VALIDATION OF THE FEM MODEL OF THE Mi-24 TAIL BOOM AND VERTICAL STABILIZER

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Abstract

The scope of this work was the validation process of the numerical model of the Mi-24 helicopter tail boom and vertical stabilizer. In order to obtain a detailed geometry of the actual structure the sophisticated reversed engineering techniques were used. The measurement was performed using two separate techniques: one based on digital photogrammetry and other based on a three dimensional laser scanning with ATOS III scanner. The numerical model was created with use of the obtained geometry, available technical documentation and detailed inspection of the structure.

The obtained FEM model was validated using strain measurements of the real structure during characteristic flight maneuvers. A system of foil strain gauges was installed on the tail boom in previously selected locations. Calibration process, using known loads, was performed in order to determine response of the measurement system. To enable a quick and reasonable comparison of results from the experiment and calculations a special element was introduced in the FEM model. Their task was to monitor local strains in places corresponding to those where the strain gauges were installed. Detailed analysis of results confirmed, that after some minor modifications, the developed finite element model represents the actual structure reasonably well. Particular attention was paid to the representation of the boundary conditions and how to implement loads, which can significantly affect the obtained results.

The analysis carried through confirms, that the presented validation technique, based on strain measurements, allows verifying a complicated numerical model in a relative cheap, fast and reliable way.

Keywords: *finite element method, Mi-24 helicopter numerical model, strain gauge measurement, validation*

1. Introduction

Numerical analysis and sophisticated measurement technologies enable one to create very detailed models which may simulate almost any physical phenomena. One must be aware that the accuracy of the final results is dependant on many factors, like: introduced constitutive equations, complexity of the model, realization of the boundary conditions etc. When creating a model one must always decide on the complexity level which is always finite since the final model will be more or less generalized .It is important to be aware how the results may vary depending on the decisions undertaken during creation of the model.

Within this article a validation method, based on strain measurements, is introduced which enables one to adjust the definition of mechanical model, boundary conditions, load application etc. , and ensures that the obtained results will be reasonable and more accurate. The measurement array used within this article was designed to gather load data during flight and is complex enough to determine different types of loads that may be considered during further work on the model.

2. Numerical model

Since the helicopters tail boom and vertical stabilizer are thin walled structures, which generally consist of ribs and spars covered with sheeting, mostly shell elements were introduced. The most common were quad elements with six degrees of freedom in each node, what enabled to consider the effect of bending. Furthermore brick elements were introduced for strength elements like ribs which are used to connect tail boom to the rest of the fuselage, by means of bolts put through aligned holes, and the vertical stabilizer to the tail boom in the same manner. In case of elements with one dimension dominant beam elements were introduced to simplify the model. The overall number of elements was around 30 000.

The geometry of the structure was obtained using reversed engineering methods like: digital photogrammetry and laser scanning [1]. Basing on these measurements, available technical data [9] and direct inspection the finite element model was created. Since the real structure is very complex and consists of tenths of thousands of parts a reasonable generalization must have been considered:

- the sheeting was considered as one surface with different thicknesses In places when overlay layers occur,
- no riveted joint were take into consideration,
- the lover shelves of spars, mounted to the sheeting, were not considered,
- elements which are not important from the structure stiffness but which masses are sufficiently high, since the inertial loads were considered, were modelled with high level of generalization,
- the global model consists of two separate models of tail boom and vertical stabilizer which were connected by merging corresponding nodes in the tail booms rear and stabilizer's front rib, which correspond to the location of mounting bolts,
- the horizontal stabilizer was reduced to a beam element to include its mass without the need to consider its detailed geometry,
- the drive shafts of the rear rotor were introduced as point masses to prevent over stiffening the structure.

The material used in the structure is D-16 aluminum alloy which basic properties are: E = 74 000 Mpa, ν = 0.3.

