

# Nonlinear Finite Element Method Solver for Design of Automotive Cable Layout

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## ABSTRACT

A new nonlinear finite element method solver has been developed for use in a simulation tool for the design of automotive cable layouts. The solver uses a hybrid method combining static implicit and static explicit methods. The use of this method has made it possible to complete calculations for models for which calculations did not converge on a solution using conventional iterative methods. A method of modeling the stiffness of the clamp-end of a cable was also developed in order to increase the accuracy of analyses. The formulation of modeling templates for different types of clamp has made it possible for designers to conduct accurate cable layout designs in short periods using simple operations. The developed hybrid method and library are in use as cable analysis tools in Honda research and development centers in Japan and overseas.

## 1. Introduction

Automobiles employ a large number of cables, including brake hoses, heater hoses, and parking wires. Figure 1 shows an example of a brake hose. The hose undergoes considerable bending and twisting in order to wind it into the gaps between surrounding parts. Automotive suspensions have an up-down stroke, and the steering system is also in the vicinity of the brake hose. From its initial layout, in addition to twisting, the brake hose is given a large bend in order to respond to the movement of the suspension. Because the movement of these cables follow the movements of surrounding parts and the cables undergo oscillation, it is necessary to employ layouts in which there is no interference between the cables and the surrounding parts.

Because during the initial stage of development it is highly possible that the positions or shapes of surrounding parts may be changed, it is necessary to conduct repeated studies of the cable layout during the layout design process at this stage in order to respond to these changes. Cable layout design has therefore conventionally employed simulations in order to make it possible to study layouts in a short period of time.

Figure 2 shows an overview of an in-house cable layout design tool. The designer sets the shape of the cable in the tool, and indicates the material and the types and positions of the clamps employed. The tool automatically generates a model using the nonlinear finite element method ("nonlinear FEM" below) employing beam elements. The tool displays the results calculated by the solver, making it possible for

the designer to study factors including deformation of the cable shape and the section force on the beam elements.

In the conventional cable layout design tool, nonlinear equations are solved using an implicit method via an iterative procedure, based on an FEM model taking geometrical nonlinearity and material nonlinearity<sup>(1)</sup> into consideration. For pure bending as the dominant deformation, it has been possible to predict the nature of deformation in actual cables even when they undergo considerable bending. However, when the cables are bent while undergoing a high level of twisting, the failure of the iterative calculations to converge on a solution results in the procedure being suspended without a conclusion, and it is not possible to study the

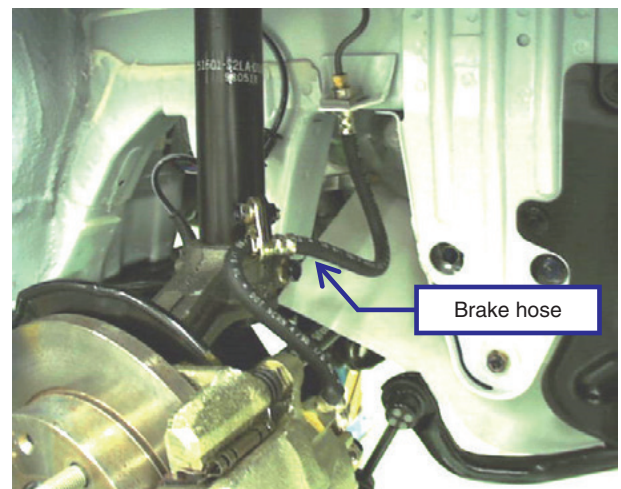


Fig. 1 Brake hose

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cable layout. It is thought that in the domain in which the iterative calculations do not converge on a solution, the state of deformation undergoes large changes in response to miniscule external input, making it unstable as a physical system. This phenomenon could be calculated using an explicit method, but in order to realize numerical stability, it would be necessary to set low load increments, resulting in a considerable increase in calculation time. It would be desirable to accurately solve nonlinear phenomena of this type in a short period. Up to the present, the cable layout design tool has employed commercial solvers, but none have been satisfactory from the perspective of accurately outputting solutions for the phenomenon of twisting of a cable as it is bent within a short period.

