SMART POLYMER COMPOSITE STRUCTURES

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ABSTRACT: Smart structures technology studies the integration of different active components in structures, in particular in polymer composites. The principal application areas in the near future will be structural monitoring and vibration control. This paper presents the concept of smart structures, some possibilities for their applications, and the most important materials suggested to be used as their active components.

INTRODUCTION

Smart structure is a structure which contains sensors, actuators and computational capability in order to control the structure. The structure may be constructed of smart materials, which contain the ingredients themselves, or simply have some integrated active elements in it.

Smart structures promise to revolutionize the way engineers think about the safety of various structures. By combining our knowledge of fiber optics, optoelectronics, and artificial intelligence, as well as the arts of materials technology and construction design, it is possible to develop structures which are capable of monitoring their integrity and usage for the purposes of enhanced safety and performance. Also new designs can be improved when "inside information" is available.

The concept of smart structures may be applied equally well to civil engineering structures as to vehicles, but the aerospace industry is currently on the forefront of this new emerging technology. Some of the proposed applications include:

- crack and failure detection in structures
- vibration/noise control and suppression by active means
- precision adjustment of large mirrors
- pointing control of space-based devices
- cancellation of thermal expansion.

There have been several attempts to define the qualities that make a structure smart. The following proposed definitions are relatively widely accepted [1][2]:

Smart structure (toimirakenne) is a structure with a built-in sensor system for the purpose of monitoring either the structure itself or its environment. It can also contain some elements for active control of the structure.

Passive smart structure (passiivinen toimirakenne) possesses a structurally integrated optical microsensor system for determining the state of the structure and in certain instances the environment in which it is operating.

Reactive smart structure (reaktiivinen toimirakenne) possesses an optical nervous system and an actuator control loop to affect a change in some property, for instance stiffness, shape, position, orientation, or velocity of the structure.

Intelligent structure (älykäs rakenne) is a smart structure capable of adaptive learning.

THE ADVANTAGES OF SMART STRUCTURES

Enhanced safety is the best aspect of smart structures. When the integrity of a structure is continuously monitored, its use can be optimized and the structure be taken out of service when required. The main motivation behind the development of smart structures, however, is undoubtedly the possibility of economic benefits associated with the decreasing design margins. These benefits can be achieved in five areas, which are briefly discussed below.

Manufacturing

The ultimate mechanical properties of composites depend on their degree of cure. When a large part is manufactured, its degree of cure between different areas can vary due to the exothermic nature of the reaction. The degree of cure is also affected by the thermal characteristics of the autoclave, varying material properties from batch to batch, and unstable handling procedures. Completeness of cure is currently assured by overcuring the part. This is both time consuming and costly.

Several methods for assessing the degree of cure have been proposed, but they tend to need calibration for each material batch and curing process [3]. Some methods can only be used on test coupons and the properties of the part are not directly measured. Possible effects of part geometry and autoclave properties are thus not accounted for.

Two methods of utilizing optical fibers in monitoring the curing process have been proposed. The sensors destined for use in the finished product are usable in providing the necessary information during the curing process. In a more ingenious method, pre-cured fibers of the matrix resin are laminated into the part [3]. During the curing process light is transmitted through the fiber. As the part cures the refraction index difference between the fiber and matrix decreases and the transmitted intensity decreases. When the cure is complete, all light sent into the fiber scatters away.

The pressure/temperature information provided by the smart structure can be used to optimize the curing process. This is a way to increase the productivity of the process, to decrease the manufacturing costs of advanced composite products, and to make composites an even more competitive alternative for metals.

Non-destructive inspection

The NDI of advanced composite parts is a necessity in order to guarantee the quality needed in many applications. This is, at the present, a laborious and cost intensive task usually involving ultrasonic C-scanning or radiographic methods. These methods are generally too clumsy for field inspections.

There are also several new NDI methods applicable to composites: ultrasound spectroscopy, real-time radiography, thermography, and eddy current inspection for carbon fiber composites. The use of these intricate methods, however, requires a high standard of training and specialization and is thus costly. The time needed for NDI can be shortened by the use of optical fibers embedded in composite structures.

The advantages of smart structures in NDI can also be realized in other fields of engineering. Acquiring information from deep inside of buildings, bridges, and dams by conventional methods is difficult. By using smart structures technology it is possible to measure internal strains in any concrete structures.

Condition monitoring

Safety critical structures are traditionally inspected at some time or usage interval basis. In addition to providing new methods for inspecting structures, smart structures make it possible to continuously monitor the inside of structures.

This can be achieved by installing a network of optical fibers into the structure. This network can then be used as a tool in continuously monitoring the structure. Smart structures can thus prevent a catastrophic failure from structural causes and thoroughly change the maintenance system and the costs associated with it. Maintenance can be shifted from the time interval basis to the as needed basis.

