VIRTUALIZING THE FLEXIBLE HOSE DESIGN PROCESS

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1. Abstract

Since several years, designers need more and more advanced technologies in order to realize the best possible design at a very early stage. Particularly, rigid and flexible hoses have to be correctly designed in order to avoid failures and vehicles call backs. They ensure different functions : fuel and coolant pipes (preformed pipes, submitted to temperature, wide sections), flexible brake pipes (great length, high flexibility and transient internal pressure), parking brake lines (aka Bowden cables), gearbox and throttle pipes (embedding cables), ...

These flexible pipes are submitted to various loadings: pressure, temperature, dynamic excitations. Moreover, each of them has specific characteristics : some of them are very flexible, other ones are preformed, and others may be interconnected (using clips or/and octopus). Independently of their use, these pipes interact with the external environment since they are attached (either by their ends, called connectors, or along their length through supports) at several points : some of these pipes being located close to other components, the designers must avoid any contact during typical maneuvers. In other circumstances, sliding contact may be authorized and must be taken into account. Furthermore, pipes may also vibrate due to their natural eigenfrequencies or due to an external solicitation. [1]

This paper describes how optimization techniques may be used to switch from real physical prototypes (time and money consuming) to virtual prototypes. Optimization is used here for two main purposes allowing the reduction of design time and reaching the right design at the first time. Classical problems that occur in pipes design are related to the positioning of the links between the pipe and the chassis. Interesting Parameters are : position and orientation of the connectors and supports, length, diameter and thickness of the pipe. Objective functions usually encountered are : maximization of the distance to obstacles, reducing torsion and bending, minimizing reactions forces. These objectives may also be seen as constraints to the optimization

problem. Optimization engines described have been widely used in the early design of the Airbus A350 XWB.

Another innovative usage of optimization in flexible hoses design is the material identification. Actually, pipe design has, historically, been based on experimental measurements and led to long iterations between designers and analysts due to the lack of accurate numerical models. In order to have a full numerical model, one must find accurate material parameters able to reproduce the real movements. An identification procedure has been used since several years based on an optical measurement system and an external optimization solver. Now this solver is embedded in the dedicated tool ; it allows the designer to find the best material parameters based on a set of measured points and a numerical model of the hose. Another step in this identification has been realized by combining the previous measurements with more classical bending and torsional tests. Here optimization parameters are: Young and Shear modulus for a homogenized isotropic material, individual thickness and stiffness of multi-layer material. Objective function is the distance between the numerical results and the measurements. A new field of investigation will be the dynamic behavior characterization of hoses. This implies vibration tests and will add the natural frequencies, modal shapes (MAC matrix) and even Frequency Response Functions as objective functions. Thanks to this combination of tests, accurate numerical models may be used early in the design phase.

2. **Keywords :** flexible hose, non-linear, optimization, material identification, pipe

3. What is virtual prototyping ?

Pipe design, especially brake hose, has been conducted, in the past, starting from an initial design based on previous car configurations and following the feelings of the designers. After this first phase, a physical prototype was used on a test rig (when it was available, quite later in the car development phase). Unfortunately, this often led to a re-design of the pipe as complete information about the surrounding environment of the pipe was not taken into account during the first design phase.

Now and since several years, car manufacturers have introduced numerical simulation in their design loop. This simulation phase occurs after the first design and, thus allows to detect earlier eventual problems related to clearances, torsion, bending. Nevertheless, later phases are still time consuming as some particularities are not yet taken into account since the very beginning.

Future hose design workflow will reduce dramatically the go-to-market time as numerical simulation is used from the beginning with advanced analyses : quasi-static simulation including large displacements and rotations, normal mode shapes, harmonic response to vibrations and optimization. As shown in *Figure 1*, the proposed design process starts from

- finding the orientation of the hose's connectors and intermediate fixing/passing points in order to provide valid specifications to the pipe manufacturer
- computing mounting configuration and successive positions due to maneuvers in order to avoid too much bending and to respect clearances
- Checking the natural eigenfrequencies of the system and looking at harmonic response due to given excitations (road, engine vibrations). This phase gives an idea of the stress increase due to these vibrations.
- Exploring the design space to find a better solution : maximizing the clearance, reducing the length, avoiding too much bending.