In addition to convergence on solutions, the calculations have also presented issues of accuracy. Figure 3 shows a situation in which a clamp and a hose are connected, and there is local bending of the hose in the area of the connection. Because the conventional cable layout design tool is not able to generate a physical model of this phenomenon, its analytic and predictive accuracy has been

inadequate, resulting in issues in terms of the accurate design of cable layouts. It was therefore necessary to newly develop a method of modeling the phenomenon of local bending of the cable, and thus increase accuracy against the conventional method.

Incorporating the stiffness of the clamp in the model would necessitate specialist knowledge of FEM modeling methods and solvers, making it challenging for designers to create the necessary FEM models in a short period. Automation would therefore be desirable in order to help enable the design of cable layouts in a short period.

## 2. Development Aims

The following four main aims were set for the research discussed in this paper:

- (1) Accurate calculation of solutions while maintaining ability of calculations to converge;
- (2) Calculation speed equivalent to that of the conventional method;
- (3) Calculations incorporating the stiffness of the connection with the clamp; and
- (4) Equivalent level of simplicity of operation as conventional method even when designers possess no specialized knowledge in relation to solvers.

The developed solver and method of modeling the stiffness of the connection with the clamp will be discussed below.

## 3. Hybrid Solution

### 3.1. Concept

Conventionally, static implicit methods<sup>(2)</sup> have been the main methods applied to the solution of nonlinear equations that numerically model static nonlinear phenomena. Static implicit methods commence from the predicted value of the solution for the equilibrium of forces at the time a specific load is applied, and seek the solution by correcting the predicted value using iterative methods such as the Newton-Raphson method. During the repeated iterations, geometrical nonlinearity and material nonlinearity are considered<sup>(3), (4)</sup>. This method is able to accurately determine physical quantities at the time a set load is applied, and because it is a completely stable time integration method, it is also possible to use large load increments<sup>(3), (4)</sup>. The method is also able to complete calculations in a shorter period than other methods, assuming that there is no issue in terms of convergence on a solution.

However, there are occasions on which iterative calculations do not converge on a solution due to nonlinearity. An example is presented below. Figure 4(a) shows a conceptual diagram of buckling, during which the solution curve features inflection points. Because the gradient of the tangent line changes rapidly in the vicinity of these inflection points, it is challenging to determine solutions to nonlinear equations using an iterative method.

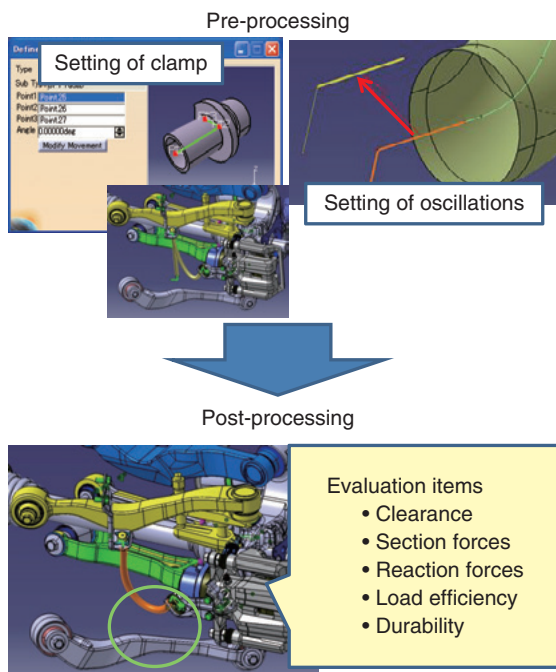


Fig. 2 In-house tool for cable layout design

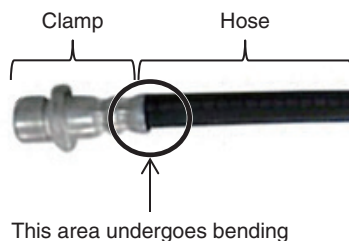


Fig. 3 Connection between clamp and hose

Figure 4(b) shows a conceptual diagram of the bifurcation of a solution. Because the solution for the nonlinear equation is non-unique, the solution bifurcates. For example, Points a and b in Fig. 4(b) are both on the solution curve, but while the input loads differ, they each have the same displacement. Real-world examples include cases in which a hose that has been routed settles into different states of deformation with the application of a miniscule load, and cases in which the solution mode varies rapidly, for example a thin-plate snap-through.