Control systems

The next step in aircraft control system development is to use non-mechanical control surfaces for improving aerodynamic efficiency, decreasing the number of moving parts, and enabling the reconfiguration of control surfaces if needed. The decreasing number of moving parts obviously means less faults and the possibility of reconfiguring the control system reduces the consequences of a failure.

It might also be possible to eliminate the possibility of hard-over failures completely by replacing hydraulics and servos with non-mechanical actuators. A shape memory alloy actuator losing power would return to its normal shape and not get stuck in some arbitrary position.

Vibration control

Vibration is usually controlled by passive methods. These methods are generally based on adding mass, in one way or another, to the structure. Using smart structures to actively or adaptively control vibrations can lead to savings in weight.

MATERIALS FOR SMART STRUCTURES

Even though the visioned smart structures are still a way ahead, there is already some consensus on the materials to be used.

Sensors

Fiber optics is the most promising solution for sensors in smart structures. Optical fibers react to changes in temperature and pressure by interfering with the signal they transmit. Due to their relatively small diameter, optical fibers can be integrated in composites and metal casts without overly degrading their mechanical properties.

Optical fiber sensors can be categorized to four groups based on their operating principle: intensiometric, interferometric, modalometric, and polarometric sensors.

The simplest type of intensiometric sensors is a plain optical fiber attached to a structure. If the structure breaks, so does the fiber, and the loss of transmission through it provides a way to detect the damage.

Another method is to send a short and intensive light pulse into the fiber and analyze the backscatter or reflections from artificial markers. By analyzing the temporal shift of reflections when the structure is being stressed, the strain between two markers can be calculated. This, however, involves expensive hardware capable of measuring time intervals with picosecond resolution.

Interferometric sensors provide a more economical alternative by monitoring the phase shift induced to coherent light in the fibre. There are several possibilities to do this. Perhaps the most promising is the Fabry-Perot sensor. In the end of the fiber there is a resonant cavity and the strain shows as a phase shift in the cavity modes. This type of sensor needs only one fiber and it is insensitive to perturbations in the lead fiber. The Fabry-Perot sensor was tested during an F-15 aircraft fatigue test [4]. The used gauge length was 19.03 mm with a minimum detectable strain of 0.01 μm/m. In comparison, the electrical strain gauges provided a resolution of 20 μm/m primarily due to bridge supply noise.

Modalometric and polarometric sensors utilize energy distribution differences between modes and changes in polarization, respectively, but the research results so far are not as encouraging as for the interferometric method.

One aspect to be considered in integrating optical fibers and other active elements is their possible detrimental effect on the mechanical properties of their host material. This subject is currently under intense research. The main causes of detrimental effects are the resin pockets created around cross-plied optical fibers and the possible incompatible moduli. The effects are worst for longitudinal compression strength with transverse optical fibers. The reduction is typically in the order of 5-25%[5]. By introducing specially made low-profile optical fibers with compatible coatings, these adverse effects should be all but eliminated.

Actuators

The choice for actuators is not as clear as the choice for sensors. One disadvantage in integrating active components in various materials is the difficulty in maintaining and repairing these components. In order to minimize the number of faults, the actuators, as well as the sensors, should be non-mechanical. The best three candidates so far are shape memory alloys, piezo-electric materials, and electro-rheological fluids.

Shape memory alloys (SMA) are nickel-titanium alloys which, upon heating, return to their "memorized" shape. The exact mechanism is not yet fully understood, but when a deformed martensitic part is heated above its transformation temperature, it returns to its regular austenitic crystal structure, thus "remembering" its shape. The transformation temperature is typically 40 °-50 ℃ [6] and it can be engineered to match the application. Nitinol (Ni, Ti, Naval Ordinance Laboratory) can return from a plastic strain of 6-8%. The austenite return stress can be as high as eight times the tensile martensitic yield stress [7].

SMA can be integrated in structures as thin films or strands. These actuators can be activated either by using their electrical resistance or by guiding optical power from a laser through optical fibers. As the actuators are heated, they try to return to their memorized shape and function by introducing internal stresses to the structure. These stresses can then be used to achieve the desired change in the shape or stiffness of a structure.

The use of SMA actuators is limited to low frequencies because the required cooling time between actuations. However, SMA actuators offer a relatively large stroke compared to piezo-electric materials.

Piezo-electric (PE) materials are another promising candidate for actuators in smart structures. Their main advantage, speed, enables their use in actively suppressing vibration, which is one of the many objectives of smart structures technology.

PE materials have so far been used as 0.25 mm thick films and as stacks of electrode separated disks [8]. PE films can be laminated inside or on to the surface of plates. They can be used for tailoring the bending properties of their host structure. PE-disk stacks can be used as active vibration suppressing members in truss structures [8]. This is an active area of research and results so far are encouraging. Another possibility is the use of PE strips as a part of a sound suppressing system.

