Tube-deployable unmanned aerial vehicle multiphysical simulation

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Abstract

The flight dynamics mathematical model for a small tube-deployable unmanned aerial vehicle (UAV) and its flight trajectory optimization is presented in this paper. The optimal stiffness of torsion spring which mechanically deploys the wings of a UAV is found from the optimization. The flight of a UAV consists of several steps. At first step, the UAV is launched from the tube with folded wings. After launching, UAV is deploying the wings over the period of 0.5 – 1 sec, which depends on the torsion spring stiffness. Due to the wings mass-inertial characteristics, the speed of wings deployment and hence spring stiffness has to be constrained in order to minimize negative influence of the inertia forces on the UAV flight trajectory. This multiphysics problem includes ballistics, flight dynamics, aerodynamics, control system simulation, deployment mechanism stiffness identification and the optimal trajectory determination. This paper is devoted to the approach which allows solving such a complex task with different physical phenomena using the combination of software packages for numerical simulation (LMS Imagine.Lab Amesim, Matlab) and optimization tools (Optimus). The described approach could be extended to different applications in aerospace industry.

1 Introduction

A deployable wing UAVs are becoming more widespread due to their packing capabilities and they find their application in civil and military fields [1]. Despite the simplicity of the deployable wing concept, the developing and modelling of this concept is enough complicated task. At first, there are a lot of opportunities how to realize the deployable wings: with mechanical tools, such as rotational or linear spring, with stepper motor or with usual motor and reducer and others. Detailed review and classification of various deploying mechanism implementations is presented in paper [1]. But this ongoing research doesn't focus on the system modeling or selecting appropriate technology for implementation of the deploying mechanism, but focuses on multiphysical simulation modeling of the already selected concept of a small UAV and mechanism of deploying. A multiphysical simulation for a small UAV in the general includes flight dynamics equations of motion which are well

Figure 1: Concept of launch system and tube deployable small UAV

known for fixed-wing aircraft [2, 3, 4], aerodynamics [4], strength and vibration calculations [5]. This paper presents a solution of a rather non-trivial optimization task: at what time should the UAV open its wings after launch from the tube, since in the initial state of the UAV the wings are folded and the UAV is located inside the pneumatic tube. Together with that some constraints arise because of specific structure of a small UAV.

This article describes stages of solving of presented problem. These stages include modelling of flight dynamics, the approach to consider deployable wings instead of fixed wings, some results of aerodynamics calculations to understand lift and drop coefficients of a UAV in the flight.

2 The design of a tube-deployable UAV

This article considers tube-deployable small UAV which flies out of the pneumatic tube at first stage, then the wings open and finally the UAV flies with fixed wing. The concept of a pneumatic tube and some views of UAV is presented in Figure 1. The deployable mechanism is designed with the rotational pair and the rotational spring unfolds the wings. The cruising speed of a UAV is about 100 km/h. Altitude is up to 200 m. The critical speed of a UAV at which it capable to fly is 54 km/h. At a lower speed, the required lift force will not be achieved. During launch, this required speed is achieved by a pneumatic tube with high pressure inside. But it is not obvious without a preliminary calculation in what time it needs to start open the wings. Also, the spring stiffness directly influences on the wings deployment time, and specific spring and its stiffness must be correctly selected. All these challenges were solved by mathematical modeling and optimization performed in LMS Amesim and Noesis Optimus software.

3 Flight dynamics of a small UAV

It is proposed to consider two stages of a flight: the first stage is only flight out from a tube with subsequent opening of the wings and the second stage is the flight with unfolded wings. Also at the first stage, the problem of determining the wings opening time is solved, depending on the stiffness of the spring. The following assumption is introduced: the dynamics of a UAV flight for the intermediate state are not considered when the wings are opening. This is due to the changing mass-

