MULTIDISCIPLINARY DESIGN OPTIMISATION FOR EMBEDDED SENSOR DESIGNS

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Abstract

Multidisciplinary design optimisation (MDO) is proposed as a method for addressing the difficulties with implementing new smart structures technologies in aerospace design applications. MDO will be used to maximise the use of available sensor information early in the design, and facilitate the re-use of sensor design information between designs and from experimental investigations. Additionally, the MDO framework will be used to handle conflicting requirements and flag important design issues for embedded sensor systems. The MDO approach may reduce resistance to sensors and the cost of design changes through a coordinated approach to design that allows clear communication of requirements early in the design process, as well as providing feedback to sensor developers regarding required directions of further sensor research. The disciplines of manufacturing, mechanical design and sensor design are identified as of particular importance.

1 Introduction

There is currently much interest in embedded sensor networks in aerospace composite structures for health and usage monitoring (HUM), damage detection, process monitoring and active structures. When bringing new sensor technology out of the laboratory and into the more demanding aircraft design, manufacturing and operational environments, the following points need to be addressed.

- The conflicting requirements of sensor systems, traditional mechanical design, manufacturing, certification and operation need to be considered early in the design while there remains design freedom to effect an overall system optimum.
- Researchers developing sensor technologies are often removed from the design and manufacture of the structures that the sensors have potential to be used in. Embedment techniques and connectors between the sensors and external devices are developed that are acceptable in the small-scale, protected laboratory environment, but which do not necessarily translate well to full-scale production. This can hinder the acceptance and uptake of these new sensor developments.
- With new sensor technologies, there is often little design experience on which to base design decisions. There is therefore a need to maximise re-use of information between designs and to ensure information from further testing is also captured and fed into the design where possible.

A difficulty with gaining acceptance for smart structures in new aerospace designs is that the design decisions for the smart structure system may have a significant impact on and be affected by other aspects of the design such as manufacturing, maintenance and structural design. Incorporation of the new smart structures design discipline into the traditional design framework will lead to an increase in the complexity of the design process, and possible resistance from traditional disciplines unwilling to make compromises for the 'newcomer'.

Imposing the requirements for the smart structures discipline early in the design process minimises the impact on the overall complexity and cost of the design process, as the cost of design changes is much less in this early design phase. Modelling the impact of the smart structure system on the overall performance of the design also helps to encourage "buy-in" by the other disciplines. To do this, however, there is a requirement to make informed design decisions while the detail known about the design is minimal. This is made more difficult because the immaturity of the technologies means that there is little historical data on which to base the required design decisions.

A coordinated multidisciplinary design optimisation (MDO) approach to handle the design data from the manufacturing, maintenance, structural design and sensor design disciplines is proposed to help realise the full potential that smart structures offer by fully considering the interaction effects and by managing the resultant complexity in the design process. A key component for the implementation of MDO for new technologies is to incorporate methods to maximise collection and re-use of design knowledge for the emerging technologies.

The manufacturing issues involved with embedding sensors in composite structures have been explored [1, 2, 3], but mostly in small scale studies based around laboratory test items rather than in a realistic manufacturing environment. Although these studies have provided useful information regarding some of the important issues involved with embedment techniques and associated strength implications [4, 5], the techniques involved are generally highly labour intensive and unsuitable for inclusion in the manufacturing environment of aerospace structures.

Life cycle costing methods are important tools to compare the effect of design decisions. Unfortunately cost analysis is difficult for new and innovative technology because the required historical data is limited. A comprehensive cost-benefit analysis has been published for advanced sensor-based structural health monitoring systems [6]. This study was of a general nature to compare automated and in-situ health monitoring with existing manual systems, and the specific technologies involved in different systems was not considered.

Much of the published work on MDO for aerospace design has concentrated on the coupling of aerodynamics, structures and propulsion disciplines for conceptual aircraft design [7, 8]. Manufacturing issues have also been successfully incorporated in the MDO environment [9, 10].