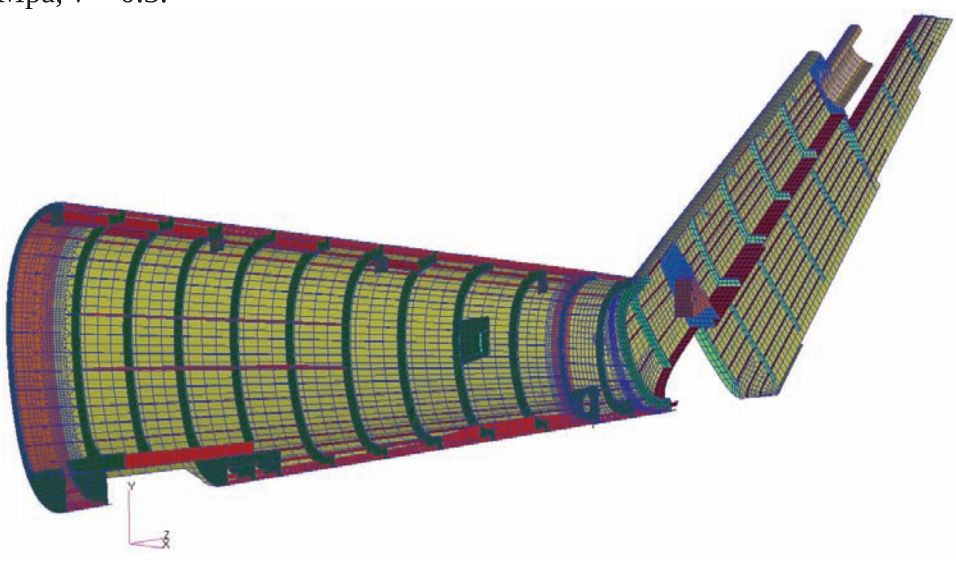

Fig. 1. Global FEM model of the tail boom with vertical stabilizer of the Mi-24 helicopter (right side) [5]

3. Validation assumptions

3.1. Loads

It was decided to use in the same loads that were used in the calibration of the strain gauge array [3]. Five cases were considered:

- bending downward,
- bending upward,
- bending left,

- bending right,
- complex bending and torque caused by rear rotor thrust.

The loads were realized by means of specially prepared belts and a calibrated, strain gauge based, force sensor. The value of the force applied in each load case was similar and close to 2000 N. In the first four cases the force was applied in the region between tail boom and vertical stabilizer where strengthened ribs, used to connect both elements by means of bolts, are applied. In the last load case the belts were attached to the rear rotor shaft.

The same loads were introduced in the numerical model. The boundary conditions were realized by constraining all degrees of freedom in the nodes lying in the outer face of first rib in a tail boom corresponding to the location of the bolts mounting the tail boom to the rest of fuselage. The gravitational forces were not included in numerical calculations, since the neutral state for strain gauges was determined under influence of these forces.

3.2. Strain gauge array

The strain measurements of the tail boom and vertical stabilizer were realized by means of foil strain gauges. Installation and calibration of the measurement array was carried out by Air Force Institute of Technology at Military Aviation Works No. 1 in Łódź [2, 3]. Localization of the measurement points is shown on the figure below.

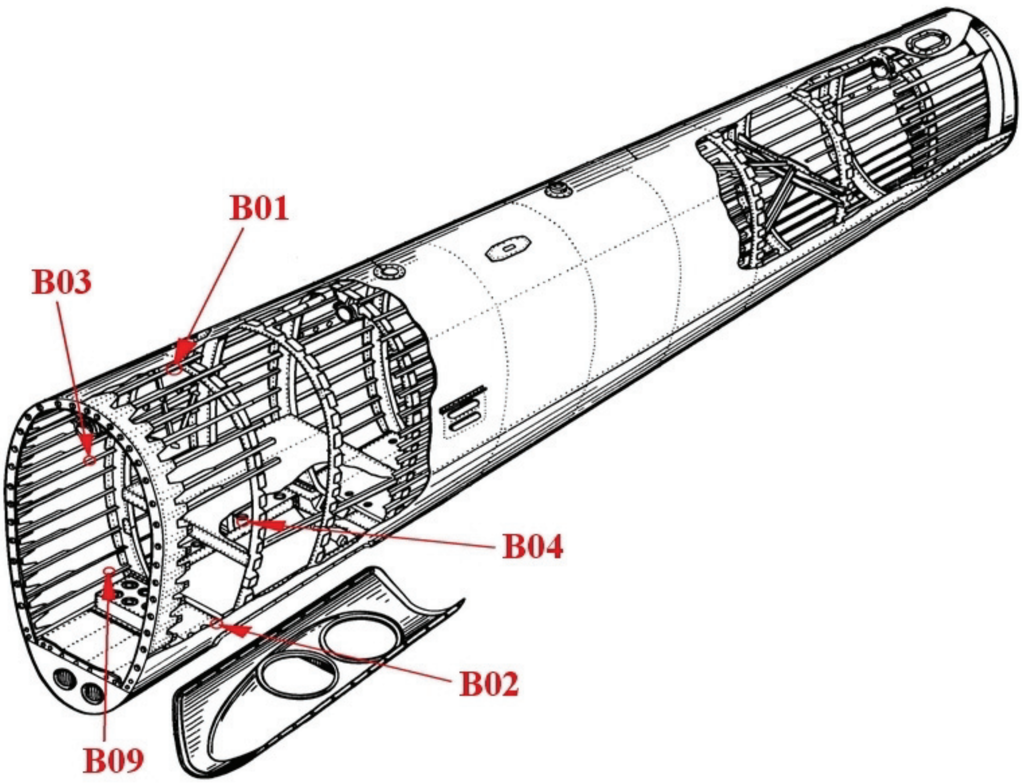

Fig. 2. Localization of the measurement points [2]