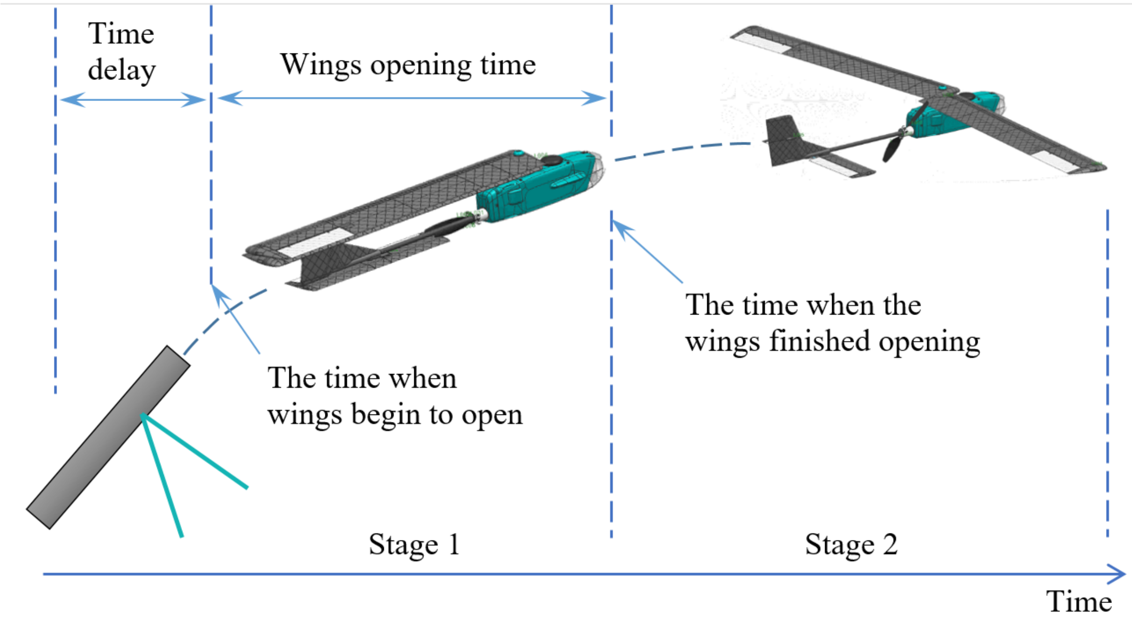

Figure 2: Stages of a flight for mathematical modelling

inertial characteristics in this state. At the second stage, the wings have already fully opened. The outline of a considered problem is presented in Figure 2.
As mentioned above, the mathematical model for flight dynamics of UAV with fixed unfolded wings is fairly well known. The body-axes equation of motion are as follows [2]:
Force equations:

$$\dot{U} = rV - qW - g\cos\theta + (X_A + X_T)/m$$

$$\dot{V} = -rU + pW + g\sin\psi\cos\theta + (Y_A + Y_T)/m$$

$$\dot{W} = qU + pV + g\cos\psi\sin\theta + (Z_A + Z_T)/m$$

Moment equations:

$$J_x\dot{p} - J_{xz}(\dot{r} + pq) + (J_z - J_y)qr = \vec{L}$$

$$J_y\dot{q} + (J_x - J_z)pr + J_{xy}(p^2 + r^2) = M$$

$$J_z\dot{r} + J_{yz}(\dot{p} - qr) + (J_y - J_x) = N$$

Moment equations:

$$\dot{\phi} = p + \tan\theta(q\sin\phi + r\cos\phi)$$

$$\dot{\theta} = p\cos\phi - r\sin\phi$$

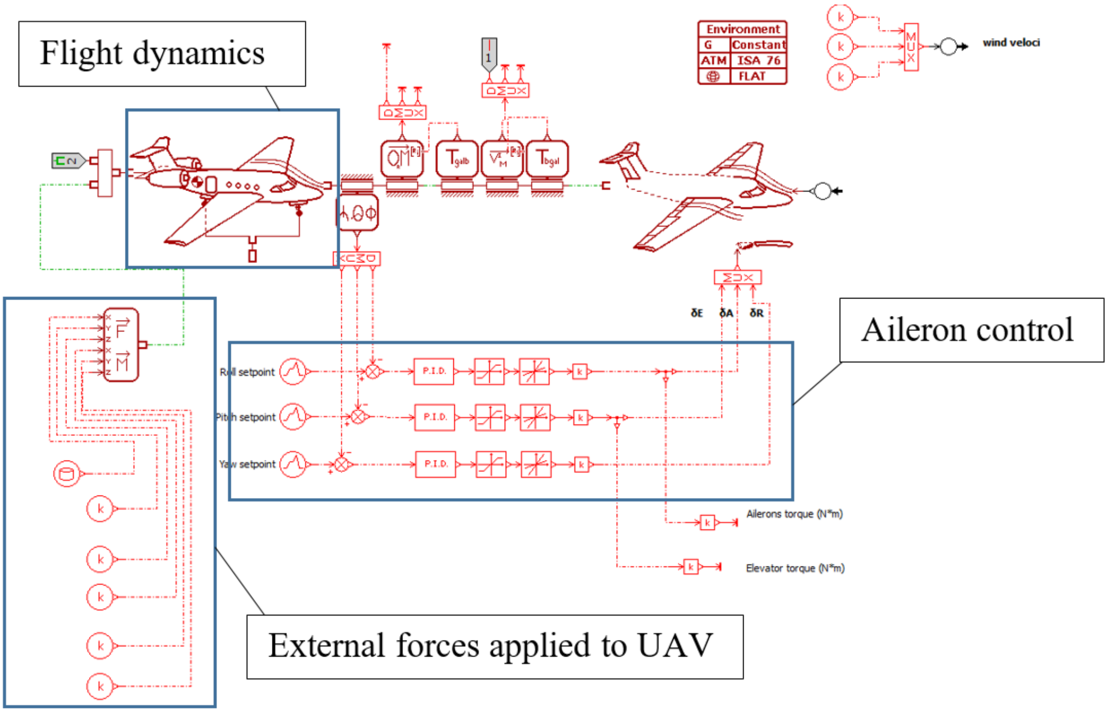

Figure 3: Mathematical model for UAV flight in LMS Amesim

$$\dot{\psi} = (q \sin\phi - r\cos\phi)/\cos\theta$$

Navigation equations:

$$\dot{p}^N = Uc\theta c\psi + V(-c\phi s\psi + s\phi s\theta c\psi) + W(c\phi s\psi + c\phi s\theta c\psi)$$

$$\dot{p}^E = Uc\theta s\psi + V(c\phi c\psi + s\phi s\theta s\psi) + W(-s\phi c\psi + c\phi s\theta s\psi)$$

$$\dot{p}^D = -Us\theta + Vs\phi c\theta + Wc\phi c\theta$$

The definition of each variable in equations is found in Ref. [2].
The equations for two stages was solved in LMS Amesim software [6]. This software includes validated library of components for many engineering applications including flight dynamics library. The circuit visualization of the mathematical model for considered UAV is presented in Figure 3.
The distinctive feature of creating models in LMS Amesim is that engineer do not need to create equations and next to translate them into hundreds of code lines. It decreases number of errors during modelling. There are some initial parameters in each element of a mathematical model. The flight dynamics element contains the most significant initial parameters, such as: mass, components of the inertia matrix, initial speed, altitude, pitch, roll and yaw angles, lift and drag coefficients, wing span, wing area. Since at the first step the wings are folded, the wing span of for analysis is taken about zero: 0.001 m. The wing span and wing area are taken as actual: 1.6 m and 0.24 m2 for the second stage.

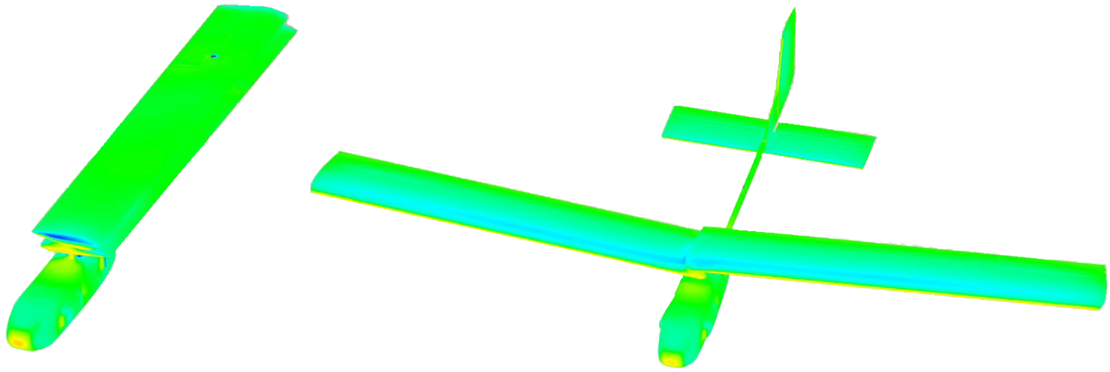

Figure 4: Results of CFD analysis for two stages of a flight. Pressure acting on the UAV

4 Determination of lift and drag coefficients

The lift and drag coefficients were obtained by CFD analysis by means of Ansys CFX. The results of calculations are presented in Figure 4.
Numerical results are summarized in the table 2.

