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Research paper

Static load estimation using artificial neural network: Application on a wing rib

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ABSTRACT

This paper presents a novel approach to predicting the static load on a large wing rib in the absence of load cells. A Finite Element model of the wing rib was designed and calibrated using measured data obtained from static experimental test. An Artificial Neural Network (ANN) model was developed to predict the static load applied on the wing rib, this was achieved by using random data and strain values obtained from the static test as input parameters. A number of two layer feed-forward networks were designed and trained in MATLAB using the back-propagation algorithm. The first set of Neural Networks (NN) were trained using random data as inputs, measured strain values were introduced as input into the already trained neural network to access the training algorithm and quantify the accuracy of the static load prediction produced by the trained NN. In addition, a procedure that combines ANN and FE modelling to create a hybrid inverse problem analysis and load monitoring tool is presented. The hybrid approach is based on using trained NN to estimate the applied load from a known FE structural response. Results obtained from this research proves that using an ANN to identify loads is feasible and a well-trained NN shows fast convergence and high degree of accuracy of 92% in the load identification process. Finally, additional trained network results showed that ANN as an inverse problem solver can be used to estimate the load applied on a structure once the load-response relationship has been identified.

1. Introduction

Monitoring of in-service flight loads is an important criteria used in understanding the behaviour of aircraft structures during flight operation, this helps in developing better safety procedures and also provides an estimation of the remaining life cycle for the structure. The parametric quantification of these loads can often prove to be an expensive and challenging task. The wing is one of the major component of the aircraft, its major function is to create the lift required for the flight. Spars, ribs and skins are the main structural members of the wing, spars carry a large portion of the wing bending loads while the ribs transmit the shear loads on the wing and also helps the wing to maintain its aerodynamic profile under loading condition. The relationship between the loads and the structural response of these members greatly depends on the wing's configuration and design, however the complexity in the design of today's wing structural members makes it difficult to formulate a relationship between the flight loads and the structural response. In addition, the uncertainty in direct quantification of the aerodynamic forces acting on these structural members during flight also contributes to the difficulty in establishing a reliable relationship.

Thus, the recent evolution in the use of mathematical techniques such as ANN to quantify these loads based on typical flight parameters like acceleration, velocities and strains has become more prominent. Extensive research have been carried out using ANN to model operational loads experienced by a fixed-wing aircraft structures [1], flight loads on a fixed-wing aircraft can generally be separated into gust and manoeuvre dominated loads, the majority of which tend to occur at frequencies of less than a few Hertz (Hz) and in the case of a rotary-wing aircraft, the loading spectrum experienced by the airframe structure is significantly more complex. A parametric full-scale fatigue monitoring system was also developed for an Airbus A330 Multirole Transporter using artificial neural network in [2], a variety of flight conditions was scheduled for the aircraft with several stain gauges installed on the some areas of the wings and fuselage to extract input data required for the ANN training. The developed technologies from the ANN was later used to design a structural health monitoring system for some major components of the aircraft. There have been a number of attempts in the last few decades at estimating loads on helicopter indirectly from flight state parameters or fixed points on the airframe with varying success [3]. In structural engineering ANN are commonly used for performance-based design, one of the classic advantages of ANN is its ability to use universal approximations which are able to

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provide continuous mapping and general mechanisms for structural models whose input to output relationship can be highly nonlinear [4]. Research on the use of ANN and Finite Element Analysis to predict structural response and damage detection on structures are presented in [5–8]. A classic case study on damage detection is presented in [9], where a damage detection procedure was developed using pattern recognition of vibration signature on a suspension bridge. Accurate damage set-ups were simulated with the response under normal operating conditions was calculated, data generated from the response spectra was introduced to a neural network for analysis, the results shows that the neural network could be used to attain a certain level of damage detection. Currently, flight loads are obtained using stain data response from major parts of wings as a result of the induced aerodynamics loads during operational flights. Introducing the measured strain as inputs to a well-trained ANN can produce a promising output result for the load acting on the wing based on the load response relationship. The advantage of this principle is that a complex structural analysis module could be substituted with a well-trained ANN model [10]. The purpose of this article is to extend the application of ANN in combination with finite element analysis to identify the static load on a large commercial aircraft wing rib without load cells, a preliminary simplified case study was conducted on an aluminium plate with the result published in [11]. In this paper, ANN was used to directly estimate the static load applied on the wing rib of a large passenger aircraft, in addition, ANN was also used to develop a load monitoring technology on the wing rib. The general concept is based on conducting a finite element analysis on the wing as outlined in Section 3, experimental static test and model calibration of the wing rib is proposed in Sections 4 and 5. Neural network implementation and load monitoring based on finite element data and random data are introduced in Section 6, capabilities and limitations of the approached are discussed in the concluding section of the paper.