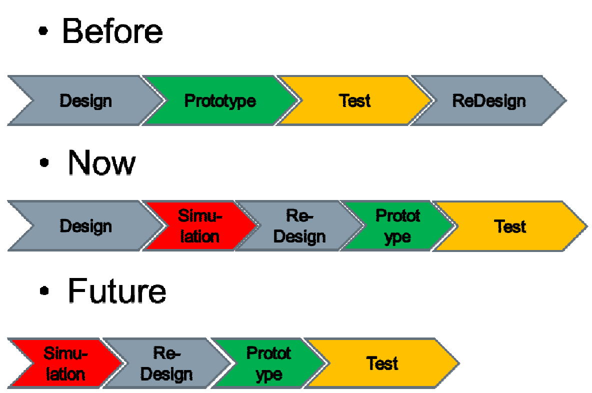


Figure 1: Hose design workflow evolution

Thanks to these early numerical simulations, taking into account all the physics of the pipe, its load cases and its environment, the full design process time is reduced and then leads to better productivity. This saved time allows the user to explore and focus on innovative solutions.

4. Typical hose design : methodology proposed

In this paper, we will focus on brake cable design ; the same methodology (at least some steps) may also be applied to other hoses/cables/pipes encountered in any vehicle. *Figure 2* describes the whole process.

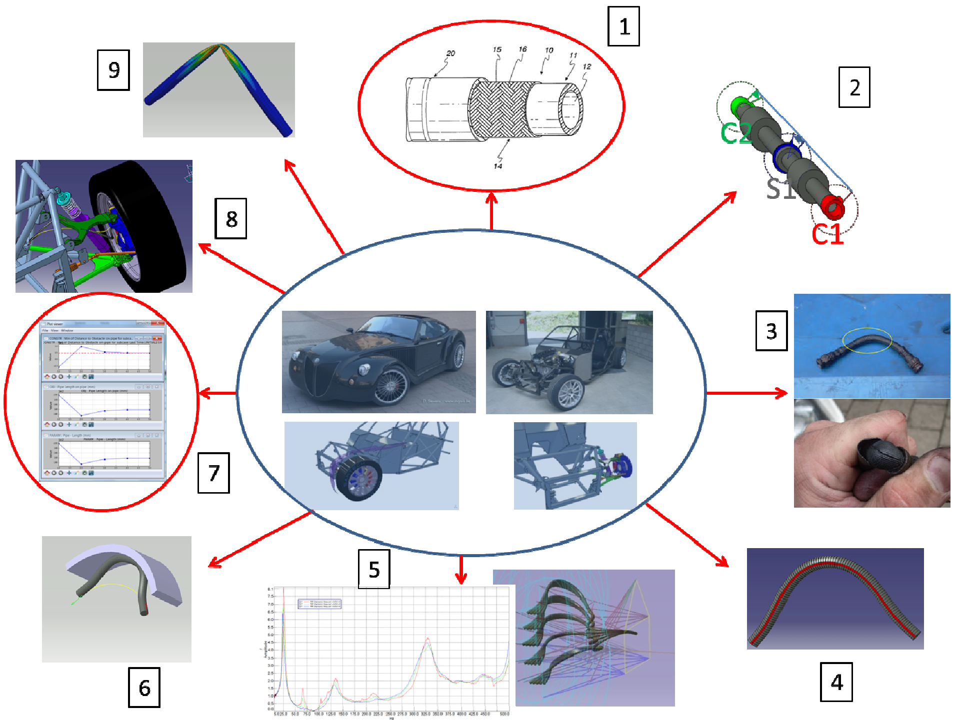


Figure 2: Hose design methodology

7.1. Material identification

Switching from a physical prototype to a full virtual prototype means that input data must be as accurate as possible. One of the major difficulties in pipe design is to find a suitable material for approaching real "composite" structure made of rubbers' and reinforcement layers.