The array installed on the helicopters tail boom and vertical stabilizer consisted of seven measurement points. First five were located just after the first tail boom’s rib, where greatest values of strain were expected. Points were aligned circumferentially to enable measuring strains caused by different loads. The last two points were located at the rear end of tail boom on the upper and lower stringer. The strain gauges were generally installed on the stringers, except points B02 and B09 which are symmetrically aligned on the sides of a hole on the bottom side.

Figure below shows an example strain gauge used in experiment.

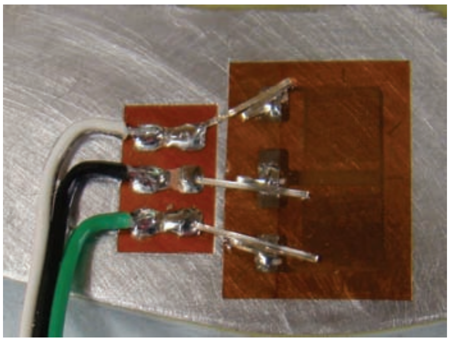

Fig. 3. An example of strain gauge used in analysis

Since the stringers generally work in tension and compression a special strain gauge configuration was used. It consisted of four gauges and enabled to compensate both temperature changes and strain caused by other loads that were not considered. The figure below (Fig. 4) illustrates the location of the gauges on a stringer and how the gauges were connected to create full Wheatstone bridge.

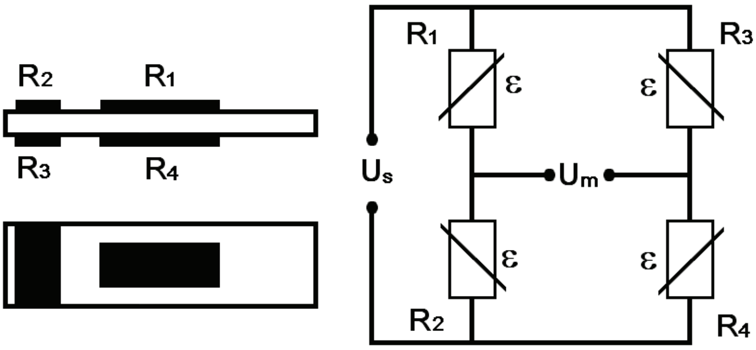

Fig. 4. Strain gauge placement and electrical scheme [6]

For the configuration shown above the output measured strain will be:

$$\varepsilon = \varepsilon_n = \frac{1}{2(1+\nu)} \times \frac{4}{k} \times \frac{Um}{Us}, \tag{1}$$

where:
e - measured strain,
en - normal (longitudinal) strain,
v - Poisson's ratio,
k - strain gauge constant (in this analysis equal 2.15),
Um - output voltage,
Us - source voltage.

To gather the strain measurements in a real time a recorder created in Air Force of Technology was used as well as AMX software. It enabled to gather coherent signals from all the sensors simultaneously. It was necessary to calibrate the whole system to eliminate possible hysteresis in strain gauges indications. In order to do so the beam was initially loaded in each direction. The values indicated after this process were assumed to be neutral [7, 8].

3.3. Modification of the numerical model

The numerical model that was to be verified had to be slightly modified. The modifications included creating special elements, which were supposed to determine strain in the exact locations where strain gauges were installed on the real structure.

The figure below shows a sample of such element. It generally consists of a bar element with material and geometric properties chosen such, that it does not influence stiffness but only enables to monitor strain in a particular location. The specific alignment of shell elements enabled to incorporate it in the already existing mesh.

