the place of the folding unit in the wing where practically the whole bending moment is perceived by the wing spars. They transfer the bending moment in a couple of forces through the eyelets of the junction "ear – fork" type. Such type of junction is used at thy aircrafts Yak-38 type. In the wing where the bending moment is mostly perceived by panels the folding is realized by means of eyelets that forms the junction rack type. At the MiG-29K type aircrafts the strengthened block is made in form of a strengthened rib which has torque and swivel junctions (Fig.3a). For the Su-33 type aircrafts the strengthened block which contains torque junctions at the fittings and an outline rack type junction at the panels is typical.
Besides the load-bearing elements of the irregular wing's zone there are non-load-bearing elements which mass we can't define by the strength estimation methods. These elements are the folding mechanism and the locking mechanism. The folding mechanism at each outer wing includes a hydrocylinder which lifts a rotary part of the wing, a control unit, a system's breaking unit, a reducer-swivels and a transmission. The rotary part of the wing turns about an axis that pass through the top eyelets. In the unfolded position the bottom eyelets are fixed by the studs situated on the bar which is moved by locking mechanism's hydrocylinder (Fig.3c).
Generally the wing's mass increment caused by folding can be calculated as the difference between folded and unfolded wings according to the formula:

$$\Delta m_{fold} = m_{wing}^{fold} - m_{wing}^{nonfold} = m_{fold}^{str.block} + m_{fold}^{mech} + m_{lock}^{mech} - m_{nonfold}^{rib} = m_{fold}^{joint} - m_{nonfold}^{rib}, \quad \textbf{(4)}$$

where $m_{fold}^{str.block}$ - the mass of the strengthened block between the immovable and rotary parts of the wing, m_{fold}^{mech} - the mass of the folding mechanism, m_{lock}^{mech} - the mass of the locking mechanism. There is a rib instead of the strengthened block in the nonfolding wing, the mass of it is $m_{nonfold}^{rib}$.
For example, let's examine the wing's structure of the aircraft Su-27 type. In the folding wing the joint between the immovable and rotary parts is made in a form of a strengthened block that consists of two parts. Each part of the strengthened block contains a rib with eyelets at the top and bottom panels and fittings at the ends of the spars. The rib and the fittings are divided into several elements: booms, eyelets and webs (see Fig.3d). Generally the mass of the strengthened block is calculated as:

$$\overline{m}_{str.block} = 2(\overline{m}_{rib} + n \cdot \overline{m}_{fit}), \quad \textbf{(5)}$$

where n – a number of longitudinal webs (spars) in the place of the joint.
We can see the results of mass calculation in the Table 1 and at the Figure 4. The elements' masses are related to the nonfolding wing's mass, that is $\overline{m}_{element} = \dfrac{m_{element}}{m_{wing}^{nonfold}}$. The calculation was done for four structural schemes that depend on the way of the load perception by the elements of the wing: : a) $80\% M_{bend}$ is taken by the panels, $20\% M_{bend}$ - is taken by the spars (Table1,a; Fig.4,a); b) $60\% M_{bend}$ is taken by the panels, $40\% M_{bend}$ - is taken by the spars (Table1,b; Fig.4,b); c) $40\% M_{bend}$ is taken by the panels, $60\% M_{bend}$ - is taken by the spars (Table1,c; Fig.4,c); d) $20\% M_{bend}$ is taken by the panels, $80\% M_{bend}$ - is taken by the spars (Table1,d; Fig.4,d). It was analyzed three variants of the folding axis location ($\overline{z}_{fold}$ = 0,32; 0,48; 0,64).