In order to simplify this identification task, LMS Samtech Tea Pipe provides a fully integrated procedure allowing the user to find an equivalent material by mastering the accuracy. This is realized thanks to a choice in the FE hypothesis (Beam or Shell) and in the material type : mono/multi-layer, isotropic, orthotropic, …

This procedure is fully described with a real example in the next chapter (Application Case : material identification).

7.2. Free torsion computation

In some applications, torsion in brake hoses is forbidden. Actually, the maximum limit is 5°/m. Above this limit, the external layer of the pipe (twisted fiber mesh) being sized in order to resist to very high pressures, could completely fail. More generally, torsion implies a higher risk of failure due to fatigue.

To overcome this problem, a specific analysis type is proposed ; it consists in a classical non-linear quasi-static computation where hinges are added at each connection points (supports and connectors). This allows recording the relative torsion that would occur with the provided/initial guess of connection's orientations. Looking at the result, the user may then adapt its design in order to provide precise specifications to the pipe manufacturer.

Torsion effects on the final position and behavior of the pipe may also be studied by using the integrated optimization engine.

7.3. Mastering bending

One of the potential failures of a brake hose comes from fatigue and too much bending. Length of the flexible is driven by several constraints : it must be long enough to be sure that all movements are doable but not too long to avoid bending and collisions with external surfaces. A compromise must then be found, keeping in mind that, a flexible that's bent most of its usage time (wheels straight and bumpers high) will have its physical properties changed ; actually, stresses due to the bending will disappear along the hoses life and will change its positioning during the kinematic moves. This will also affect the dynamic behavior (mode shapes and frequencies).

7.4. Mounting strategy assessment

Cars should be assembled by following always the same steps, in the same order and with the same precision. Unfortunately, as brake hoses are quite flexible, a little change in the orientation during the physical mounting on the chassis could lead to a completely different positioning. In order to master this physical mounting, it's mandatory to simulate the intermediate steps required. On one hand, it allows the car manufacturer to describe clearly the mounting procedure (reproducibility) but it also allows to explore other mounting strategies and to be confident in the sensitivity of the mounting procedure.

In this scope, mounting history is divided in simple movements : position in space, orientation and finally torsion. Amongst these simple steps, others are also available such as pressure, acceleration, temperature, initial curvature, …

7.5. Mode shape and Harmonic response

Once the mounting position (and those relative to the kinematic moves) has been found using a quasi-static simulation (taken, eventually, into account body forces), it's recommended to switch to more advanced analysis type. Actually, the dynamic behavior of the vehicle may have an important impact on the positioning of the brake hoses. We may distinguish two types of dynamic analyses :

- Linear Harmonic response [2,3] : this is often used in order to find the natural mode shapes of the hose mounted on the chassis. Engine, bumpy roads, loose fittings may lead to vibrations at some frequencies and it's important to understand if the eigenmodes are excited or not. First effect on the hose is a change in the position at resonance frequencies (that may lead to collision with surfaces far enough for a simple quasi-static computation). Second and important effect is an overstress when compared to the stresses coming from the mounting and the kinematic movements. This analysis is conducted in the Frequency domain.

- Non-linear transient response [2] : a simple quasi static computation doesn't take into account inertia and damping effects. These may become important when fast moves are used as boundary conditions and, when the flexibility and the weight of the brake hose are important. This kind of analysis should be always realized in order to verify the quasi-static hypothesis. Again, advanced non-linear analysis may lead to overstresses and bigger displacement in the encumbered area of the engine compartment. This analysis is conducted in the time domain.