Table 2: Lift and drug coefficients

	Deployed wing	**Folded wing**
C_{yo}	0.18	0
C_y^α	0.0677 1 deg	0.0117 $1/deg$
C_{xo}	0.0575	0.04
C_x^α	0.0031 1 deg	0.002 $1/deg$

Numerical results of CFD analysis were the initial data for flight dynamics calculations.

5 Mathematical model for the wings opening

Mathematical model for time determination of a wing deployment takes into consideration inertia of a wings, wind speed and the UAV speed. The equation of motion for this problem is as follows [7].

$$J\ddot{\varphi} + B\dot{\varphi} + K\varphi = M(t)$$

,
where J is moment of inertia, *ПЗ* is the rotational angle,B is damping coefficient,K is stiffness coefficient, *M(t)* is applied external moment acting on the wings.
External forces, specifically the moments from wind speed and the UAV speed are taken from the flight dynamics calculation. The problem was solved in LMS Amesim software and some results of calculations are presented below. The dependency of

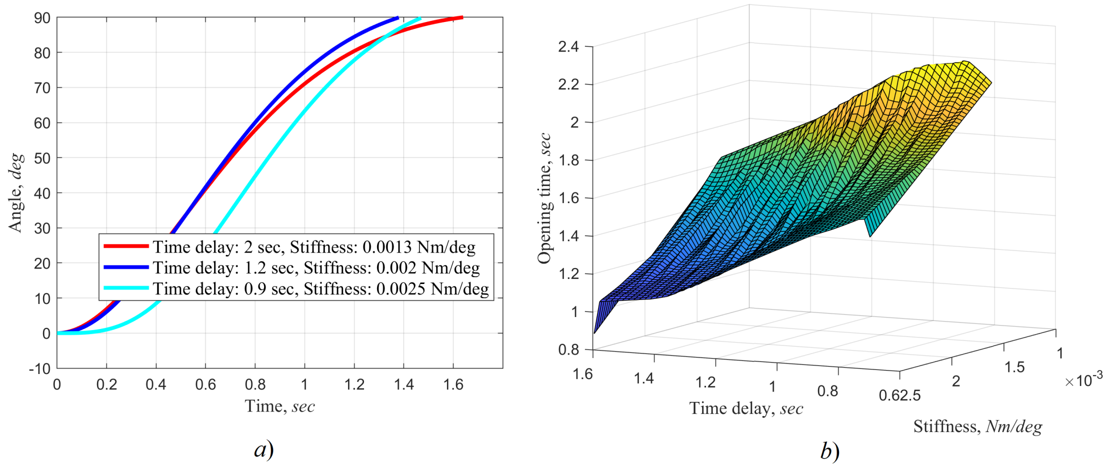

Figure 5: Results of calculations obtained from mathematical model of the wing opening: a) Angle over time; b) Opening time depending on the time delay and stiffness

angle over time is presented in Figure 5a and the opening time of a wing depending on time delay and stiffness is presented in Figure 5b. Time delay is the time when the wings begin to open (Figure 2).

The results of calculations shown in 5 pointed on the nonlinear dependency of opening time from time delay and stiffness. This is explained by the non-constant moment applied to wings. This moment strongly depends on the delay time.

6 Flight dynamic calculation results

In order to clarify the described problem, the flight trajectory of a UAV on the first and on the second stage are presented separately. The trajectories of a flight are presented below in Figure 6.

It is obvious that, the UAV should fall with folded wings at the first stage. But not clearly in what exactly time it should the wings should be deployed and what stiffness of a spring should be chosen to achieve maximum altitude at the second stage. It is proposed to solve these problems by means of optimization.

Important point is to understand limits for the initial parameters when optimization is applied. For the considered problem, there are two initial parameters: the stiffness of a spring and the time delay before starting to deploy the wings. Limits for the rotational spring stiffness are taken from the required dimensions and 3D calculations of a spring: 0.001–0.0025 Nm/deg. The low limit for the delay time is determined by physical restriction: the UAV cannot deploy the wing inside the tube, therefore the low limit is the time when UAV already has flown out from the tube (Figure 2). The value for that time was calculated for the tube length 2 m and is 0.1 s. The upper bound is determined by the time when the altitude of a UAV becomes less than zero (Figure 6) and this time is equal 5 s.