2 MDO Tool for Embedded Sensor Designs

A coordinated approach to the design of smart or sensory structures requires the development of a design tool to facilitate the simultaneous consideration of important multidisciplinary design drivers and to manage the complexity of the multidisciplinary approach to design. The aim is to overcome the problems that make these systems difficult to implement in the real manufacturing and operational environment, despite success in the laboratory.

The tool must combine established structural design and optimisation techniques using tools such as finite element (FE) analysis with specialised controls and functions to provide the required MDO capability. The major components of the design tool are discussed in the following sections.

2.1 Optimisation of geometry

2.1.1 Optimisation formulation

The first consideration is how to formulate the optimisation problem. The optimisation problem may be written in the general form:

Minimise

$$f = f(\mathbf{x}), \qquad \mathbf{x} = [x_1 x_2 x_3 \ldots x_m] \qquad (1)$$

For

$$\underline{x}_i \leq x_i \leq \overline{x}_i \qquad (i = 1, 2, \ldots, m) \qquad (2)$$

Subject to

$$\underline{g}_j \leq g_j(\mathbf{x}) \leq \overline{g}_j \qquad (j = 1, 2, \ldots, n) \qquad (3)$$

Where

f	is the objective function
$\mathbf{x}$	is the vector of design variables
$\underline{x}_i$ and $\overline{x}_i$	are the lower and upper bounds of the design variables respectively for $i = 1, 2, \ldots, m$.
g_j	are the state variables for $j = 1, 2, \ldots, m$, and
$\underline{g}_j$ and $\overline{g}_j$	are the lower and upper bounds of the state variables respectively for $j = 1, 2, \ldots, n$.

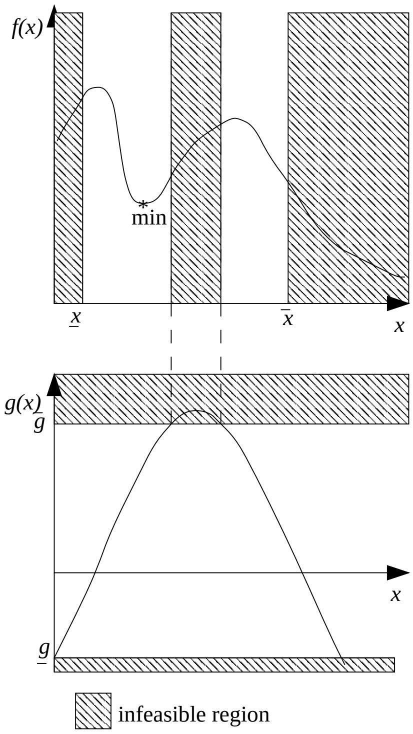

Fig. 1 Basic optimisation problem

Fig. 1 shows the optimisation problem to minimise the function $f(x)$ for one design variable, x, and one state variable, g. The feasible region is constrained by the bounds on the state and design variables, $\underline{g}$, $\overline{g}$, $\underline{x}$ and $\overline{x}$.

Optimisation of a finite element analysis model may be implemented by formulating the model using parametric *design variables*, which are varied within bounds set by design variable constraints to create a series of design sets. *State variables* are calculated for the design sets. They are dependant on the design variables and also have lower and upper bounds to identify the feasible design space. The optimisation algorithm controls the movement between design sets in the search for the set that minimises the *objective function* (equation 1) while satisfying the state variable and design variable constraints (equations 2 and 3).

The objective function, design variables and state variables must be chosen carefully to ensure a successful optimisation. Common causes for failure of the optimisation are insufficiently or over constrictive state variables resulting in a feasible design space that does not reflect reality, too many or two few design variables leading to convergence problems or impractical designs, or an inappropriately defined objective function. A full understanding of the design space is required. Other issues to consider include whether idealisations or limitations in the model will lead to unrealistic results in certain areas of the model, or whether speed and size savings can be made by concentrating on areas of the model known to be of particular interest.