7.6. Taking into account sliding surfaces

In very small cars or in vehicles that require long hoses, it's sometimes impossible to avoid contact with the external surfaces. In this case, pipes are surrounded by metallic spirals to avoid direct contact between the rubber and hot parts. Now that the hose is protected, simulation takes into account the external surfaces during the mounting phase and after the kinematic moves. This functionality is mandatory because it's almost impossible to "guess" the final position on the pipe ; good practices and engineer's feeling are not enough to find the real position when sliding contact occurs.

7.7. Parametric design and optimization

Reducing the time to market for a car design is still bettered by running several analyses (static and/or dynamic) to explore the design space. In this scope, parameters are chosen for the model : these are variables that may be changed within a range like the length, the position/orientation of the connectors and supports, the number of supports, … Typical results are then plotted, stored and compared in terms of design constraints : curvature, torsion, clearance, …

Depending on the number of variables, analyses launch and result exploitation may become cumbersome ; that's where automatic dimensioning helps a lot. In Tea Pipe, we use the following definition of optimization:

- Choosing the design variables (length, connector position/orientation, ..)
- Minimizing/Maximizing one or more result (length, curvature, distance to object, ..)
- Under several constraints (minimal distance, maximum curvature)

Before launching an **optimization**, one would want to explore the design space. Doing this is called a **parametric study** where parameters are changed step by step and results are only monitored.

The **optimization** and the **parametric study** need the same kind of data and run the same kind of process, the differences being that the evolution of the parameters is determined by the program in the first case, in order to improve the solution, whilst it is imposed from the beginning in the second case, in order to explore the range defined by the user.

- Parametric Study (**Table 1**)

  Analyses are launched sequentially.

  The number of analyses is cumulative ; this means that all parameters' variations are combined.

  For example, if the user has selected three parameters with 3, 5 and 6 steps, 3*5*6 = 90 analyses will be launched !

Parameters	Functions
For each listed parameter, the user must also define the number of steps The step defines the number of values taken by the variable for the whole analysis (thus, including the two bounds, starting from the lower one to the higher one). Initial value is ignored.	The selection of result functions is not necessary but it is sufficient to activate the function. The other data are not relevant because the scope of a parametric study is to monitor change in results following a predefined path in the design space

Table 1: Parametric study

- Optimization (**Table 2**)

Target value is used as limit for constraints and as weight factor for objective functions.

Each iteration needs (n_V+1) computation if n_V is the number of design variables : computation for the set of values + n_V computations for the "sensitivities" (derivatives).

Parameters
For each listed parameter, the user must define the minimal, initial and maximal values. The number of steps is ignored. Minimal and maximal values (also known as bounds) define the limits within the variables may vary (depending on what will give the optimization solver), Initial value is used as starting point for the optimization process.

Functions

The selection of result functions is necessary. All columns must be defined.

Type	Meaning
<	Constraint function: the function must remain smaller than a bound
>	Constraint function: the function must remain larger than a bound
Min	Target function: the function should be as small as possible
Max	Target function: the function should be as large as possible

Table 2: Optimization

- Optimization principle [4,5] :

An optimization solver is dedicated to explore the design space (defined by the hyper-space bounded by variables limits). In order to explore efficiently this space, the solver evaluates, at each step, the implied functions (and constraints) by mixing them with a given weight.

As functions are not simple (resulting from a complete FE analysis), they have to be simplified. That's what determines the solver type ;

CON(vex)LIN(earization), S(equential)Q(uadratic)P(rogramming), M(ethod of)M(oving)A(symptots) and finally G(lobally)C(onvergent)M(ethod).

GCM represents the best compromise in terms of convergence, problem size, CPU time and good balance between opposite requirements. Its main characteristic is that it will, first, try to respect constraints before dealing with objective minimization (or maximization). It's currently used for Composite Boxes of the new AIRBUS A350 !