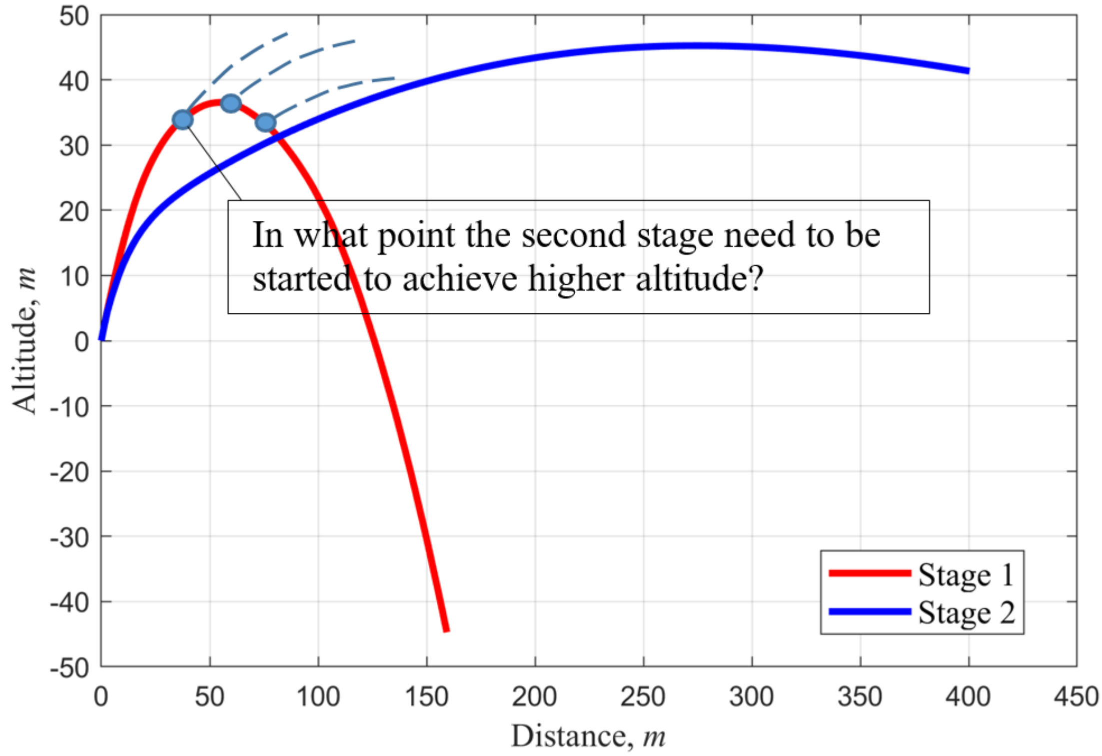

Figure 6: Trajectories of stage 1 and 2 separately

7 Statement of the optimization problem

Considering all the above, optimization problem is proposed as follows: to find the best combination of time delay and stiffness of a rotational spring which will lead to the maximum of altitude at the end of stage 2. To solve this problem, the calculation chain was created which involved three mathematical models: time opening and two stages of a flight dynamics. The calculation chain was created in Noesis Optimus Software and the outline of this chain is presented in Figure 7.

The results of the optimization problem are presented as a set of figures and also the specific recommendations on the choice for stiffness of a spring and the delay time. The goal altitude, which is at the end time of stage 2 depending on the stiffness at the specific time delay and depending on time delay at the specific stiffness are presented in Figure 8 a) and b).

The results presented in Figure 8 show dependencies which describe the optimal solution slices. The results summarize the multiphysics simulations and allow to obtain the best combination of initial parameters to achieve higher altitude. For example, one could choose time delay about 0.4 sec and achieve 70 m altitude with stiffness of a spring about 0.0015 Nm/deg.

The important result is nonlinear dependency between altitude and time delay (Figure 8b). From there it's shown that there is specific time delay from 0.8 up to 1.2 s which leads to low altitude almost with all values of stiffness. In this case, the optimization results did not lead to a specific optimal pair of the values but the range of poor initial points which leads to low altitude was calculated.