A second consideration is the choice of optimisation methods and tools. Most optimisation software contains a choice of optimisation methods, which use different optimisation algorithms to search the design space and find the optimal design based on the objective function. Optimisation tools are also often offered. These do not find an optimal design but offer ways of viewing the design space and investigating the behaviour of the design variables. This can be useful both when setting up the optimisation problem and deciding what variables and constraints to select, and after performing the optimisation to investigate the validity of the solution or examine sections of the design space in more detail.

There are several issues which need to be considered when creating the finite element model to be used in the analysis and optimisation. Important issues include whether geometric or material nonlinearity must be considered, whether symmetry may be exploited to reduce the model size, what boundary conditions are required, how loads should be applied, how the model should be meshed, etc. When designing an optimisation model, solution time is a high priority because several loops will be required to search the design space. Meshing controls must also be carefully considered. Density of the mesh and choice of element type affects the accuracy of the results and the processing time.

2.1.2 Shape optimisation example - adhesive bonded joints

Shape optimisation of a bonded joint may be formulated to minimise the stress concentration by altering the profile of the joint. An objective function termed the least squares objective function was presented in [11] for the optimisation of isotropic or composite plates with cutouts. This method aims to produce a constant stress along a boundary through the application of an averaging equation which relates the stress at a point to the average stress along the entire boundary. This objective function was adapted to bonded joint design by using the path along the adhesive as the boundary.

$$\text{Minimise } \frac{\sum(\sigma_i - \sigma_{av})^2}{k^2} \tag{4}$$

Where

σ_i = adhesive elemental Von Mises stress at element i

σ_{av} = average elemental Von Mises stress along adhesive

k = number of adhesive elements

The cross sectional profile of a two-dimensional plane strain model of a bonded double lap joint was optimised using the least square objective function above. The shear stress in the adhesive was defined as a state variable and the design variables defined the cross section of the joint as shown in Fig. 2. The optimisation

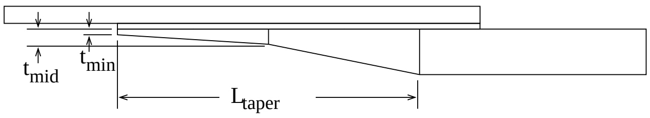

Fig. 2 Design variables for optimisation of double lap joint (half joint modelled due to symmetry)

process reduced the minimum thickness from 2.75 mm to 0.13 mm, the mid-taper thickness from 2.75 mm to 0.68 mm and increased the tapered length from 150 mm to 158 mm. This optimisation resulted in a reduction in the peak stresses of the joint, and a increase in the average stresses in the middle of the joint as can be seen from Figures 3 and 4. The

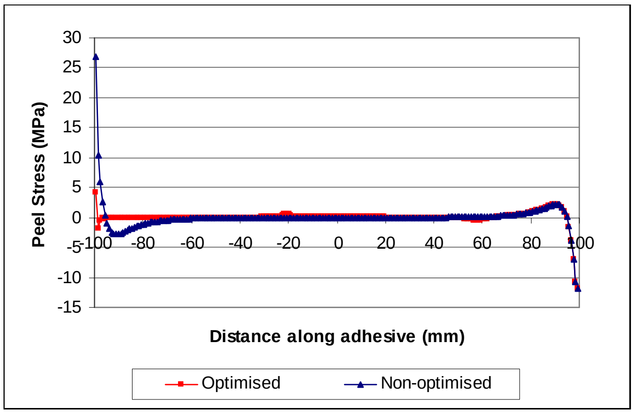

Fig. 3 Peel stresses in optimised and non-optimised joints

results were compared with results presented by Ojalvo [12] where the profile of double lap joints was optimised to achieve uniform adhesive shear stresses. Ojalvo's solution was a single curvature profile of the tapered section. Uniform adhesive shear stresses were only achieved in double lap-joints through an impractical design with the thickness approaching infinity at the far end of the outer adherend. Non-optimum solutions were considered where the maximum thickness