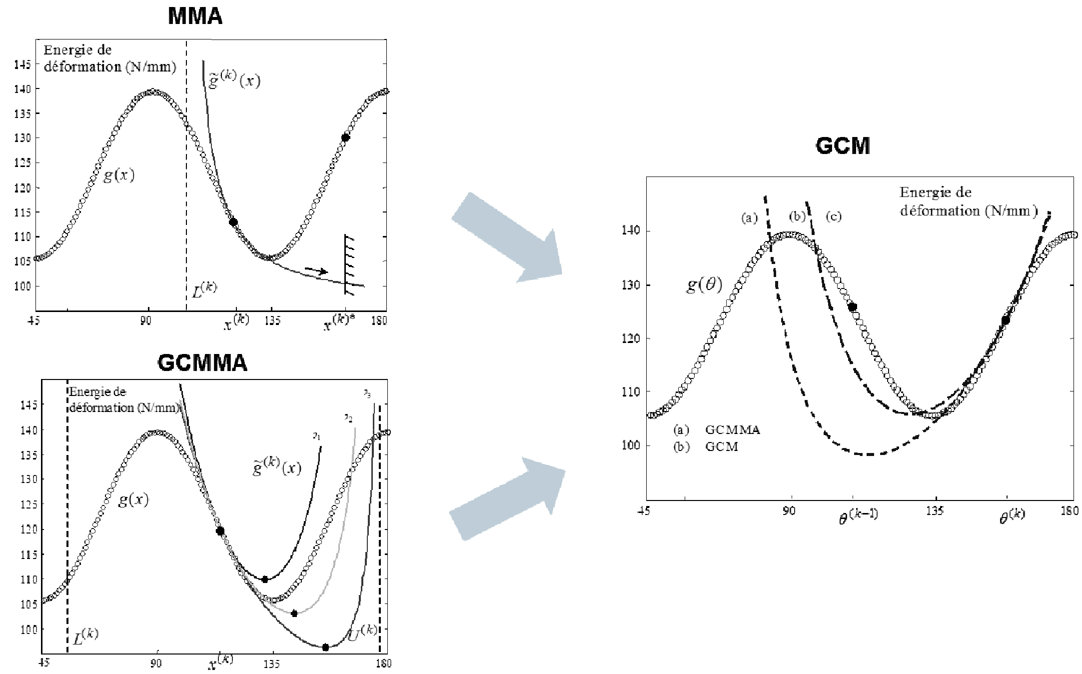


Figure 3: Optimization solver approximation

Figure 3 shows a comparison of different approximations used to solve a series of simplified models. Equations are available in [5].

- MMA : monotonous approximation
- GCMMA : non monotonous approximation
- Both have asymptotes : defined with Upper and lower bounds for GCMMA, U or L for MMA
- In GCMMA, approximation and asymptotes are updated heuristically and based on the first derivative.
- GCM combines both approaches (MMA and GCMMA) and may then switch between behaviors : monotonous, non-monotonous and linear based on the derivative of the current step and the previous one.

7.8. Complete CAD model integration and verification

Once the pipe design is finalized, CAD results are created and included in the full vehicle CAD model. This step is important as it closes the loop of the virtual prototype. During this phase, final verifications are made such as clearance with external parts. As principal results are native CAD shapes, these will be re-used during all the car conception phase.

7.9. Verifying modeling option : detecting crushing

A final phenomenon has to be checked before going further in the pipe design workflow. Depending on the material data, on the pipe geometry (length, diameter, thickness) and on the imposed boundary conditions, hoses may not behave like a simple beam. Actually, the cross-section may vary (ovalization) and even crushing may appear. LMS Tea Pipe has two modeling options (beam and shell) that allow the user to test this behavior ; it's made easy as a simple button click is enough to switch from one hypothesis to the other. Shell modeling also allows taking into account more details in the results (uneven distribution of the stresses around the section).

8. Application Case : material identification

As already mentioned, switching to a fully virtual prototype imposes to have accurate input data. One of these is the material that will be used to model the hoses. It could be homogeneous or heterogeneous (reinforcements, bundles of aluminum and rubber pipes).