Table 1: The relative elements' masses of the folding joint for different structural schemes and folding axis locations

a) $80\% M_{bend}$ is taken by the panels, $20\% M_{bend}$ - is taken by the spars							
	$\overline{m}_{rib}$			$\overline{m}_{fitting}$			$\overline{m}_{str.block}$
$\overline{z}_{fold}$	$\overline{m}^{ex}_{rib}$	$\overline{m}^{bo}_{rib}$	$\overline{m}^{web}_{rib}$	$\overline{m}^{ex}_{fi}$	$\overline{m}^{bo}_{fi}$	$\overline{m}^{web}_{fit.}$	
0,32	0,010	0,079	0,009	0,003	0,010	0,001	0,283
0,48	0,004	0,045	0,006	0,002	0,004	0,001	0,150
0,64	0,001	0,017	0,003	0,001	0,002	0,000	0,057

b) $60\% M_{bend}$ is taken by the panels, $40\% M_{bend}$ - is taken by the spars							
	$\overline{m}_{rib}$			$\overline{m}_{fitting}$			$\overline{m}_{str.block}$
$\overline{z}_{fold}$	$\overline{m}^{ex}_{rib}$	$\overline{m}^{bo}_{rib}$	$\overline{m}^{web}_{rib}$	$\overline{m}^{ex}_{fi}$	$\overline{m}^{bo}_{fi}$	$\overline{m}^{web}_{fit.}$	
0,32	0,010	0,136	0,008	0,008	0,027	0,001	0,527
0,48	0,004	0,080	0,005	0,004	0,012	0,001	0,275
0,64	0,001	0,029	0,002	0,001	0,004	0,000	0,100

c) $40\% M_{bend}$ is taken by the panels, $60\% M_{bend}$ - is taken by the spars							
	$\overline{m}_{rib}$			$\overline{m}_{fitting}$			$\overline{m}_{str.block}$
$\overline{z}_{fold}$	$\overline{m}^{ex}_{rib}$	$\overline{m}^{bo}_{rib}$	$\overline{m}^{web}_{rib}$	$\overline{m}^{ex}_{fi}$	$\overline{m}^{bo}_{fi}$	$\overline{m}^{web}_{fit.}$	
0,32	0,008	0,170	0,008	0,015	0,049	0,0008	0,761
0,48	0,004	0,105	0,006	0,007	0,021	0,0006	0,396
0,64	0,001	0,041	0,002	0,002	0,007	0,0003	0,147

d) $20\% M_{bend}$ is taken by the panels, $80\% M_{bend}$ - is taken by the spars							
	$\overline{m}_{rib}$			$\overline{m}_{fitting}$			$\overline{m}_{str.block}$
$\overline{z}_{fold}$	$\overline{m}^{ex}_{rib}$	$\overline{m}^{bo}_{rib}$	$\overline{m}^{web}_{rib}$	$\overline{m}^{ex}_{fi}$	$\overline{m}^{bo}_{fi}$	$\overline{m}^{web}_{fit.}$	
0,32	0	0,198	0,008	0,023	0,075	0,0008	1,007
0,48	0	0,132	0,005	0,010	0,033	0,0006	0,532
0,64	0	0,048	0,003	0,003	0,011	0,0003	0,188

Due to the elementwise division of the joint we can observe that most influencing to the mass' increment element is the strengthened block. The booms of the rib influence especially gratly. So in practise they try to lighten the booms by means of the different openings.