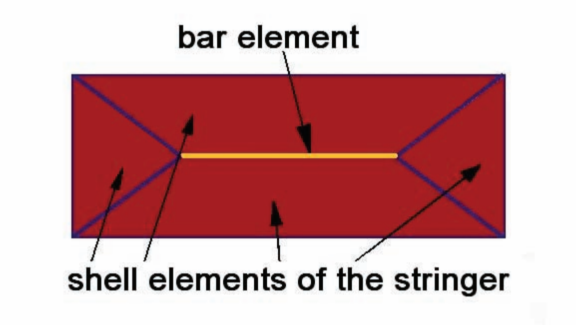

Fig. 5. Numerical strain gauge used in the model

Tab. 1. Properties of the numerical strain gauges

Parameter	Value	Unit
Young modulus	7 100	[MPa]
Poisson's ratio	0.3	[-]
diameter	0.2	[mm]
length	20	[mm]

4. Validation process

The experiment took place in the Military Aviation Works No. 1 in Łódź. As mentioned above the loads were applied by a set of specially prepared belts. The coherent signals, from both the strain gauges installed on the fuselage and one from force sensor, were captured (Fig. 6). From each of the five load cases the highest stable values of loads were chosen and the values of strains read.

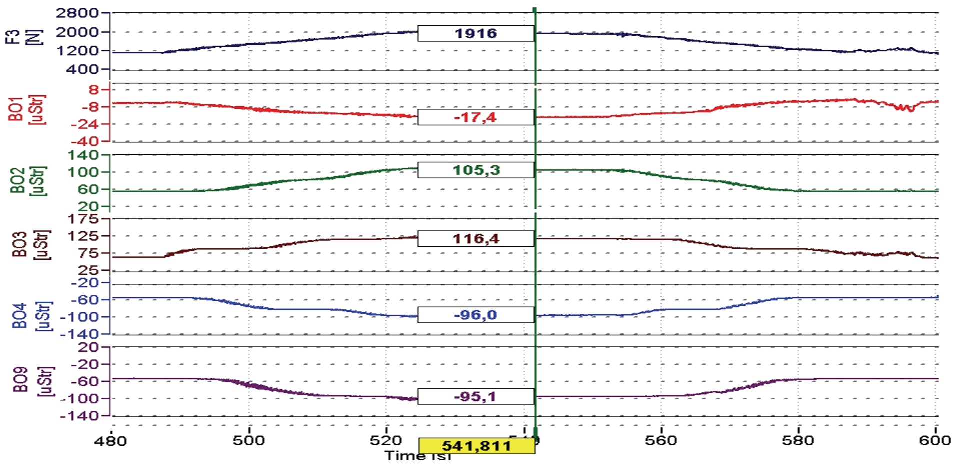

Fig. 6. Captured signals during the experiment. Complex bending and torque load case [4]

The read values of force, F3, from the experiment were then used as loads in numerical model. Values obtained from calculations were compared with those from experiment and after some necessary modifications to the model a reasonable accuracy was obtained.

5. Results

The final results have been tabularized below. In each table columns, which are crucial for particular case, are highlighted. It is related with the way the tail boom was loaded, since some points in particular cases lye in the neutral banding plane region and thus should not be considered crucial for this case. As a final result the ratio of the two obtained values, expressed in percents, and the difference between the values are presented.

Tab. 2. Result comparison for load case - bending downward

point	B01 [µStr]	B02 [µStr]	B03 [µStr]	B04 [µStr]	B09 [µStr]
experiment	55	-32	30	5	-39
calculations	50	-30	3	3	-30
ratio in %	91%	94%	10%	60%	77%
difference	5	2	27	2	9

Tab. 3. Results comparison for load case - bending upward

point	B01 [µStr]	B02 [µStr]	B03 [µStr]	B04 [µStr]	B09 [µStr]
experiment	-91	56	-83	-1	50
calculations	-92	54	-5	-5	56
ratio in %	101%	96%	6%	500%	112%
difference	1	2	78	4	6

Tab. 4. Results comparison for load case - bending left

point	B01 [µStr]	B02 [µStr]	B03 [µStr]	B04 [µStr]	B09 [µStr]
experiment	0	-24	58	-35	18
calculations	0	-60	51	-31	61
ratio in %	100%	250%	88%	89%	339%
difference	0	36	7	4	43

Tab. 5. Results comparison for load case - bending right

point	B01 [µStr]	B02 [µStr]	B03 [µStr]	B04 [µStr]	B09 [µStr]
experiment	22	29	-84	55	-38
calculations	1	70	-60	36	-72
ratio in %	5%	241%	71%	65%	189%
difference	21	41	24	19	34

Tab. 6. Results comparison for load case – complex bending and torque

point	B01 [µStr]	B02 [µStr]	B03 [µStr]	B04 [µStr]	B09 [µStr]
experiment	-17	-95	116	-96	105
calculations	0	-93	98	-61	95
ratio in %	0%	90%	84%	64%	98%
difference	17	10	18	35	2

In the Table 2 and 3 the crucial points are B01, B02 and B09. The ratio is no lower than 77% what is considered to be a satisfying result. Values of B03 and B04, which are in neutral bending plane, are low both in the experiment and computer simulation. Values B02 and B09 which are symmetrically aligned on sides of hole in the lower part of tail boom show identically levels of strain both in experiment and simulation.