Figure 4 describes the brake hose to be studied. Connector 1 has all its degrees of freedom fixed. Connector 2 is also fixed but torsion is varied between -30° (green pipe), 0° (blue pipe) and +30° (white pipe). The three tubes represent the same one with different angular fitting.

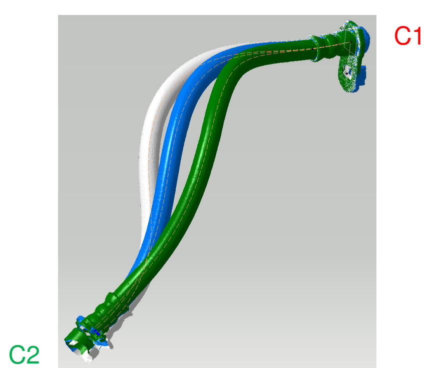


Figure 4: Torsion test for material identification

A specific experimental setup has been developed in order to measure the real hose in these configurations (*Figure 5*). It's composed of a rotating device to hold the pipe and 3 cameras. External surface of the measured pipe is imported in the CAD system as a cloud of points.

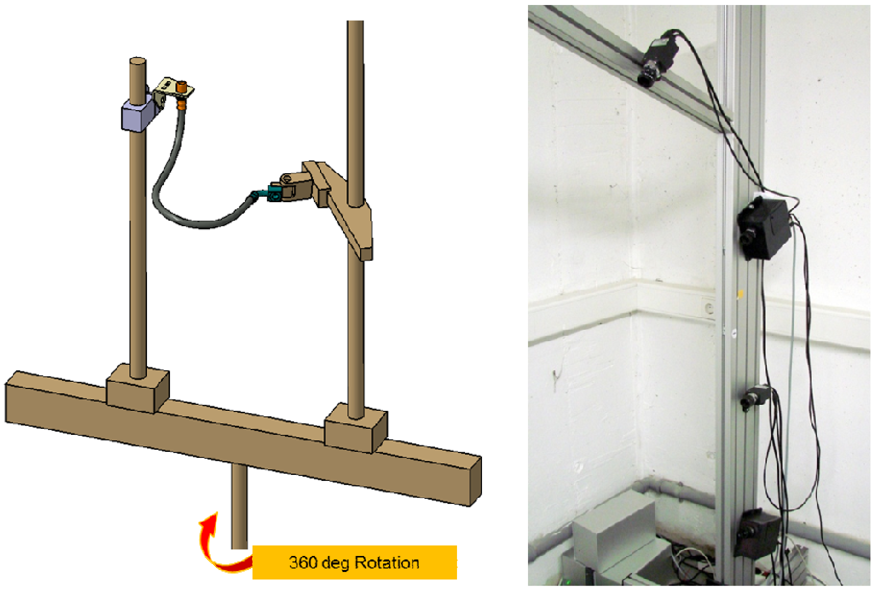
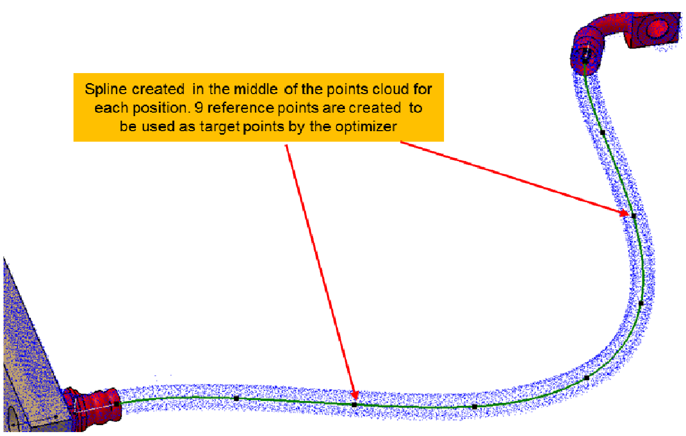


Figure 5: Experimental setup for material identification

From this cloud, the center line is extracted and 3D positions in space are recorded for some interesting points on the pipe. Generally, 5 to 12 points along the length are sufficient to capture all the potential configurations encountered in the automotive market.