As this indicates, when seeking numerical solutions for strongly nonlinear phenomena, there are cases in which, when using static implicit methods, the calculations will not converge on a solution, and it will not be possible to continue the calculations. A method by means of which calculations could be conducted stably up to their conclusion was therefore desirable. Static explicit methods<sup>(5)</sup>, in which solutions were successively determined while seeking equilibrium, irrespective of iterations, represented methods of this type.

Static explicit methods are methods that do not repeat iterations, but determine the value of increments, such as increases in the strain in elements or the degree of rotation of nodal points, within an allowable range. These methods make it possible to stably complete the calculation process and determine a solution, but because it is not possible to use large load increments in order to help ensure numerical stability, calculation time increases against implicit methods. Given this, it was necessary to find a means of minimizing the amount of use of static explicit methods within the entire calculation process.

A hybrid solution method was therefore proposed. Combining the advantages of the implicit and explicit methods, this hybrid method would use an implicit method in the domain within which an implicit method could generate a solution, and use an explicit method in the domain within which an implicit method could not generate a solution.

Figure 5 shows a flow chart of this hybrid method. First, solutions are sought using a static implicit method. Following this, if it is judged that the phenomenon displays strong nonlinearity and it will not be possible to find a

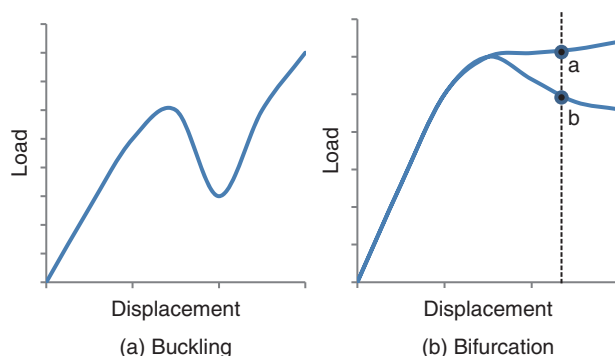


Fig. 4 Typical nonlinear phenomena

solution using an iterative method (Condition A), the method switches to a static explicit method and continues to seek a solution. The method continues to seek a solution using a static explicit method, but if it is judged that the nonlinearity of the phenomenon has become weak and it is possible to once again seek a solution using an implicit method (Condition B), the static implicit method is returned to, and the method continues to seek a solution. This alternation continues until the calculation is concluded.

### 3.2. Switching from Static Implicit Method to Static Explicit Method

When it is judged that the calculation will not converge on a solution when a static implicit method is used (Condition A), the method switches to a static explicit method. The method of switching is as follows: First, when the calculation does not converge on a solution after a predetermined number of iterations, the time increments (load increments) are reduced (this is termed “cutback”), and the predetermined number of iterations is again conducted in order to have the calculations converge on a value. When cutback is repeated and the operation is performed for the set number of times without convergence on a value, it is judged that a solution cannot be found using a static implicit method, and the tool switches to a static explicit method.

### 3.3. Switching from Static Explicit Method to Static Implicit Method

It would be possible to continue using the static explicit method until the calculations reach their conclusion, but when it is possible to employ the static implicit method (Condition B), the tool switches to this method in order

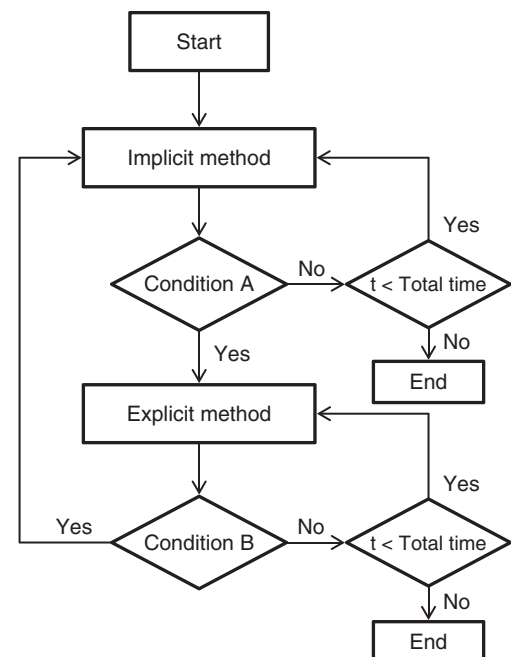


Fig. 5 Flowchart of hybrid method

to reduce calculation time. It was necessary to attempt to ensure that, having switched to the static implicit method in such a case, the tool did not immediately switch back to the static explicit method when the iterative method failed to produce a convergence in the calculations. It was therefore essential to avoid areas of strong nonlinearity, for example when buckling occurs, when switching from the static explicit to the static implicit methods.

