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Multilevel Optimization Approach Applied to Aircraft Nose Landing Gear

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General multilevel approach of large-scale multidisciplinary structural problems is considered. Optimization approach is applied to multidisciplinary structural problems like: minimum weight of aircraft nose landing gear structure under various strength and stiffness constraints, directional aircraft stability and control during taxiing and take off. Optimality criteria approach (Dual algorithms) and finite element method (FEM) for stress analyses, in system level, are applied to achieve minimum weight design of nose landing gear structure. Nonlinear mathematical programming (NMP) methods based on multicriteria optimization algorithms for Pareto optima (Weighting method), in local levels, are applied to stability maximization and turning capability of nose wheel structure. In local levels the nose wheel castering length and damping of damper are considered as optimization parameters in stability maximization and controllability during taxiing and take off. The use of finite element methods in parallel with optimization techniques such as dual and multicriterion optimization techniques make it possible to address large-scale and complex structural problems such as aircraft landing gear or composite structures.

Key words: **multilevel optimization, aircraft landing gear, finite element method, optimality criteria, multicriterion optimization.**

Introduction

OPTIMIZATION plays an active role in computer-aided engineering because it attempts to make the best use of analysis capabilities in making important types of design decisions. One of the major tasks in the design of large-scale structural systems such as aircraft structures is the sizing of the structural members to obtain the desired strength, weight, and stiffness characteristics. Optimization algorithms have been coupled with structural analysis programs for use in this sizing process. Most of the difficulties associated with large structural design are solution convergence and computer resources requirements. The use of finite element methods (FEM) in parallels with optimization techniques such as nonlinear mathematical programming (NMP) or optimality criteria (OC) make it possible to attack large and complex aircraft structural problems. More recently, the works in References [1-3] have illustrated the uniformity of the methods. Nevertheless, each approach offers certain advantages and disadvantages. The MP methods are extremely useful in defining the design problem in proper mathematical terms. When the design variables are few these methods can be used quite effectively for optimization. However, in the presence of a large number of variables these methods are very slow. The rate of convergence for OC methods is initially very fast, step size determination is critical closer to the local optimum where the number of active constraints increases and the computations of Lagrange multipliers become more complex. Ideally, a methodology that exploits the strength of both approaches could be employed in a practical system. The object of the present research effort is to develop such design method that can efficiently optimize large structures that exploit the power of the MP and OC methods.

The motivation of this study is to come up with a multilevel optimization method using optimality criteria and mathematical programming techniques. Multilevel optimization permits a large problem to be broken down into a number of smaller ones at different levels according to the type of problem being solved. This approach breaks the primary problem statement into a system level design problem and set of uncoupled component level problems. Results are obtained by iteration between the system and component level problems. The decomposition of a complex optimization problem into a multilevel hierarchy of simpler problems often has computational advantages. It makes the whole problem more tractable, especially for the large engineering structures, because the number of design variables and constraints are so great that the optimization becomes both intractable and costly.

In designing aircraft nose wheel it is necessary to consider many different (sometimes - opposing) requirements. Mainly, the requirements are: good aircraft behavior during ground motions; mass minimization; convenient design and technology; easy maintenance; etc.

The investigation of nose wheel behaviour during aircraft taxiing and take-off is very important within designing and testing fazes. A lot of different nose wheel designs are realized, with satisfactory behaviour during

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aircraft ground motion. Problems occur mainly due to strong oscillations. From the pilot's point of view, the way the aircraft respond to command and/or disturbances during taxiing and take-off is very important. Two deferent requirements might be of interest: good stability on the runway (low deviation from the path to outside noise) and easy control to obtain the desired aircraft pointing.

Mass is the prime interest while aircraft designing. Both the nose wheel position and nose wheel design affect the mass of the nose wheel. In this paper, the nose wheel design to the mass minimization will be considered. Nose wheel geometry is important because it affects load distribution, nose wheel cinematic, volume in retracting position, etc.

Certain nose wheel parameters like castering length, spring and damping have significant influence on the aircraft motion and parameters like: stability and control during ground motion, mass of the wheel, the geometric values and other requirements. Therefore, the optimization of those parameters during design phase is essential. For the parameter analysis and optimization, it is necessary to have a convenient mathematical form.