Input file content for the material optimizer. Each point is listed according to its position on the spline and his coordinate in space

pos(%)	X(mm)	Y(mm)	Z(mm)
0	185.1678	60.2	518.4986
12.5	187.4151	42.58753	467.7136
25	195.7992	8.896136	425.8234
37.5	211.1933	-28.0457	388.9367
50	243.1297	-54.812	354.6713
62.5	293.4691	-61.6036	337.8697
75	346.4264	-50.5791	342.1459
87.5	395.1208	-28.7657	352.9643
100	434.8531	7.003637	359.8841

Figure 6: 3D positions to be compared for material identification

The simulation pipe is then defined by respecting the connectors' positions and orientation. An initial isotropic guess material is chosen according to classical values encountered in rubber brake hoses.

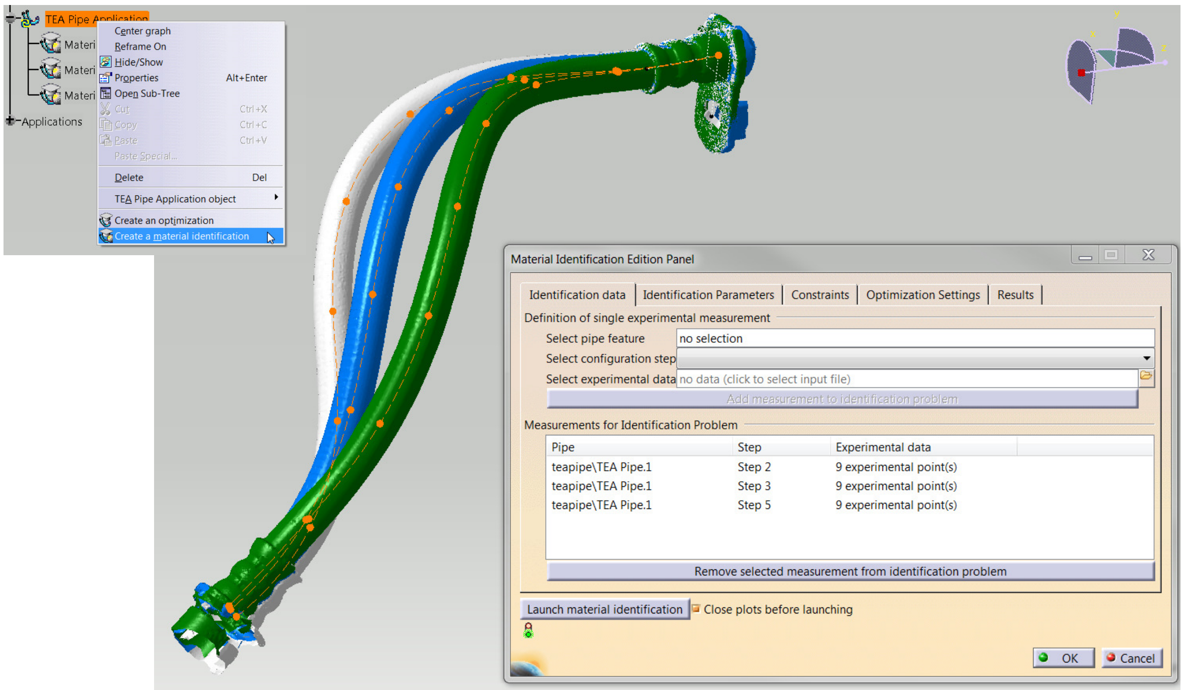


Figure 7: Defining the material identification problem

The material identification procedure is based on the comparison between the measured points and their equivalent on the numerical model. The goal is to minimize the distance between those. The GUI has been thought to be as simple as possible. Actually, the procedure is based on optimization and is quite complex for simple designers (that, sometimes, don't even know about Finite Elements methods).