It is known that when using a static explicit method, residual error generally increases when nonlinearity increases<sup>(5)</sup>. The developed tool therefore switches to the static implicit method when residual error is lower than a specific value.

The following two characteristics can be ascribed to buckling and the bifurcation of solutions as standard examples of the failure to achieve convergence on a solution<sup>(3), (6)</sup>:

- (1) At the point of buckling, the determinant of the stiffness matrix is zero; and
- (2) At the point of bifurcation, the eigenvector and the load vector of the stiffness matrix are orthogonal.

Based on the above, a rule for judgment of switching dependent on the determinant and the eigenvector of the stiffness matrix and residual error was proposed. Because determining the eigenvalue and eigenvector of the stiffness matrix each time would increase calculation time, the tool judges whether or not it is possible to calculate these values from the residual error. In addition, even when the eigenvalue is being calculated, calculation time is reduced by applying the Sturm-Liouville theorem<sup>(7)</sup> in order to achieve a result using the minimum calculations.

The use of this method minimizes the use of static explicit methods while also controlling the decline in accuracy and the increase in calculation time.

The combination of static implicit and static explicit methods in a hybrid method as described above realized a method making it possible to accurately produce a solution even when calculations do not converge on a solution using static implicit methods.

### 3.4. Comparison with Conventional Solver

In order to verify the usefulness of the developed method, calculations were conducted for a model for which calculations did not converge on a solution when the conventional solver was used, using a static implicit method, a static explicit method, and the hybrid method, and time to completion of the calculations and time increments were compared. Table 1 shows the results. When the static implicit method was used, the calculations were stopped without convergence on a solution. When the static explicit method was used, the calculations were completed, but because it was necessary to reduce the total numbers of time increments, the number of time increments increased, and calculation time also increased. The calculations were also completed when the hybrid method was used, but there was also a considerable reduction in calculation time

Table 1 Comparison of three solver algorithms

|                 | Elapsed time   | Increments     |
|-----------------|----------------|----------------|
| Static implicit | No convergence | No convergence |
| Static explicit | 38 min         | 47283          |
| Hybrid          | 6 min          | 487            |

Table 2 Comparison of solver speed

|                 | Elapsed time | Increments |
|-----------------|--------------|------------|
| Static implicit | 13 sec       | 124        |
| Hybrid          | 15 sec       | 132        |

against the use of the explicit method in isolation. Table 2 shows a comparison of results for calculation time for the conventional solver and the developed solver using a model for which the conventional solver was able to converge on a solution. The results show similar calculation times for the two methods. The results discussed above demonstrated the advantage offered by the developed method.

## 4. Study of Method of Modeling Clamp Stiffness

As indicated in Chapter 1, because bending stiffness in the connection between a clamp and the cable is low in the case of some cables, local bending deformation occurs at the connection. However, because this stiffness has not been considered in conventional models, it has not been possible to express local bending in the calculations.

A modeling method that enabled the cable to rotate relative to the clamp was therefore formulated, and a corresponding solver function was developed. Figure 6 shows a schematic diagram of the model. A joint (“universal joint” below) giving the cable freedom of relative rotation around two axes (two axial directions are both orthogonal to cable axial direction) is defined at a nodal point at the end of a clamp and a nodal point on the cable in the same position<sup>(8)</sup>. This biaxial rotation is defined as a rotational spring. A stopper is also defined in the direction of rotation in order to regulate the angle of relative rotation<sup>(9)</sup>. A contact model was substituted in the stopper in order to function as a contact constraint<sup>(10)</sup> when the angle of rotation exceeded the threshold value.