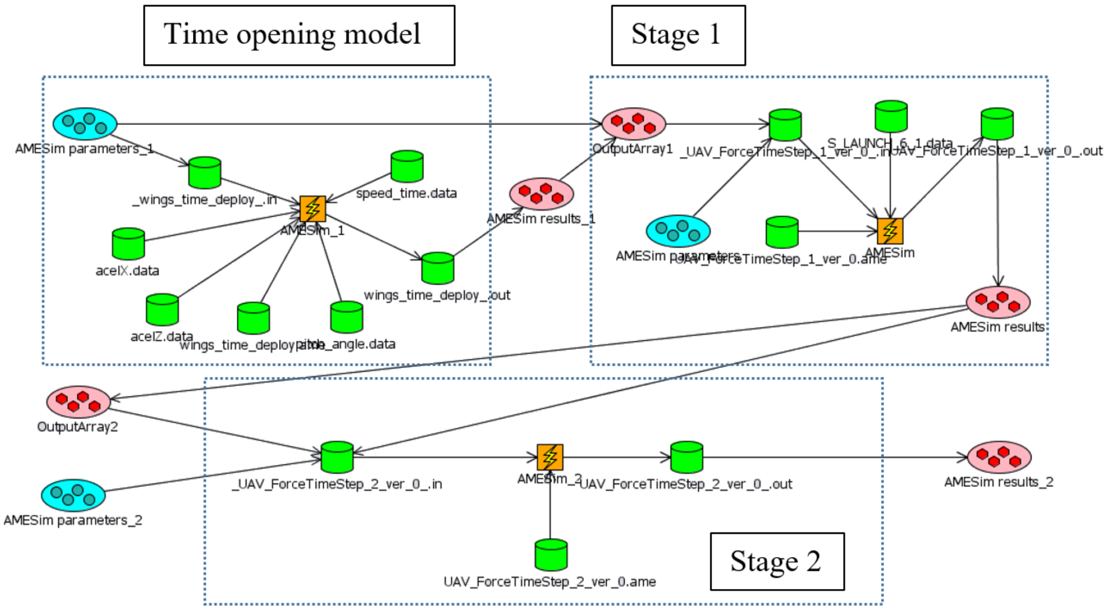

Figure 7: Outline of the calculation chain

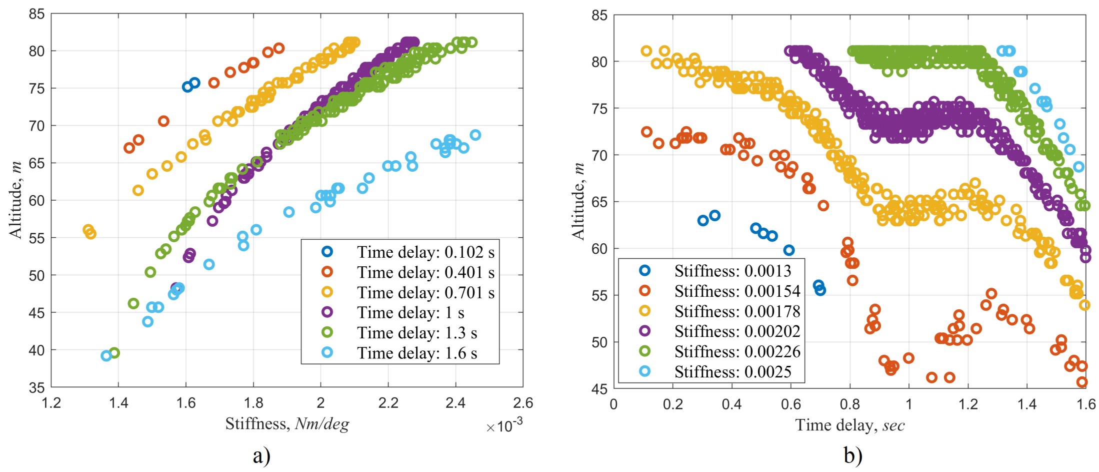

Figure 8: Results of optimization: a) Altitude depending on stiffness changing, b) Altitude depending on time delay changing

Although UAV considered in this paper is not the industrial case but this approach of multiphysics simulations and optimization can be extended to the real product development.

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