The third considered actuator type is based on electro-rheological (ER) fluids. These fluids change their viscosity as a function of the electric field they are subjected to. The required electric field is in the order of 2 kV/mm and the viscosity change takes only some milliseconds. This phenomenon is thought to find some use in helicopter rotor blades. The blades could be dynamically tuned to optimum in varying environmental and performance conditions [9].

APPLICATIONS

Built-in structural monitoring system

One of the most interesting applications of smart structures is their use as a built-in or integrated structural monitoring system. This system would constantly monitor the structure and prompt for actions when needed. Many fields of engineering could find use for such a system. For example the structural monitoring of pipelines or pressure vessels is a promising application area.

In an aircraft of the future an integrated structural monitoring system (ISMS) could be a part of the aircraft's flight control system (FCS). ISMS would warn the FCS of sustained damage thus enabling the continuous updating of the performance and manoeuvering limits. The system would function as follows [10][2]:

1. At power-up the central computer assesses the airworthiness of the aircraft. It can be achieved by mapping the aircraft with the help of acoustic-emission transducers by transmitting a signal out from one of them at a time and receiving it with the others. By comparing this structural map with a reference map of a sound structure, the possible between-flight damage can be caught.

2. During pre-takeoff taxi the dynamic response of the aircraft can be evaluated and the stiffness matrix compared with one produced by ground vibration tests.

3. During flight the central computer continuously monitors the load state and the damage status of the aircraft. In military aircraft the system also assesses the seriousness of battle damage, calculates the residual strength and informs the pilot of possible manoeuvering limits. Control surfaces can also be reconfigured for the new situation.

4. After landing the system gives the ground crew a report of the load history, possible damage, and the need of maintenance. The accumulating load history is also invaluable for fleet monitoring and future aircraft design purposes.

At present the research of ISMS has produced the first aircraft part, which is a composite leading edge for Boeing-de Havilland DASH-8 aircraft [11]. The leading edge is instrumented with 250 optical fibers in order to detect bird-strikes and other foreign object damage. This system is approaching its first flight test, but it is not yet a system for real-time in-flight monitoring.

Vibration control

Another field of application for smart structures is vibration control. This can be divided into two areas: to the modification of the vibration mode and to the active reduction of the vibration amplitude.

The more novel of these two approaches is the modification of the vibration mode. This is best suited for SMA. Two methods for the modification of modes have been suggested [7]. These are active modal modification and active strain energy tuning.

In active modal modification, nonstrained strands of SMA are activated and the increase in their modulus changes the vibration mode. In active strain energy tuning, activated strands are strained before their incorporation to the host material. On activation they introduce compressive stresses to the material thus changing the strain energy distribution and modifying the mode of vibration.

PE materials are better candidates for the active damping of vibration. They have been proposed for the stabilization of pointing devices in space, damping out structural vibration, and cancellation of cabin noise. The published research is currently just advancing from proof of concept experiments forward. In one experiment the radiation from a panel was decreased by 40 db when the cancelling-out field was introduced [12]. The result was achieved by a single piezo-ceramic strip with one microphone error sensor located 1.8 m from the panel.

This line of research may lead to interesting applications, such as active noise cancelling casings for gears and motors etc. They could actively tune themselves for optimum performance in varying excitation conditions.

Other applications

The pointing and shape control of space based reflectors using smart structures technology has also been studied [13]. The reflector is affected by the vibrations of the supporting truss structure and its shape is affected by thermal gradients in the reflector itself. The natural frequencies of the support structure are typically in the order of 0.01 - 0.1 Hz [13]. At these frequencies the damping is very low and remarkable performance improvements can be achieved by using smart structures technology in counterbalancing these oscillations. The shape of the reflector itself can be controlled by PE strips.

One interesting idea could be to cancel thermal expansion with SMA. As the thermally stabilized part is heated, the integrated SMA actuators would activate and create compressive stresses to the material in order to cancel the thermal expansion. By varying the SMA actuators activation temperatures, the thermal expansion curves could be engineered for different applications.

CONCLUSIONS

Smart structures will be the norm in the future. Their use facilitates a new approach to engineering, which enables engineers to base their designs and lifetime estimates on the actual use instead of guesstimates. The research of smart structures is still in its early stages and the research field is in a state of fast diversification and specialization. Successful research of smart structures needs strong crosscommitment due to the multidisciplinary nature of the subject.

Measures from the University of Toronto has written about the future of smart structures [14]: *"In the 21st century it may be regarded as unacceptable engineering to build any structural component, that could jeopardize the lives of people, without a built-in structural monitoring system."*

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