Figure 7 shows the deformation occurring when the left end of the cable is fixed and the other end is oscillated to

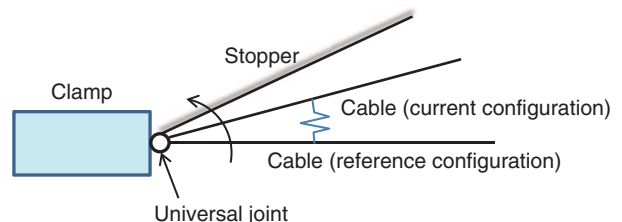


Fig. 6 Schematic image of stiffness of end of clamp

bend the cable. The incorporation of the bending stiffness of the clamp in the model has made it possible to realize values approaching actual values in the entire displacement direction of the cable.

In addition, the use of a one-dimensional model for the entire additional section has controlled the increase in the degree of freedom of the model. This means that it is possible to design cable layouts with sufficient accuracy with minimal increase in calculation time and using a simple modeling procedure.

However, the proposed modeling method involved the addition of a number of finite elements against the conventional model, and the imparting of stiffness values in response to the type of clamp employed. These operations necessitated detailed knowledge of solver use and FEM modeling tools, making it challenging for designers to conduct analyses in short periods. Modeling templates for simulations were therefore created in order to reduce the burden of modeling operations, making it possible to formulate models via simple operations using the specialized cable layout design tool. As Fig. 8 shows, when the designer selects the clamp type following the setting of coordinates for three points on the end of the cable in the specialized layout design tool (shown as red dots), the bending stiffness of the clamp, based on material characteristics, is reflected

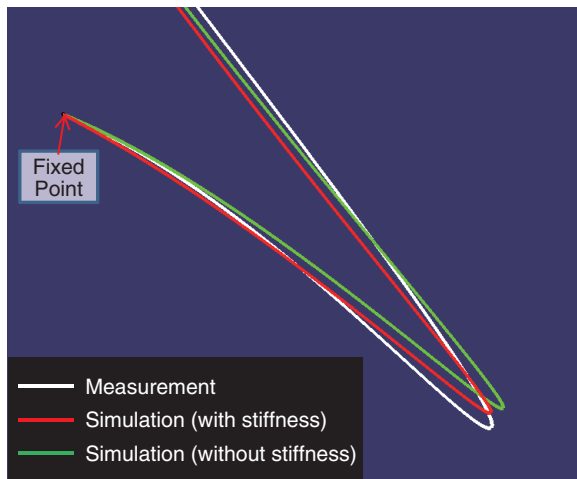


Fig. 7 Contribution of bending stiffness of clamp to cable deformation

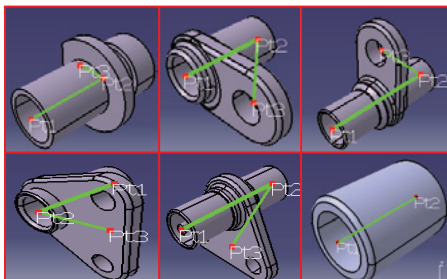


Fig. 8 Library of clamps

in the model in the tool, and the universal joint and contact conditions are set automatically. The use of this tool has made it possible for designers to conduct cable layout design more accurately than was previously the case.

## 5. Verification

### 5.1. Comparison for Up-down Stroke

Simulation results were compared with measurement results for the deformation of a brake hose fitted in a vehicle positioned on a plane surface. The comparison focused on the minimum distance from surrounding parts with which there would be potential interference as calculated by the developed solver. Figure 9 shows the simulation results, and Fig. 10 shows measurement results. The distance between the hose and brackets and calipers in the same position, parts with which there might be interference, was compared. The areas compared are areas in which the radius of curvature of the cable is at its lowest, making prediction challenging, but the maximum difference