Tables 4 and 5 show bending sideways. In this load cases the B03 and B04 channels are the most crucial. Once again one can see that the values both from the experiment and simulation are show good correlation.

Rear rotor thrust causes a combined bending and torque state in the tail boom. The direction of bending moment is sideways hence points B03 and B04 are considered to be the most crucial. Since B02 and B09 are offset from the vertical plane of symmetry of the tail boom, they also show sufficiently high signal to be taken into consideration. One can see that the ratio for both these points is sufficiently high, not lower than 90%.

Based on these results a chart showing the module of differences in results from experiment and numerical calculations is shown in a figure below (Fig. 7).

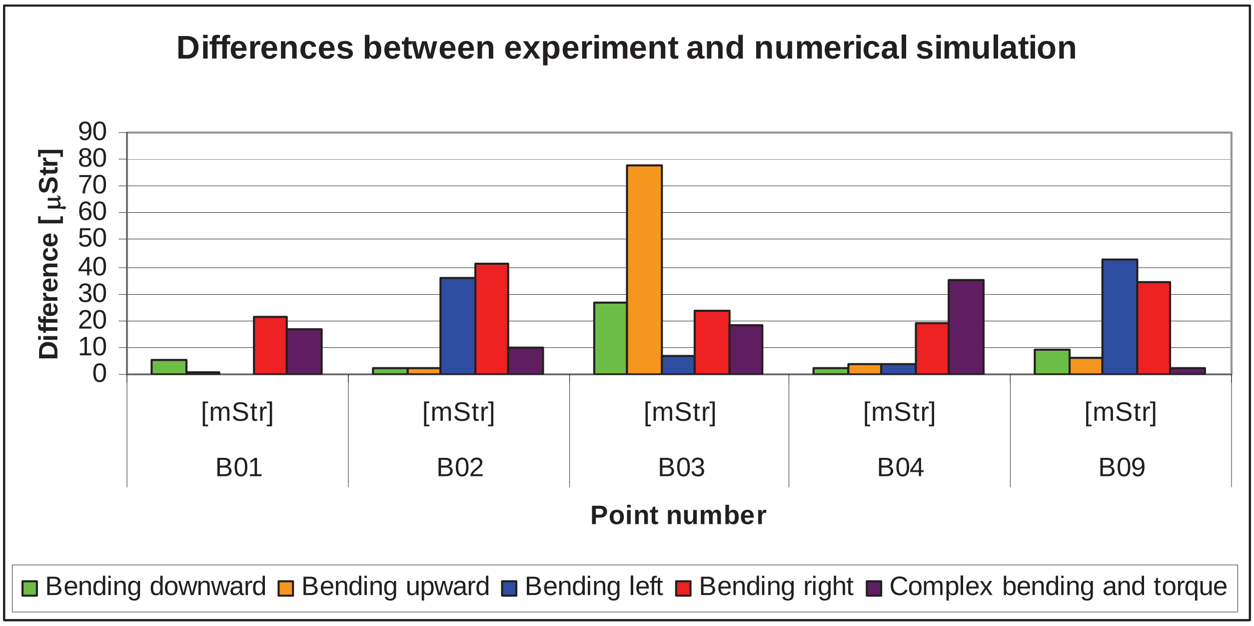

Fig. 7. Module of differences of results for each point

6. Conclusions

After accomplishment of the analysis the following conclusions have been drawn:

- the validation carried through allows to state, that the presented numerical model represents the real structure with sufficient accuracy, and the simplifications didn't have significant influence on the reliability of the global model,
- the demand to simplify the model in order to reduce calculation time and to amount of work needed to accomplish complicated numerical model impose a finite convergence with the real structure,
- the presented model, after necessary modifications, can be applied in further numerical analysis of the Mi-24 helicopter structure,
- the validation process presented within this article enables to significantly increase reliability of the numerical model and to verify the boundary conditions,
- strain gauge measurement is a relatively fast and exact method for validation of a mechanical structure.

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