When the numerical pipe and the measurements files have been defined, all other tabs are automatically completed :

- material parameters coming from the chosen hypothesis : Young Modulus and Poisson ratio (initial value and lower and upper bounds)
- objective functions and constraints : minimization of distances for all configurations and all points. A best practice is to find a solution with maximum 1 diameter of error in positioning.

After several steps of optimization, final parameters are found and the goal is reached as all distances are less than 3 mm knowing that the pipe's diameter was 9.6 mm.

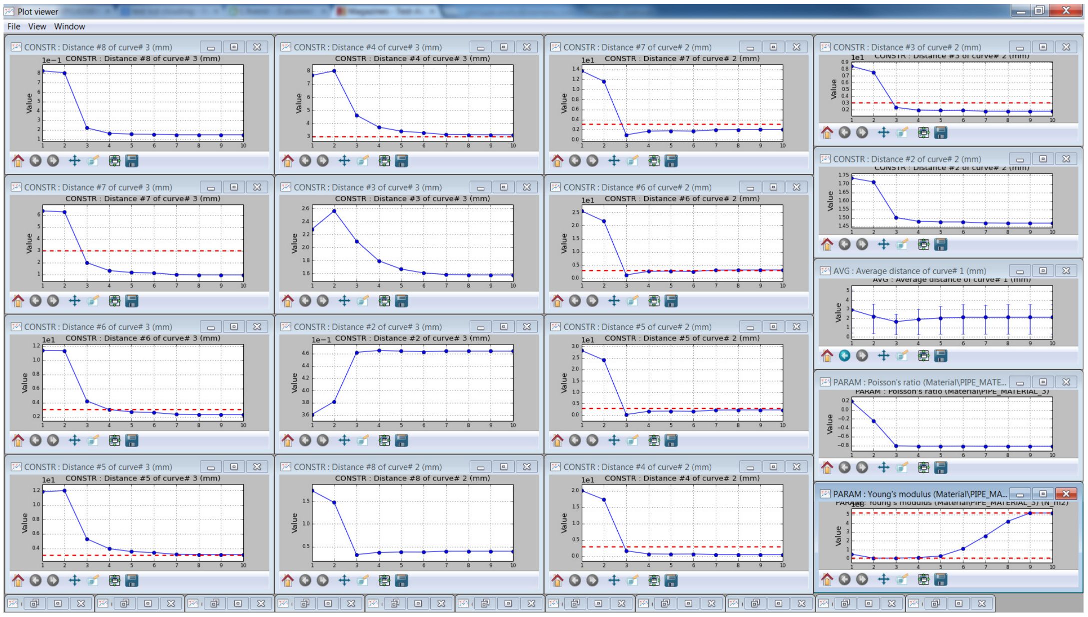


Figure 8: Optimization evolution and final results

9. Conclusions

This paper describes how a typical hose design process may be fully virtualized. This is achieved by following several steps that ensure the user that his prototype will respect all the constraints of the final real vehicle.

This innovative virtual methodology has the following characteristics :

- GUI must stay simple as it will be used at different level of expertise. Finite Element and optimization knowledge mustn't be a limit (and this is not) for applying the methodology.
- Advanced Finite Element Analyses are made available in order to reach a high accuracy needed in such pre-design phase. Simple geometric solution is not enough to model the complexity of very large displacements and rotations.

- Finite Element hypothesis choice (beam or shell) is important to detect and prevent crushing or ovalization phenomena when needed by keeping a fast running process.

- Optimization techniques are used in order to reduce the time spent to explore alternative configurations and to respect behavior constraints.

- Optimization is also used to provide a simple to use procedure for material identification. This methodology also allows comparing several numerical models (evaluation on the effect of material orthotropy, arrangement of layers in composite, FE hypothesis effect).

- Further works on identifying the dynamic characteristics of equivalent pipes will be conducted to further improve the process (frequency and temperature dependence of the material, damping).

10. References

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