Directional aircraft stability/control is analyzed in this paper. The equations of aircraft ground (directional) motion are presented. The equations contain the aircraft and nose wheel coupling. The stability conditions are discussed. The influence of certain parameters (nose wheel castering length, spring and damping) on the aircraft stability and motion is analyzed. In the design phase the parameters calculation, combined with development testing, might lead to satisfactory aircraft behaviour during taxiing and take-off, as well as the nose wheel structure mass/design optimization.

Separate optimization problems like stability and controllability, nose wheel mass minimization, convenient geometry are functions of nose wheel parameters (especially the nose wheel castering length). Each of those optimizations gives a different optimization point. That is why combined multicriterion optimization is considered. Different waiting coefficients are addressed to each separate optimization problem and the effect of change of waiting matrix to optimization point is analyzed. The method is illustrated by numerical example for light training aircraft.

Theory of multilevel optimization

It is common practice nowadays to use optimization methodologies to deal with multidisciplinary industrial design Let D and d represent sets of system and component design variables, respectively. Then the problem can be stated as: find vectors D and d such that

$$W(D) \Rightarrow \min \tag{1}$$

subject to

$$G_q(D,d) \geq 0\,, \quad q \in Q \tag{2}$$

and

$$g_{lj}(d_j, D) \geq 0\,, \quad l \in L; \;\; j \in M \tag{3}$$

The G_q (D,d) represents constraints that are strongly dependent on the D vector and are implicit functions except for the side constraints. The $g_{lj}(d_j, D)$ represent constraints that are primarily dependent on the j component variables d_j , and they are either explicit or implicit functions of d_j, depending on the type of constraints. Symbols Q and L denote set of system and component level constraints respectively, M denotes the number of components and d^T=[d_1^T, d_2^T,..., d_M^T]. Then system and local analyses and optimizations are carried out separately and tied together by an iterative scheme going from one level of design modification to the other and vice-versa, seeking an overall optimum design.

The system level optimization

The two optimization problems typically addressed in structural optimization have been sizing and shape optimization. In sizing optimization, the variables define local geometric characteristics such as thickness, width, etc. In shape optimization, the optimal shape of a structure is sought by varying the boundary shape defined by an appropriate spline function, with the design variables defined in a function form. To achieve minimum weight of nose wheel structure here, both types of optimization (sizing and shape optimization) are included. Using standard optimization procedure based on combining OC and finite elements, the weight optimization can be expressed as [1-3]: Find vector D such that

$$W(D) = \sum_{i=1}^{N} \frac{w_i}{D_i} \Rightarrow \min \tag{4}$$

and

$$G_q(D, d^*) \geq 0; \;\; q \in Q \tag{5}$$

where d^* implies that the parameters strongly dependent on the detail design variables d (i.e. directional aircraft stability and control during taxiing and take off) do not change during the system level design modification stage. The w_j are positive fixed constants corresponding the weight of the set of finite elements in the j-th linking group when D_j=1. The set of independent design variables after linking is denoted by **N**. The selection of design variables, especially in shape optimization, is very important in the optimization process. It has to be decided a priori where to allow for design changes and to evaluate how these changes should take place by defining the location of the design variables and the moving directions. In many investigations, the design variables were chosen as the positions of the nodes on the boundary, or the coefficients of polynomials defining the boundary and control points of the Bezier and B-splines. In the present study, the coordinates of the key points are specified as design variables. The use of the coordinates at key points as design variables leads to fewer design variables and more freedom in controlling the shape of the structure. Shape design sensitivity analysis is an important part of optimization. The exact semi analytical sensitivity analysis method [5] is used (the exact derivative of $\partial k / \partial a_i$ can be evaluated – where k is elemental stiffness matrix and a_j is the nodal coordinate of the element).

Local level – multicriterion optimization

Optimization form

In many engineering applications, including mechanical and structural design problems, however, often exist several, usually opposed criteria to be considered by the designer. It has been common practice in the references to represent the objective function as a weighted sum of those desirable properties, but this approach has proved quite unsatisfactory except in some specific cases. On the other hand, multicriterion optimization seems to offer a very promising possibility to consider effectively all the different, mutually conflicting requirements inherent in the design problem. The recent emergence of the multicriterion approach in structural mechanics can be seen, to the author's knowledge, from the references published in the second half of 1970s [7,8] that applied the control theory approach to a bicriterion problem with weight and stored energy as criteria, and obtained analytic solutions for some structural elements, naming the results natural structural shapes. Baier [9] studied multicriterion optimization of structures from a general point of view, choosing weight and stored energies in separate loading conditions as design criteria. Several techniques for solving multicriterion nonlinear vector optimization problem have been presented in the references. They usually turn the original problem into a sequence of scalar optimization problems, which can be solved numerically by applying adapted methods of nonlinear programming. For this purpose, the weighting method is used in solving multicriterion optimization problem. Perhaps one of the most commonly used approaches to the problems with several criteria is to form one scalar objective function as a weighted sum of the criteria. A drawback of this technique is the difficulty concerning the choosing of the weights for the criteria. In convex multicriterion problems, however, it is possible to apply the method in a parametric form to the determination of a pareto-optimal set. If the notation $a^T = \lfloor a_1 \; a_2 \; ... a_n \rfloor$ is used for the vector of weighting coefficients, the problem takes the form