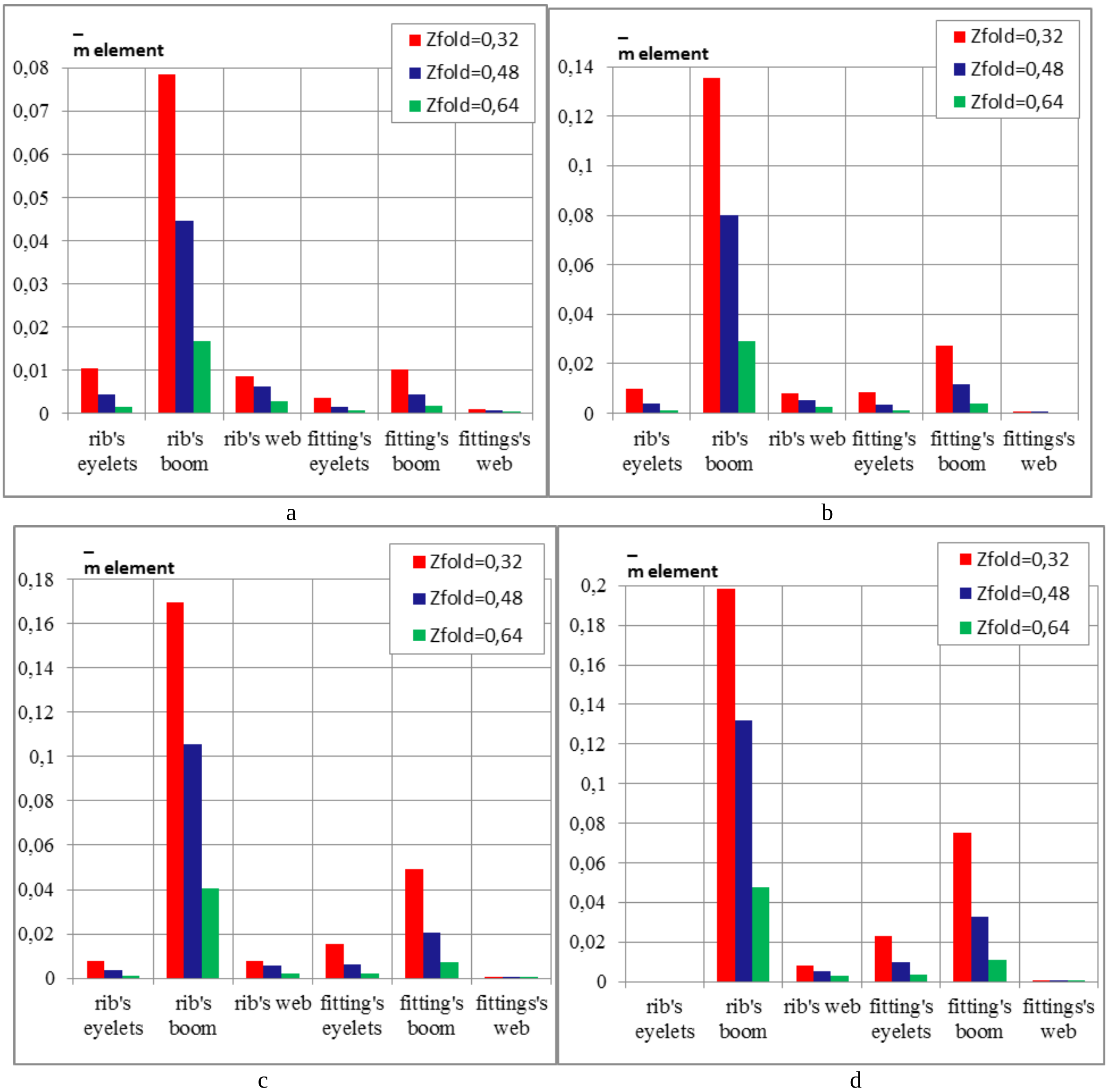

Figure 4: The relative masses of the joint elements' distribution (for different structural schemes and the folding axis' location)

In the Table 2 we can see the information about the relative masses of the joint's elements with a glance of the load-bearing element's mass and masses of the folding and locking mechanisms.

Table 2: The masses of the joint's elements

$80\% M_{bend}$ is taken by the panels, $20\% M_{bend}$ - is taken by the spars			
$\bar{z}_{fold}$	$\bar{m}_{str.block}$	$\bar{m}^{mech}_{fold}$	$\bar{m}^{mech}_{lock}$
0,32	0,283	0,083	0,022
0,48	0,150	0,051	0,017
0,64	0,057	0,015	0,014

The calculation is not exactly accurate because of the following reasons: we don't take into account the openings in the booms and webs of the ribs, we have no exact information about load distribution along the wingspread, and we made the calculation only for the one load case.

