GENETIC MODELLING AND VIBRATION CONTROL OF A TWIN ROTOR SYSTEM

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Abstract

A dynamic model for the characterisation of a twin rotor multi-input multi-output system (TRMS) in hovering mode is extracted using genetic algorithms (GAs). The TRMS behaviour in certain aspects resembles that of a helicopter, with a significant cross-coupling between longitudinal and lateral directional motions. Hence, it is an interesting identification and control problem. The global search technique of GA is used to identify the parameters of the TRMS based on one-step-ahead prediction. The extracted model is then employed for designing and implementing a feedforward/open-loop control law for vibration suppression. Open loop control is often the preliminary step for development of more complex feedback control laws. The paper investigates open-loop control strategies using shaped command inputs for resonance suppression in the TRMS. Digital low-pass filtered/shaped input is used on the TRMS test bed, based on the identified modes of vibration. The approach has shown to result in satisfactory vibration reduction.

1 Introduction

The increased utilisation of flexible structure systems, such as flexible manipulators and flexible aircraft in various applications has been motivated by the requirements of industrial automation in recent years. Flexible structure systems can be operated at high speeds and are capable of handling larger payloads as compared to rigid systems with the same actuator capabilities. Moreover, they offer several other advantages, including light weight, lower energy consumption, safer operation due to reduced inertia, smaller actuator requirement, low mounting strength requirement, low rigidity requirement and less bulky design [9]. Due to such advantages, flexible systems are extensively being used in various applications. However, system vibration arising from the structural flexibility is a major constraint in realising the advantages of flexible systems. Accordingly, control of flexible systems has been a challenge for researchers and engineers. A number of techniques have been proposed and implemented to control structural vibration of flexible systems. One of the popular methods involves shaping the input command with filters to suppress energy input at the dominant frequency modes and accordingly reduce system vibration [4,12]. This method requires accurate detection of the vibration modes through appropriate identification and modelling techniques.

Genetic algorithm (GA) is one of the global stochastic search algorithms based on natural biological evolution [2,7,8]. Genetic algorithms constitute global and data independent search techniques. They operate on a population of potential solutions by applying the natural evolutionary process (i.e. principles of survival of the fittest) to produce better and better approximation to a solution and as such it is flexible and parallel in nature. These attractive features have made GAs easy to realise, implement and use in solving practical problems [1]. Since their introduction by Holland [7] as evolutionary algorithms, there has been growing interest among scientists and engineers in the use of GAs in identification and control applications [9,10].

This paper addresses modelling of an experimental test rig representing a complex twin rotor multi-input multi-output system (TRMS) in hovering mode using GAs. The hovering property of helicopter/TRMS is the main area of interest in this work. Station keeping, or hovering, is vital for a variety of flight missions such as load delivery, air-sea rescue etc. Such a plant is thus a good benchmark problem to test and explore modern identification and control methodologies.

The modelling is done assuming no prior knowledge of model structure or parameters relating to physical phenomena, i.e. black-box modelling. This is realised by minimising the prediction error of the actual plant output and the model output. Different identification algorithms such as least mean square (LMS), recursive least squares (RLS) and neural networks have previously been used to model the system and to obtain the dominant vibration modes [3,5,11]. The various attractive features of GAs as described earlier motivate utilisation of a GA for this purpose. In this investigation Butterworth type low-pass filtered bang-bang input is developed on the basis of the vibration modes detected through GA-based modelling technique and applied to the system to reduce motion-induced system vibration.
It is evident from the system behaviour that structural vibrations occur due to uneven rotor load and motor torque while in operation. A practical way of controlling a system with resonance modes is to use a combination of feedback and feedforward schemes. This paper also investigates a feedforward control technique known as “command/input shaping control,” where an input signal is shaped so that it does not contain spectral components at the system’s resonance frequencies (Figure 1). The approach requires that the resonance frequencies of the system be determined through suitable identification and modelling techniques, and GAs are used for this purpose.

2 Experimental set-up

The TRMS, shown in Figure 2, is a laboratory set-up designed for control experiments [6]. In certain aspects it behaves like a helicopter. The TRMS rig consists of a beam pivoted on its base in such a way that it can rotate freely both in the horizontal and vertical directions producing yaw and pitch movements, respectively. At both ends of the beam there are two rotors driven by two d.c. motors. The main rotor produces a lifting force allowing the beam to rise vertically making a rotation around the pitch axis (vertical angle). While, the tail rotor (smaller than the main rotor) is used to make the beam turn left or right around the yaw axis (horizontal angle).

In a typical helicopter, the aerodynamic force is controlled by changing the angle of attack of the blades. The laboratory set-up is constructed so that the angle of attack of the blades is fixed and the aerodynamic force is controlled by varying the speed of the motors. Therefore, the control inputs are supply voltages of the d.c. motors. A change in the voltage value results in a change in the rotational speed of the propeller, which results in a change in the corresponding position of the beam [6].

Although the TRMS system permits MIMO experiments, this paper addresses the problem of modelling and control of the system in a single-input single-output (SISO) mode in the longitudinal axis (i.e., vertical movement). The horizontal movement caused by the tail rotor was physically locked and as a result there is no cross-coupling effect between the two channels of the TRMS. The problem of MIMO modelling and control is an interesting issue, and will be looked at in future studies.