$$\min_{x \in \Omega} a^T \; J(x) \,.$$

Without the loss of generality, a can be normalized so that the sum of its components, which are non-negative and not all zero, is equal to one. Now Pareto-optimal solutions can be generated by parametrically varying the weights a_i in the objective function. In this paper, the compromise between more optimization tasks is proposed as multicriterion optimization in the form

$$J^m(x) = c_1 \left|J_1(x)\right|_N + c_2 \left|J_2(x)\right|_N + ... + c_n \left|J_n(x)\right|_N \,, x \in R^n \quad (6)$$

$$f_i(x) \le 0$$

where is:

$J^m(x)$ multicriterion optimization form,

$\left|J_k(x)\right|_N$ absolute norm of each single optimal criteria (in this formula, norm means that the maximum value of the referred criteria is brought to one),

$c_1,...c_n$ weighting coefficient, $\left(\sum_1^n c_i = 1\right)$. By these coefficients c_i, the designer (according to his judgment) gives more or less significance to the certain single optimization criteria $J_i(x)$,

$f_i(x) \le 0$ posed constraints.

To perform multicriterion optimization, the algorithm is as follows:

1. Each optimality criterion $J_i(x)$ has to be performed separately and optimization point b^i which satisfies criteria $J_i(b^i) = [J_i(x)]_{\max} = J_i^{\max}$ found
2. The norm of each optimality criteria is defined as $\left|J_i(x)\right|_N = \left|\dfrac{J_i(x)}{J_i^{\max}}\right|$
3. The weighting coefficients $c_1,...c_n$ are chosen,
4. The constrained $f_i(x) \le 0$ are imposed,
5. The multicriterion optimization $J^m(x)$ is performed, usually applying certain numerical methods.

Through this process, the designer has optimal point b^i for each separate criterion and optimal point b as results of combined criteria or multicriterion problem. The optimal solution of the parameters $b = x_{opt}$ may be between separate optimization points, but close to some separate results, as a function of the chosen weighting coefficient.

Nose wheel parameters optimization

Both aircraft and nose wheel equations of motion, as a connected system, might be represented as liberalized second order system [5]. There are a lot significant parameters in the nose landing gear design, taking into consideration system performances like stability, controllability, mass, technological aspects and others. From the experience, the most significant parameters are: castering length, spring stiffness, damping, tire, etc. In this paper, to show the optimization procedure, two parameters having an obvious effect on the stability, controllability, mass, and technology, the castering length and damping of damper were selected.

a) Different criteria are applied to castering length and damping optimization, as:

- stability index $J_1(l,H_p) = \xi(l,H_p)\omega_n(l,H_p)$ (or σ_1 - lower periodic root)
- aircraft controllability index defined by transfer function gain $J_2(l) = K_{M_{Nu}}^{\psi}$
- geometry (technology) complexity index determined $J_3(l,H_p) = T_0 - T_1 \cdot l^{0.5} - l \cdot H_p$
- mass defined as $J_4(l,H_p) = 0.95/(1+200 \cdot l^2) - 0.9/20 \cdot H_p \cdot l$

Stability condition introduce positive nose wheel length as constraint, l>0.

Each of these optimization criteria gives different optimization point for nose wheel castering length and damping. Stability criteria determine lower castering length and the aircraft controllability criteria have no significant effect. Geometry complexity index tends to decrease castering length and so on.