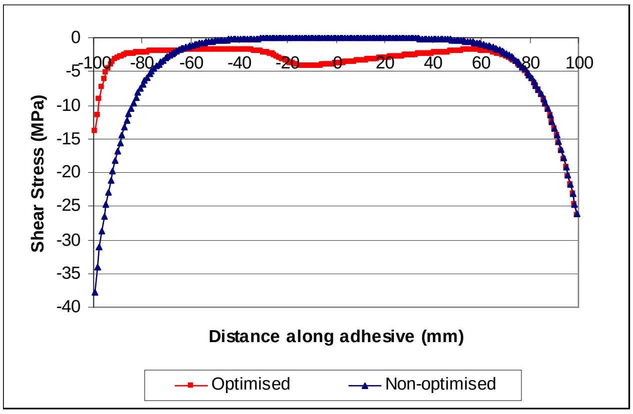

Fig. 4 Shear stresses in optimised and non-optimised joints

of the adherend was limited to a specific value. Fig. 5 shows the current linear and bilinear optimised solutions with the numerical solution from Ojalvo using a load transfer ratio, C, of load retained within the inner adherend to load applied of 0.3, and truncating at a maximum thickness of 2.75 mm. It can be seen that the current method produces very similar results.

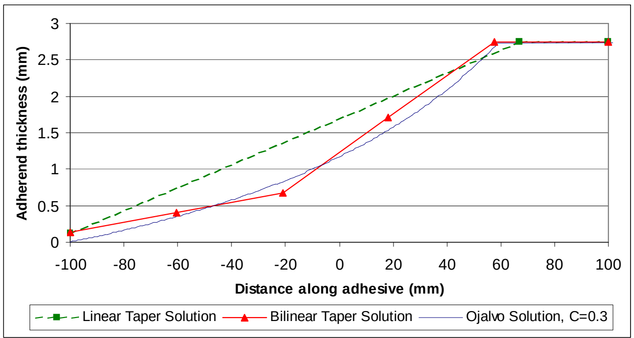

Fig. 5 Bilinear taper profile and Ojalvo solution

2.2 Manufacturing 'discipline'

The manufacturing discipline has a strong influence on the success of any design and must be considered early to ensure manufacture is both feasible and economical [13]. Small changes in the design such as a reduction in the number of parts or use of standard material gauges, can result in significant cost savings without loss in performance. Automation also plays an important role in reducing manufacturing costs and improving part consistency, although initial development and acquisition costs may be high. Manufacturing issues are particularly important when introducing innovative technology such as embedded sensors into the design. It may be difficult to integrate the new technologies into the existing manufacturing environment without excessive development costs, sacrifice of quality or reverting to manual rather than automated techniques. Manufacturing issues therefore need to be considered in parallel with the development of the new technologies.

It is desirable for the manufacturing issues of both the structure itself and the integration of the sensors to be considered early in the design. Of particular interest is the ability to include evaluation of cost implications, and to highlight which manufacturing design decisions have a significant impact on other 'disciplines'. This may be included in the design tool by adding qualitative and quantitative information to the model in addition to the usual data required for the FE analysis.

Manufacturing information may be added to the model through the incorporation of a capability to request additional information from the user. For example, the user might be requested to choose a material and then be asked to choose the material form and appropriate manufacturing process, and specify other details, such as required tolerances or surface finish. Controls are required to manage the linking between materials, material forms, manufacturing processes, etc., and match this information to the required cost data. In this way the relative costs of choosing different materials or manufacturing methods can be compared. These controls and rules may also link the material and manufacturing information to the geometry of the model. This will allow the model geometry to be constrained by realistic manufacturing constraints, such as available sizes for the material form or material maximum and minimum thickness, and also allow geometry information, such as number of parts, part geometry and assembly, to be included in the manufacturing cost modelling.

As well as being able to choose the generic materials and manufacturing processes available in the tool, there must also be the capability of adding more information, controls and design rules as they become available. Other details of the manufacturing environment may also be incorporated, including particular equipment available at a site, certification requirements, internal processing control procedures, quality control, etc.