3 Genetic Algorithms

Unlike steepest descent approaches to nonlinear parameter identification, GA requires no calculation of the gradient and is not susceptible to local minimum problems that arise with multimodal error surfaces. The algorithm begins with a collection of parameter estimates, called chromosomes. Each chromosome is evaluated for its fitness in the problem domain. At each generation (algorithm time-step) the most-fit chromosomes are allowed to mate and bear offspring. The new parameter estimates (offspring), then, form the basis for the next generation. GA operators, such as selection, crossover and recombination are then re-employed to process the next generation [1]. This process is repeated several times to satisfy some criteria. The mutation feature is often introduced to guard against parameter convergence.

3.1 Dynamic modelling of TRMS with GA

In this investigation, a GA is used for parametric identification of the TRMS in hovering operation mode, essentially to determine the vibration modes of the system. Randomly selected parameters are optimised for different, arbitrarily chosen order to fit to the system by applying the working mechanism of GA. The fitness function utilised is the sum-squared error between the actual output, $y(n)$, of the system and the predicted output, $\hat{y}(n)$, produced from the input to the system and the optimised parameters:

$$f(e) = \sum_{i=1}^{n} (y(n) - \hat{y}(n))^2$$  \hspace{1cm} (1)

where, $n$ represents the number of input/output samples. With the fitness function given above, the global search technique of the GA is utilised to obtain the best set of parameters among all the attempted orders for the system. The output of the system is thus simulated using the best set of parameters.
The system was excited with a sequence of Gaussian random signal (GRS) of different bandwidths (0-10 Hz) in order to ensure that all system resonance modes are captured. The GRS signal level, ±0.2 volts, was selected so that it does not drive the TRMS out of its linear operating range. Good excitation, as shown in Figure 3, was achieved from 0-5 Hz that covers all the important rigid body and flexible modes of the system.

The system was modelled from the input volt to vertical angle/movement. Satisfactory results were achieved with the following set of parameters:
- Generation gap: 0.9
- Crossover rate: 0.8
- Precision: 14 bits
- Mutation rate: 0.0062

The vertical-angle model was investigated with different model orders. The best result was achieved with an order 4. The GA was designed with 80 individuals in each generation. The maximum number of generations was set to 200. The algorithm achieved the best sum-squared error level of 0.0014429 in the 200th generation. Figure 4 shows the algorithm convergence and the simulated output with the parameter set that resulted in the 200th generation. The main vibration mode, as found from the GA simulated output was at 0.3515 Hz.

Figure 3: Gaussian random input signal.

Figure 4: Genetic modelling of the TRMS.
The stability of the model was monitored using its pole-zero diagram. It was observed that all the poles remained inside the unit circle (Figure 5). Although, there were some zeros outside the unit circle which indicates the system has a non-minimum phase behaviour. This will have an impact on controller design in a feedback configuration.

4 Vibration Control

Approaches that have been employed for controlling flexible systems can be broadly divided into feedback and feedforward methods. Feedback control approaches utilize measurements and estimates of the system states to reduce vibration. However, fast tracking performance is always constrained by the physical limit of the actuator rate. An alternative approach is to use a feedforward filter, which alters the tracking command or setpoint so that system oscillations are reduced. The performance of feedback methods can often be improved by additionally using a feedforward controller and suitably designed feedforward compensators can significantly reduce the complexity of the required feedback controllers for a given level of performance. The current study will be confined to the design and implementation of a digital feedforward filter for command shaping and will consider combined feedforward and feedback control in future investigations.

4.1 Filter Implementation and Results

Open-loop control methods have been considered in vibration control where the control input is developed by considering the physical and vibrational properties of the flexible system [4]. In this investigation, digital filters are used for pre-processing the input to the plant, so that no energy is ever put into the system near its resonance.

To study system performance initially an unshaped doublet bang-bang input is used, and the corresponding system response is measured. The main objective of this section is to suppress the system vibration at the dominant resonance mode, determined earlier. A low-pass Butterworth filter of order three with a cut-off frequency at 0.1 Hz was designed and employed for processing the bang-bang input. The shaped bang-bang input is then injected to the TRMS and its response is measured. The unshaped and low-pass (LP) filtered bang-bang and their corresponding spectral densities are shown in Figure 6.

Figure 5: Pole-zero diagram.

Figure 6: Unshaped and LP-filtered band bang signal

Figure 7 shows the response of the system to the unshaped and low-pass filtered bang-bang signals. It is noted from Figure 7b that attenuation in the level of vibration at the main resonance mode of the system was 30dB with the shaped input in comparison to the system response with unshaped doublet.

5 Conclusion

A one degree-of-freedom SISO TRMS model, whose dynamics resemble that of a helicopter has been successfully identified using GAs. System identification is an ideal tool to model non-standard aircraft configurations, whose flight mechanics are not well understood. Both time and frequency domain analyses were utilised to investigate and develop confidence in the obtained model. The extracted model has predicted the system behaviour well. The extracted model has been employed for designing and implementing feedforward/open-loop control in the second stage of this work.
A simple feedforward control technique known as “input shaping control”, has been designed and implemented for system vibration suppression. In this methodology, the system command input signal is shaped so that it does not contain spectral components at resonance frequencies of the system. The study revealed that good performance in attenuation of system vibration at the resonance modes is achieved with the employed low-pass filtered input. Open-loop control forms an important preliminary part of closed loop control design, in particular for flexible systems like flexible aircraft/TRMS. This is a topic of future investigation.

References