Ground motion equations

Both the aircraft dynamic and nose wheel dynamic equations of motion, as a connected system, are [4]

$$\ddot{\Psi} + H\dot{\Psi} + K\Psi = C\delta_r + \frac{1}{I_z}\left(M_w + M_u - M_{NN}\right) \quad (7)$$

$$I_{N0}\ddot{\varphi} + \left(H_L + H_p\right)\dot{\varphi} + \left(K_{op} + K_{MN}\right)\varphi = \\ = M_{NN} + M_{NU} + M_{NW}$$

Cinematic relation can be added,

$$(d_N - l\cdot\cos\varphi)\cdot\sin\Psi = l\sin\varphi \text{, or } (d_N - l)\cdot\Psi \approx l\cdot\varphi \qquad (8)$$

Where:

$$C = \frac{Sqb}{I_z}C_{n\delta r}\ ,\ K = \frac{Sqb}{I_z}C_{n\beta}\ ,\ H = -\frac{Sqb}{I_z}\frac{b}{2u}C_{nr}\ ,$$

$C_{n\beta}, C_{nr}, C_{n\delta r}$	Aerodynamic coefficients,
β	Side slip angle,
Ψ	Yawing angle,
S	Wing area,
b	Wing span,
l	Castering length,
d_N	Nose wheel distance from cg,
q	Dynamic pressure,
I_z	Moment of inertia,
δ_r	Ruder deflection,
u	Air speed,
M_w	Wind disturbance,
M_u	Aircraft control moment (deferential engine control, differential breaking),
φ	Turning angle of the nose wheel,
I_{N0}	Nose wheel moment of inertia,
H_L	Nose wheel damping,
H_P	Moment of damper,
M_{opr}	Centering spring moment,
M_{FB}	Moment of wheel side force (F_B –),
M_{NN}	Nose wheel moment.

Linear coupled system is:

$$A\ddot{\varphi} + B\dot{\varphi} + D\varphi = I_z C\delta_r + M_w + M_U + M_{NU} + M_{NW} \qquad (9)$$

where:

$$\Psi \cong \frac{i}{d_N - l}\varphi$$

$$A = \frac{l}{d_N - l}I_z + I_{0N}\left[\approx \frac{l}{d_N}I_z \quad for \quad (I_z >> I_{0N})\right]$$

$$B = \frac{l}{d_N - l}I_z H + H_L + H_P\ ,$$

$$D = \frac{l}{d_N - l}I_z K + K_{op} + K_{MN}$$

The equation (5.3) is second order system, describing coupled aircraft and nose wheel yawing motion during taxiing and take-off. The oscillations are determined by damping ξ and natural frequency ω_n. The transfer function gain (controlling the aircraft by nose wheel moment) is

$$K^{\Psi}_{M_{NU}} = \frac{l}{d_N - l}\frac{1}{D}\ .$$

Numerical examples

To illustrate the application and versatile multilevel approach some aspects of the optimal design of nose wheel structure are considered. Let light training aircraft with the following parameters be considered: I_z=3812 kgm^2, $C_{n\beta}$=0.152, d_N=1.408, C_{nr}=-0.213, H_L+H_P=500, $C_{n\delta r}$=-0.0018, b=9m, S=13m^2, F_N=2590 N → static nose wheel load, K_N=4 1/rad → for dry surface, K_N=2.8 1/rad → for wet surface.

There are a lot significant parameters to the nose landing gear design, taking into consideration system performances like stability, controllability, mass, technological aspects and others. From the experience, the most significant parameters are: castering length, spring stiffness, damping and tire. In this paper, to show the optimization procedure, two parameters having an obvious effect on the stability, controllability, mass and technology -the castering length and damping of damper were selected.