2.3 Sensor 'discipline'

The inclusion of the sensor discipline in the design process allows design decisions to be made based on the functionality of the sensors, structural integrity after sensor embedment and cost.

2.3.1 Sensor functionality

The functionality of the sensors may be included in the tool by modelling the response of a sensor based on the strain calculated using the finite element model under particular loading conditions and/or damage scenarios. Measurement errors and temperature effects may also be modelled. This will allow different sensor types and arrangements to be compared based on the information they provide. A quantitative analysis of the additional cost of including the sensors against added functionality and long term cost benefit may also be performed. This may be used to make informed decisions on whether the functionality is required for the particular application and whether the cost is justified.

Damage Detection Fig. 6 shows a plot of the longitudinal strain in the bondline of an adhesive bonded double lap joint for the undamaged case, and for the case where a disbond is present between the adhesive and the inner adherend. Fibre Bragg grating strain sensors are located at a spacing of 10 mm and the output from the sensors is indicated by the marker points. The change in strain distribution allows damage

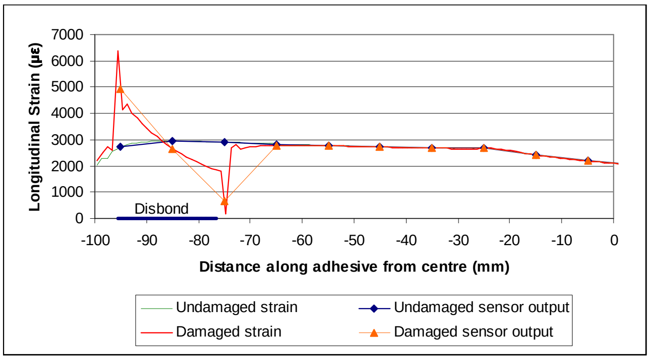

Fig. 6 Adhesive strain distribution for internal disbonds

to be identified and characterised. However, the resolution of the sensor strain measurements, the sensor interrogation and temperature compensation procedures, the maximum allowable number of sensors and rate of change in loading all need to be taken into account when deciding the sensor placement configuration and the confidence levels for detecting damage of a particular size.

A simple damage identification method uses adjacent sensors to calculate a local strain gradient. If this strain gradient is greater than a value determined by the resolution of the strain measurements and the load level, damage is likely to be present. For the case of internal disbonds, in the centre of the disbond there is a point where the strain level will be equal to the strain in the undamaged structure, and a small gradient might be calculated. Therefore, for this method to be safely used, the sensor spacing must be less than or equal to half the length of the disbond required to be detected. Table 1 shows the sensor outputs for a 20 mm disbond in a 200 mm overlap joint for sensors spaced at 10 mm and 20 mm. It can be seen that for the 10 mm spaced sensors, damage is clearly indicated by the high strain gradients calculated for the three sensors in the damaged region. However, for the 20 mm spaced sensors, the single sensor in the disbonded region falls in the centre of the disbond and the strain gradient calculated is very small and does not clearly

Table 1 Sensor output

	Undamaged		Damaged			
	10mm spaced sensors				20mm spaced sensors	
Distance along adhesive (mm)	Strain ($\mu\varepsilon$)	Strain gradient ($\mu\varepsilon/mm$)	Strain ($\mu\varepsilon$)	Strain gradient ($\mu\varepsilon/mm$)	Strain ($\mu\varepsilon$)	Strain gradient ($\mu\varepsilon/mm$)
-95*	2724	22.9	4940	-228.0**	–	–
-85*	2953	-5.0	2659	-198.4**	2659	6.3
-75*	2903	-6.4	6766	211.1**	–	–
-65	2839	-6.2	2786	-1.7	2786	-3.4
-55	2777	-5.8	2770	-5.2	–	–
-45	2719	-4.6	2718	-4.5	2718	-2.4
-35	2673	-0.3	2673	-0.4	–	–
-25	2670	-25.5	2669	-25.3	2669	-24.2
-15	2415	-22.9	2416	-23.0	–	–
-5	2186	-17.6	2186	-17.6	2186	-16.2

* Damage location ** Damage indicated by high strain gradient

indicate the presence of the damage. Modelling of sensor functionality in this way allows the required sensor configuration to be quickly assessed for different joint designs produced in the optimisation process.