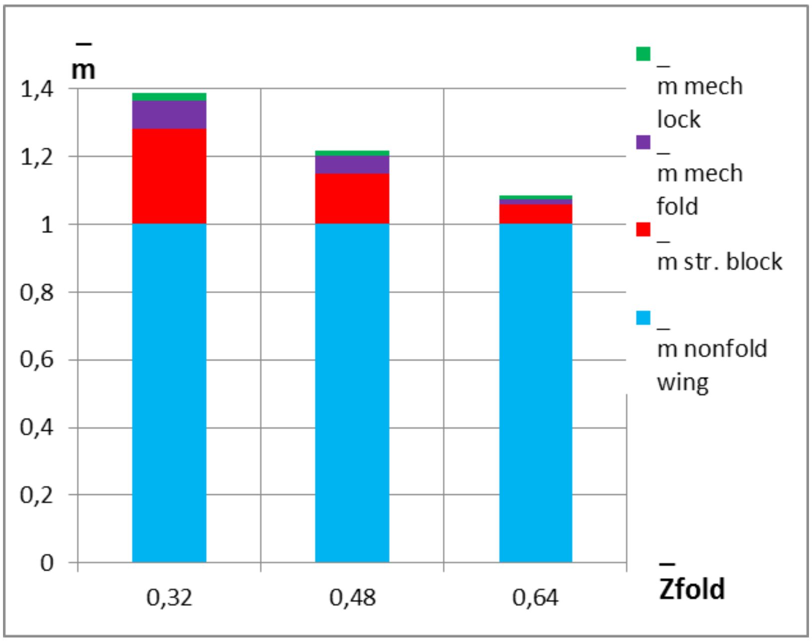

Figure 5: The relative mass' increment change along the wingspread

At the Figure 5 we can see the process of the relative summary wing's mass changing according to the folding axis location. The relative mass of the nonfolding wing is taken as one. We can observe that the mass increment depends gratly on the folding axis location: when $z_{СКЛ} = 0{,}64$ it is $\Delta m = 18\%$; when $z_{СКЛ} = 0{,}48$ it is $\Delta m = 21\%$; when $z_{СКЛ} = 0{,}32$ it is $\Delta m = 39\%$.

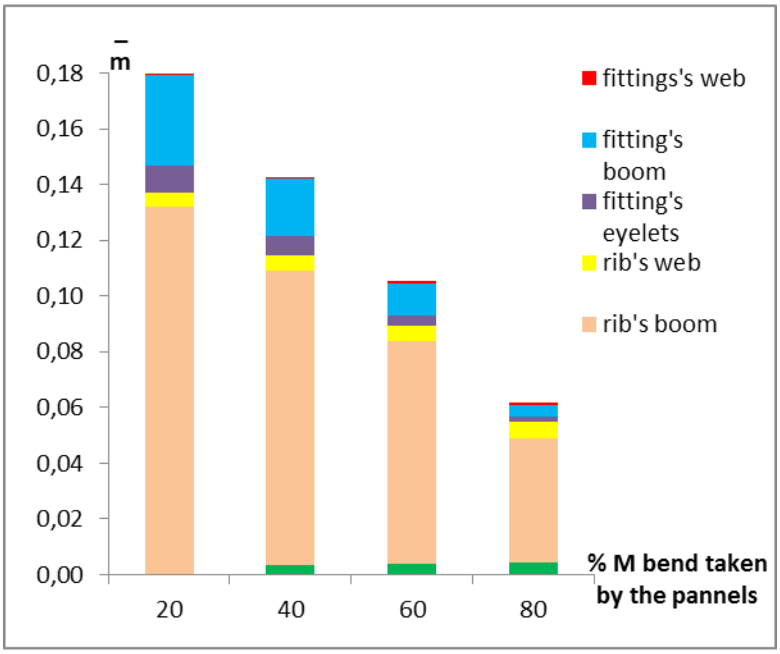

Figure 6: The elements' mass change depending on the load distribution

In the Figure 6 we can see the elementwise division of the strenthened block mass. We can observe that if the load persived by the wing's pannels decreases then the relavive mass of the join increses. Using these diagrams we can choose the optimal location of the folding axis and the rational structural scheme.