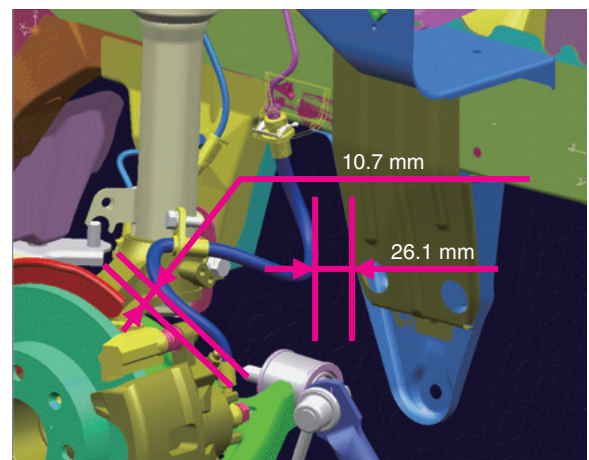


Fig. 9 Simulation result

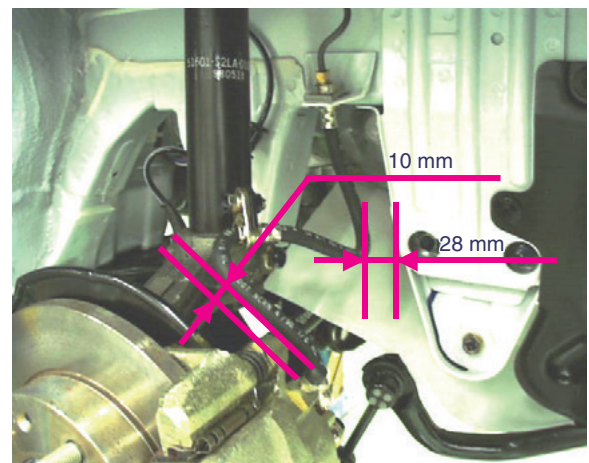


Fig. 10 Measurement result

between simulation and measurement results is around 7%, indicating that the developed method achieves sufficient accuracy for cable layout design.

## 5.2. Comparison with Combined Stroke and Steering Input

Figure 11 shows an example of simultaneous up-down suspension stroke and steering input. This figure compares the deformation of the brake hose following oscillation when the up-down tire stroke is  $\pm 60$  mm and the steering wheel is turned a maximum of 30 deg for each stroke position. The solid line shows simulation results, and the broken line shows measurement results. The simulation is able to approximately reproduce measured values for the stroke in isolation and the stroke in combination with steering input. These results demonstrate that the developed method achieves sufficient accuracy for the design of layouts even in cases in which the brake hose undergoes a high degree of twisting as it is bent as a result of stroke and steering input.

The results of these verification tests indicated that when used by designers for the design of cable layouts, the developed method would display no issues of accuracy even when local bending occurred at clamps, and would be able to generate accurate solutions even for models for which calculations did not converge on a solution using the conventional method. The solver and library function discussed in this paper are in use as cable layout design tools in research and development centers in Japan and overseas.

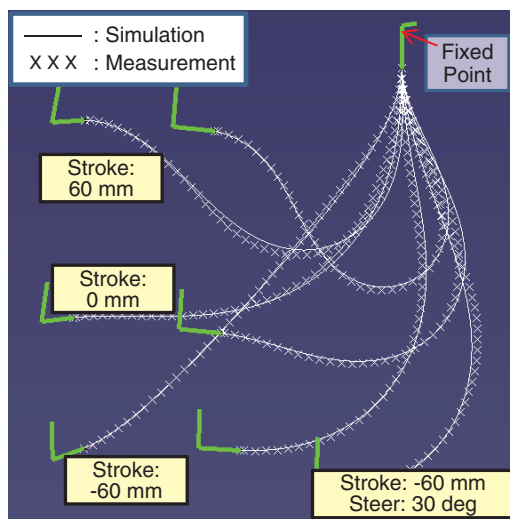


Fig. 11 Comparison of measurement and simulation results

## 6. Conclusion

A development was conducted in order to make it possible to accurately design automotive cable layouts in a short period.

- (1) A hybrid method switching between static implicit and static explicit methods was proposed as a method of maintaining the ability of calculations to converge on solutions, and developed as an original tool.
- (2) The developed method displayed similar calculation times to the conventional method even for models for which calculations converged on a solution using the conventional method.
- (3) A modeling method able to incorporate the bending stiffness of connections between cables and clamps was developed, increasing analytic accuracy.
- (4) The ability to select the necessary clamps from a library and the automatic generation of models within the tool has made it possible for designers to conduct analyses using simple operations, helping to enable cable layout design to be conducted in a short period.

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