2.3.2 Structural integrity

The structural integrity may be considered by using an estimation of the strength reduction to modify the finite element results surrounding the embedded sensor. An embedded sensor may be modelled as a flaw of a particular size, shape and orientation based on the sensor characteristics (e.g., type, geometry, embedment method, surface material, etc.). When available, information about actual strength reductions from tests may be used. Using this, sensor placement may be optimised by avoiding critical locations where the load carrying capacity of the structure may be significantly reduced by embedding the sensors.

2.4 Inspection and Maintenance 'discipline'

An advanced health and usage monitoring system involving embedded sensors may allow savings in operating costs due to early detection of damage or flaws and reduction in the high costs associated with traditional non-destructive evaluation and inspection (NDE/I) resulting from the complex and costly support equipment, requirement for partial disassembly of the structure and labour intensive support equipment [6]. Including inspection and maintenance cost data is therefore required when comparing the life-cycle cost of different sensor systems for the structure.

The sensor capability may increase the operating costs in certain areas. The cost estimation needs to be detailed enough to consider effects such as the added complexity of the sensor system, the use of unproven technology and the need to inspect and maintain the sensor system itself.

2.5 Management of design data

As the sensor discipline is new and there is little historical data available on which to base design decisions, the design tool must maximise the collection and re-use of design knowledge for the emerging technologies. It must therefore be easy to add to the database of sensors as new sensors are developed and as new information becomes available about existing sensors.

If the tool has the capability of modelling and/or monitoring the system in service there will be a path by which relevant sensor data can be returned to the system. Sensor data, such as response under loading, errors, short- and long-term structural integrity, etc., collected during manufacture, testing or in-service, may be analysed and used to update the design tool.

2.6 Management of design process

The inclusion of smart structures in a design adds complexity. This tool aims to manage this complexity to reduce design process cost. The impact of the smart structure system on overall performance is modelled to allow informed design decisions to be made more easily, and to encourage "buy-in" by the established disciplines.

The tool may also be used in preliminary design studies by members of a single discipline to allows multidisciplinary implications to be considered without the requirement for the full involvement of all disciplines. This is of particular benefit to the sensor discipline when developing sensors and embedment techniques. The use of MDO to investigate the impact of the new sensor systems on the overall performance of the design allows identification of future research needs and performance goals required for the system to be viable. Once the technologies have matured, this multidisciplinary experience will help identify applications where the technology will have most benefit in terms of both functionality and cost, and will help in the preparation of the 'business case' when approaching the established disciplines.

3 Implementation in Ansys

The commercial finite element package, Ansys [14] is well suited to implementation in 'vertical' applications, such as MDO tools, because of the integrated parametric design language, APDL, used primarily for automatic model generation and optimisation, and support for the scripting language Tcl/Tk [15]. Tcl is a cross-platform scripting language providing program control and the ability to execute other programs, to allow existing programs to be assembled into a new tool. The Tk toolkit provides commands for the creation of a graphical user interface (GUI). The Tcl/Tk interpreter has been provided as part of Ansys since version 5.5 and special Ansys commands are provided to call Tcl/Tk scripts. These are,

- `~tcl,`*`'commands'`* — executes Tcl and custom Ansys commands using tclsh interpreter.
- `~Tk,`*`'commands'`* — executes Tcl, Tk and custom Ansys commands using wish interpreter.
- `~eui,`*`'commands'`* — creates enhanced environment for interpretation of Tcl, Tk and custom Ansys commands, including the [incr Tcl]/[incr Tk] package.

These commands may either be entered directly in the Ansys input when running Ansys interactively, or be called from an Ansys macro or APDL script.