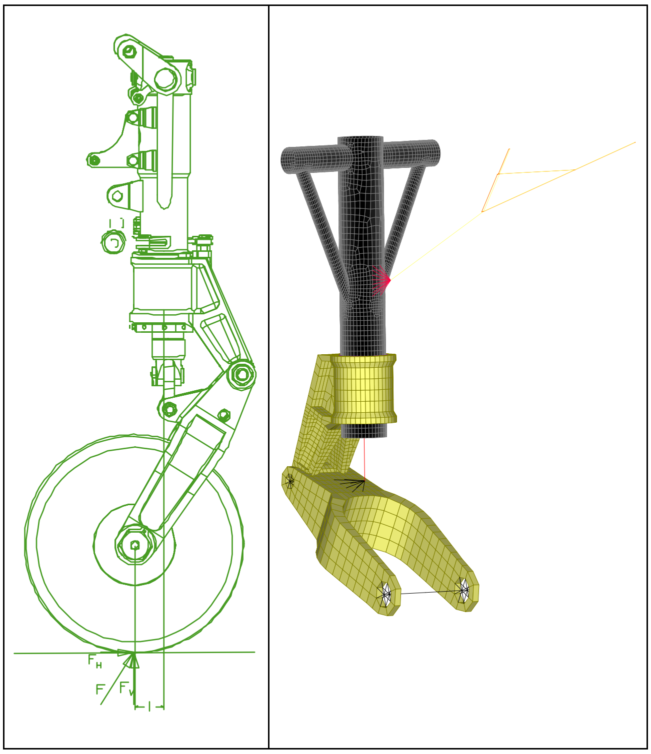

Figure 1. Nose wheel and castering length

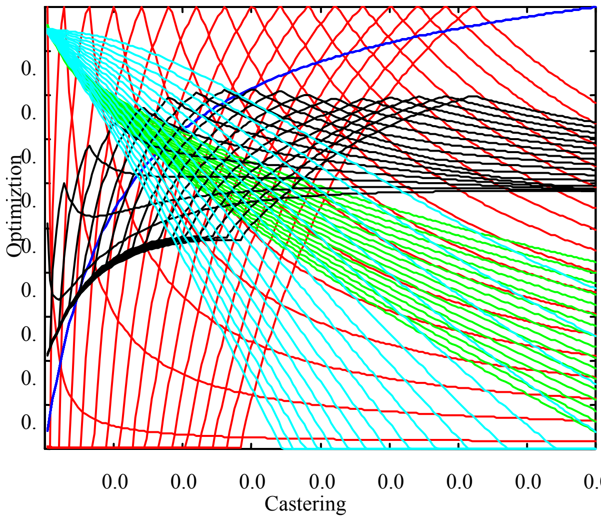

Figure 1.a) Two dimensional plot of optimisation form J=$J(l,Hp)$, for: single optimisation (defined in Nose wheel parameters optimization) J_1-red (stability index), J_2-blue (aircraft contro-llability index), J_3-green (geometry complexity index), J_4-creyon (mass); and local level optimization J=$J(l,Hp)$=$c_1J_1(l,Hp)$+$c_2J_2(l,Hp)$+ $c_3J_3(l,Hp)$+$c_4J_4(l,Hp)$ - bleak. The optimization parameters are: l - Castering length (presented as x-axis), Hp–Damper damping (varying from 15 to 495 - increment 30)

Single optimization for different criteria gives four different optimization points for nose wheel castering length and damping as: l_1^{loc}=22.0 mm and H_{p1}^{lpc}=195.0 Nms, l_2^{loc}=80.0 mm, l_3^{loc}=0.0 mm and H_{p3}^{lpc}=0.0 Nms, l_4^{loc}=0.0 mm and H_{p4}^{lpc}=0.0 Nms, Fig.1.

Local level optimization gives optimal point as l^{loc}=30.0 mm and H_p^{lpc}=255.0 Nms, and optimization level $J^m(l{=}0.030,\ H_p{=}255){=}0.812$. Local level optimization gives optimal point for nose wheel castering length as 30.0mm, Fig.2. The optimization point is determined for ground speed as 10 m/s.

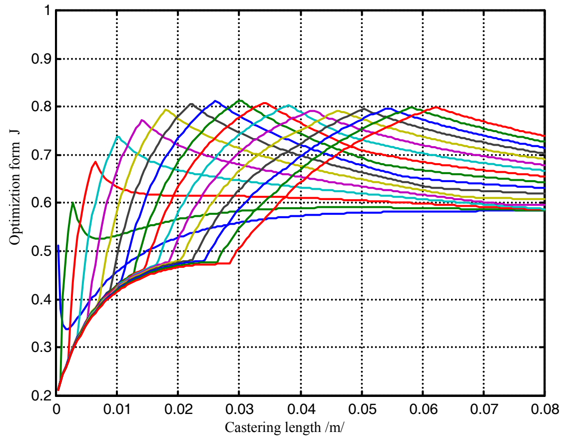

Figure 1.b) Two dimensional plot of local level optimization form *J=J(l,Hp)=c₁J₁(l,Hp)+c₂J₂(l,Hp)+c₃J₃(l,Hp)+c₄J₄(l,Hp)*. The optimization para-meters are: *l* – Castering length (presented as *x*-axis), *Hp* – Damper damping (varying from 15 to 495 - increment 30)