5. A generalized formula for the relative folding wing's mass estimation

Expressing formula (2) in the following form $\overline{m}_{wing}^{fold} = \overline{m}_{wing}^{nonfold}(1+\Delta\overline{m}_{fold})$ and using the expression $\Delta\overline{m}_{fold} = \overline{m}_{fold}^{str.block} + \overline{m}_{fold}^{mech} + \overline{m}_{lock}^{mech} - \overline{m}_{nonfold}^{rib}$ we will have the following formula:

$$\overline{m}_{wing}^{fold} = m_{wing}^{nonfold}(1+\overline{m}_{fold}^{str.block} + \overline{m}_{fold}^{mech} + \overline{m}_{lock}^{mech} - \overline{m}_{nonfold}^{rib}). \quad \textbf{(6)}$$

Formulas that define the relative mass of the strengthened block were calculated according to the information taken from Table 1. There are these formulas for four variants of load dispensing:

a) $\overline{m}_{fold}^{str.block} = 0{,}24(\overline{m}_{rws} - 0{,}924)^2 - 0{,}007$, b) $\overline{m}_{fold}^{str.block} = 0{,}45(\overline{m}_{rws} - 0{,}916)^2 - 0{,}02$,
c) $\overline{m}_{fold}^{str.block} = 0{,}696(\overline{m}_{rws} - 0{,}874)^2 - 0{,}01$, d) $\overline{m}_{fold}^{str.block} = 0{,}84(\overline{m}_{rws} - 0{,}98)^2 - 0{,}107$ **(7)**

Using statistics from the Table 2 we can calculate the analytical expressions for the relative masses of the folding and locking mechanisms:

$$\overline{m}_{fold}^{mech} = \frac{m_{fold}^{mech}}{m_{wing}^{nonfold}} = -3{,}76(\overline{m}_{rws} - 0{,}2)^2 + 0{,}08,$$

$$\overline{m}_{lock}^{mech} = \frac{m_{lock}^{mech}}{m_{wing}^{nonfold}} = -0{,}6(\overline{m}_{rws} - 0{,}2)^2 + 0{,}02. \quad \textbf{(8)}$$

The strengthened torque's mass is calculated by means of the formula:

$$\overline{m}_{rws}(z) = \frac{(b_Z + b_K)(0{,}5l - z)(\overline{c}_Z b_Z + \overline{c}_K b_K)}{(b_0 + b_K)l_{wing}(\overline{c}_0 b_0 + \overline{c}_K b_K)}. \quad \textbf{(9)}$$

6. A conclusion

Using the developed algorithm of the folding wing's mass calculation we can define the mass increment caused by folding. We can trace the mass changing for the different structural schemes and the folding axis locations. The analysis of the separate elements' masses permit to describe the elements that influence the wing's mass more. So we can optimize these elements. As the result the generalized formula for the relative folding wing's mass estimation was created.

References

[1] Sheinin, V.M., Kozlovsky, V.I. 1997. Design and efficiency of the civil aircrafts. Volume 1. Weight calculation and weight planning. 343.
[2] Jaeger, S.M., Mishin, V.F., Liseitsev, N.K. 2005. Aircrafts design. 648.
[3] http://www.lissys.demon.co.uk/pug/c04.html - «Chapter: 04. Mass Estimation» - 03.06.2010, 12:30
[4] Endogur, A.I. 2009.The design of the aviation structures. The design of the details and units. 540.
[5] Yarygina, M.V., Popov, Y.I. 2011. Method of folding wing weight analysis. In: 43rd Trudy MAI. 253-258.