Additional communication functionality between Ansys and Tcl/Tk scripts is provided through a series of custom Tcl/Tk commands, which allow parameters to be queried, Ansys commands to be sent and picking operations to be controlled. The most commonly used of these custom commands are **`ans_sendcommand`** to execute Ansys APDL commands from within the Tcl script and **`ans_getvalue`** to query the Ansys database and return the information to the Tcl script. GUI elements created using Tk may be given the look and feel of Ansys for seamless integration by specifying the Ansys resource class. MDO may be implemented by combining APDL and Tcl/Tk to provide the necessary disciplinary controls and coupling while using Ansys as the analysis engine. Dialogs created using Tcl/Tk scripts may prompt the user for the information required to create the model and run the optimisation.

3.1 Ansys optimisation for MDO tool

Optimisation using Ansys requires the generation of an analysis file written in the APDL scripting language, which defines the generation of the model, the material characteristics, the meshing of the model, the FE solution and the calculations required for the state variables and objective function. When using Ansys for optimisation in an MDO tool, the analysis file must be assembled based on the geometry and optimisation control information provided by the user for the particular case being considered, and a skeleton script containing the commands required to build, solve and post-process the FE model of the structure. Ansys uses the analysis file to create a 'loop' file which it runs on each optimisation step. Skeleton scripts may be edited and saved by advanced users when non-standard modelling options are required, or the user may accept the defaults in the existing scripts.

The two main optimisation methods available in Ansys are the sub-problem approximation method and the first order method.

The sub-problem optimisation method uses curve fitting techniques to find approximations of the objective function and the state variables. The approximations are updated at each optimisation loop and it is the approximation of the objective function, rather than the objective function itself which is minimised. Looping stops when the following convergence criteria are satisfied: 1) change in objective function from the best feasible design to the current design is less than the objective function tolerance; 2) change in objective function between the last two designs is less than the objective function tolerance; 3) changes in all design variables from the current design to the best feasible design are less then their respective tolerances; or 4) changes in all design variables between the last two designs are less than their respective tolerances. Looping may also terminate before convergence if the maximum number of iterations has been performed or the maximum number of consecutive infeasible designs has been reached. Convergence or termination based on these criteria may not mean that the global minimum has necessarily been found, and therefore additional controls and checking criteria may be required to ensure that the design space has been fully searched.

The first order method calculates gradients of the dependent variables with respect to the design variables at each iteration to determine search direction and a line search strategy is adopted to minimise the problem. At each optimisation iteration, several analysis loops are required to calculate the required gradients and search direction. Convergence occurs when, 1) the change in the objective function from the best design to the current design is less than the objective function tolerance, or 2) the change in the objective function from the previous design to the current design is less than the objective function tolerance. Termination may also occur if the maximum number of iterations has been reached. The first order method is computationally intensive and may converge to a local minimum, or an infeasible design.

Other optimisation tools available for the exploration of the design space are random design generation, design space sweep, factorial tool and gradient tool. A mixture of methods and tools may be used in sequence to reduce the risk of convergence to a local rather than global minimum, or an infeasible design.

4 Conclusion

Incorporating a sensing capability in structures through embedded sensors offers attractive benefits for in-situ health and usage monitoring, detection of damage events, automated NDE/I and adaptive structures. The design of such structures is complex due to the high level of coupling between the major design disciplines involved (structure, manufacturing, maintenance and sensors).

The major components for a design tool for smart structures have been described. The geometric optimisation, manufacturing, sensor and maintenance disciplines have been discussed. An MDO capability is required to manage the complexity and reduce the design time while these disciplines and the interactions between them are considered. To maximise the use of information available for innovative sensor technologies, the tool must be easily updated as more sensors become available and as the technologies mature. An in-service modelling or monitoring capability in the tool will strengthen the link to return in-service sensor data back to the design tool.

Implementation of an MDO tool is possible using commercially available FE packages, such as Ansys, as the analysis engine for vertical applications assembled using custom code from programming languages, such as Tcl/Tk, to provide the MDO functionality.

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