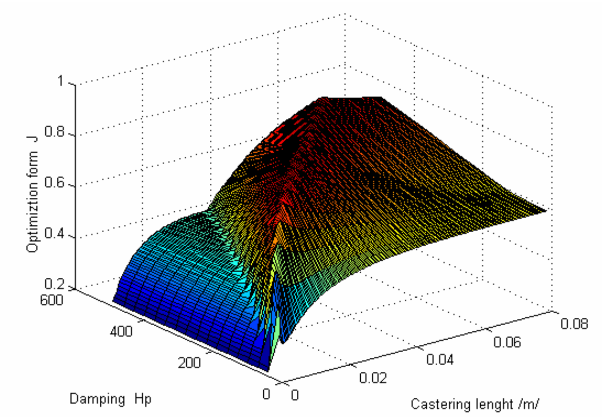

Figure 2.a) Tree dimensional plot of local level optimization form $J=J(l,Hp)=c_1J_1(l,Hp)+c_2J_2(l,Hp)+c_3J_3(l,Hp)+c_4J_4(l,Hp)$. The optimization para-meters are: *l* – Castering length, *Hp* – Damper damping

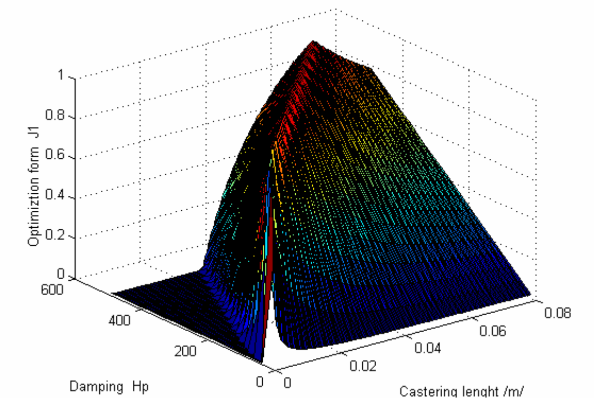

Figure 2.b) Tree dimensional plot of single optimization form $J=J_1(l,Hp)$. The optimization parameters are: *l* – Castering length, *Hp* – Damper damping

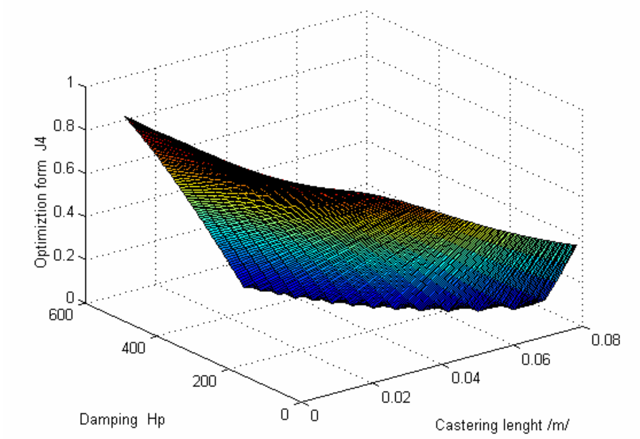

Figure 2.c) Tree dimensional plot of single optimization form $J=J_4(l,Hp)$. The optimization parameters are: *l* – Castering length, *Hp* – Damper damping

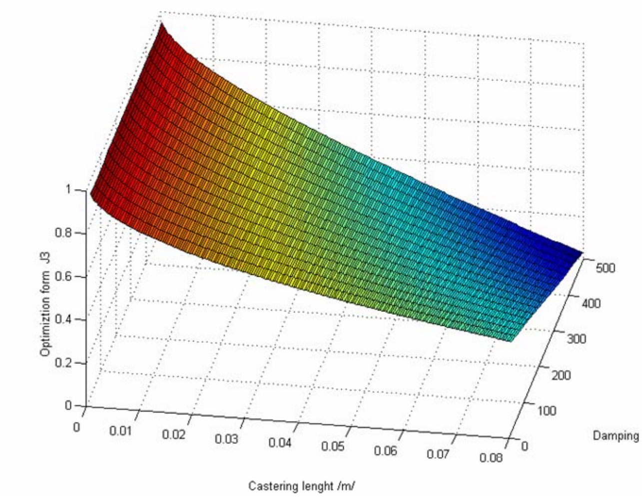

Figure 2.d) Tree dimensional plot of single optimization form $J=J_3(l,Hp)$. The optimization parameters are: *l* – Castering length, *Hp* – Damper damping