2. Artificial neural network

Artificial neural network (ANN) are information processing units which are referred to as parallel computational structures derived from the study of biological neurons, the structures are considered to impersonate and operate in the same principal to which a human brain works. The principle and development of ANN was first introduced in [12], it has since then been studied and applied in a range of scientific and engineering related topics. The presence of the simple processing units called neurons makes it possible for a Neural networks to perform any computational task such as function approximation, system classification and pattern recognition. ANN have been successfully applied to a range of engineering and structural reliability related problems with detailed examples presented in [13], other applications of ANN in structural engineering and construction management with examples of pattern recognition and function approximation is presented in [2,14–16]. Back Propagation (BP) algorithm is often used in many engineering based NN application due to the simplicity involved in the training process. For a NN based on supervised learning algorithm to accurately perform any classification and approximation task, a training process must be involved. Training a network with a supervised BP learning algorithm involves finding the parametric function of the link that connects the nodes together, this is achieved by using a set of training examples. This parametric function is often called weight. The error between the actual outputs from the training set and the computed output is reduced iteratively using the sum of the square method and the rule for training also helps to identify how the weights can be improved during each iteration [17]. The BP algorithm is one of the most adopted algorithms to train different types of network such as the feed forward neural network, according to the literature a BP algorithm assumes random values for its weight which is then used to operate the NN to obtain a calculated output. Using the error minimization and training rule the weight can be modified as explained in the previous paragraph. The weight optimization process is then repeated until a network with minimum error is achieved, the NN is trained again and then also used for prediction [18].

2.1. Design and training of a neural network

ANNs consist of two major components: the processing elements which are called neurons and the connection links between the neurons. The neurons work as information processors with several inputs and outputs while the connections serves as a means of information storage in an ANN configuration. To use a NN, it is mandatory to initial identify a network architecture. The architecture of a neural network can be classified as the number and type of neurons present in the network, the method of connection between the neurons and how they are connected to the external source all contribute to the architecture of a NN. The number of neuron present in a network is a significant factor in a NN design, the number of neurons often decides the degree of freedom of the network.

Fig. 1 shows a diagram of a neuron with connections going in and out of it. Each neuron p first calculates the ‘activation state’, consisting of a weighted sum of the input signals and the addition of a threshold or bias, then applies a transfer function f called ‘activation function ‘to this sum and outputs the result (Yp), which can be used by other neurons of the network or directly as the network output. Feedforward ANNs have layered architectures and can also possess a pattern connected topology. The inputs of a stated layer and the output of a different definite layer are then connected to an outer parameter while all the other layers are classified as hidden layers [19]. A common layered architecture which is often used in most network configuration is the feedforward layered architecture, a feedforward architecture has no feedback loops. A multi-layer feed forward network consist of different

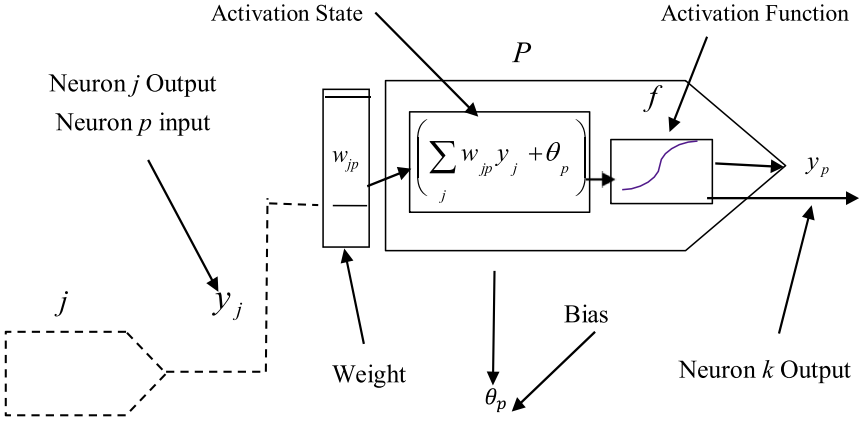

Fig. 1. Single neuron architecture.

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