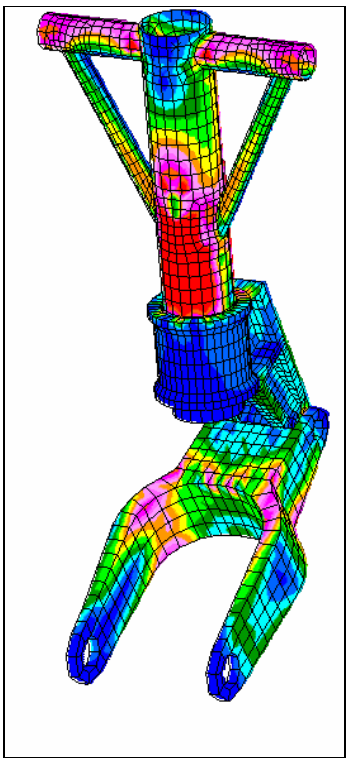

Figure 3. System level – structural optimization

Based on this optimization point on local level, structural optimization on the system level is performed. The result of structural optimization is mass minimization, Fig.3. Fig.3 shows typical stress distribution of the nose wheel structure after optimization subject to stress, displacement and geometry shape constraints. In this study shape optimization is also included.

Fig.4 shows the shape of the nose wheel structural element, before and after shape optimization and 5 shows stress distributions in this structural element after optimization.

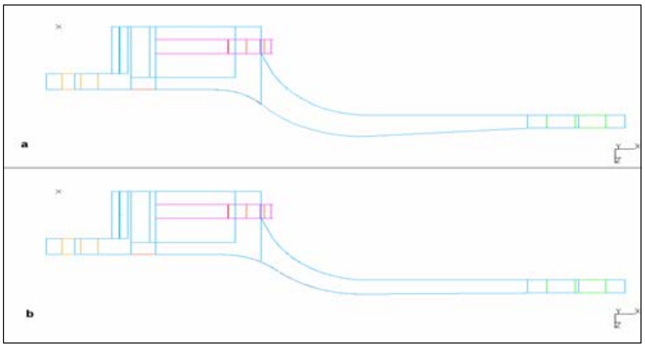

Figure 4. Geometry of nose wheel structural part: a) Before shape optimization

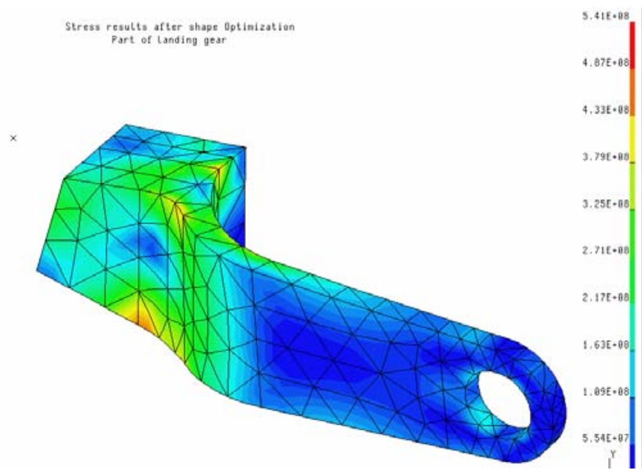

Figure 5. Stress distributions in structural part after shape optimization

Conclusion

The obtained results demonstrate the practicality of multilevel optimization in the design of the multidisciplinary complex aircraft structures such as aircraft nose wheel. In this study two-level optimization algorithm is applied, on the system and component level. Combining FEA, approximation concepts and OC or dual algorithms, has led to a very efficient method for minimum weight sizing of large-scale structural systems. Finally, minimum weight designs obtained for the aircraft nose wheel structure illustrate the application of the multilevel approach to a relatively large structural system.

Recent optimization technique contributed significantly to the system parameters determination during the design process. On the other hand, the engineering judgment remains a design tool. The contribution of this paper lies in a combined effect: application of optimization methods including the engineering preference and experience. The engineering judgment and influence is expressed through the weighting coefficient c in the multicriterion optimization function.

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Višestepeni pristup optimizacije primenjen na strukturu nosne noge aviona

U radu je razmatran višestepeni pristup optimizacije velikih strukturalnih sistema. Prezentovani pristup optimizacije je primenjen na multidisciplinarni problem kao što je minimizacija mase strukture nosne noge aviona uz zadovoljenje ograničenja u pogledu čvrstoće i krutosti kao i stabilnosti i upravljivosti za vreme taksiranja i poletanja aviona. Kriterijumi optimalnosti (Dualni algoritmi) u sprezi sa MKE za analizu naponskih stanja su korišćeni na sistemskom nivou čime se obezbeđuje minimalna masa strukture nosne noge uz zadovolljenje zahteva u pogledu čvrstoće i krutosti. Metode nelinearnog matematičkog programiranja (NMP) zasnovane na algoritmima višekriterijumske optimizacije za Pareto optimum, na lokalnim nivoima, su korišćene za maksimizaciju u pogledu stabilnosti i obrtljivosti nosne noge aviona. Na lolokalnim nivoima dužina zabacivanja točka nosne noge i prigušenje su

razmatrani kao parametri optimizacije pri maksimizaciji stabilnosti i upravljivosti za vreme taksiranja po pisti i poletanja. Primena MKE u sprezi sa optimizacionim tehnikama kao što su dualna i višekriterijumska optimizacija čini mogućim da se vrši optimizacija velikih strukturalnih sistema kao što su stajni organi aviona ili kompozitne strukture.

Ključne reči: **višestepeni pristup optimizaciji, nosna noga aviona, metoda konačnih elemenata, kriterijum optimalnosti, višekriterijumska optimizacija.**

Многоступенчатый подход оптимизации применнёный на структуре носовой ноги самолёта

В настоящей работе рассматриван многоступенчатый подход оптимизации больших структуральных систем. Показанный подход оптимизации пименён на многодисциплинарную проблему вроде минимизации массы структуры носовой ноги самолёта, с ограничением прочности и жёсткости, а в том роде и управления и устойчивости в течении руления и взлёта самолёта. Критерии оптимальности (алгорифмы решения двойственной задачи) в связи с МКЕ для анализа напряжённых состояний пользованы на уровне системы, чем обеспечивается минимальная масса структуры носовой ноги, с удовлетворением требований прочности и жёсткости. Методы нелинейного математического программирования (НМП) обоснованы на алгорифмах многокритерийской оптимизации для Парето-оптимума, на местном уровне использованы для достижения максимума устойчивости и способности разворота носовой ноги самолёта. На местных уровнях длина забрасывания колеса носовой ноги и демпфирование здесь рассматриваны в роли параметров оптимизации при достижении максимума управления и устойчивости в течении руления по лётной полосе и во время взлёта. Применение МКЕ в связи с оптимизационными техниками вроде двойственных задач и многокритерийских оптимизаций делают возможным выполнение оптимизации больших структуральных систем вроде шасси самолёта или смешанной структуры.

Ключевые слова: многоступенчатый подход оптимизации, носовая нога самолёта, метод конечных элементов, критерий оптимальности, многокритерийская оптимизация.

Approche à l'optimisation à plusieurs niveaux appliquée à la structure du trein d'atterrissage avant de l'avion

Dans ce papier on considère l'approche à plusieurs niveaux à l'optimisation de grands systèmes structuraux.Cette approche est appliquée au problème multidisciplinaire de la minimisation de la masse de structure du trein d'atterrissage avant en satisfaisant les contraintes liées à la solidité, la rigidité, la stabilité et la commande pendant le roulement au sol et le décollage de l'avion.Les critères d'optimalités (algorithmes doubles) avec MKE pour analyser les états de tension sont utilisés au niveau du système, ce qui assure la masse minimale de structure du trein d'atterrissage avant, en satisfaisant les exigences à l'égard de la solidité et de la rigidité.Les méthodes de programmation mathématique non-linéaire (NMP) basées sur les algorithmes d'optimisation multicritère pour PARETO optimum sont employées, au niveau local, pour la maximisation de stabilité et du tour de roue du nez d'avion. Au niveau local, la longueur de jet de roue du nez et l'étouffement sont considérés comme paramètres d'optimisation lors de la maximisation de stabiilité et de commande pendant le roulement au sol et le décollage d'avion. L'application de MKE liée aux techniques d'optimisation, telle que l'optimisation double et multicritère, rend possible l'optimisation de grands systèmes structuraux, tels que le trein d'atterrissage ou les structures composites.

Mots clés: **approche à l'optimisation à plusieurs niveaux, trein d'atterrissage avant, méthode des éléments finis, critère d'optimalité, optimisation multicritère.**